The Graphene Flagship Technology and Innovation Roadmap

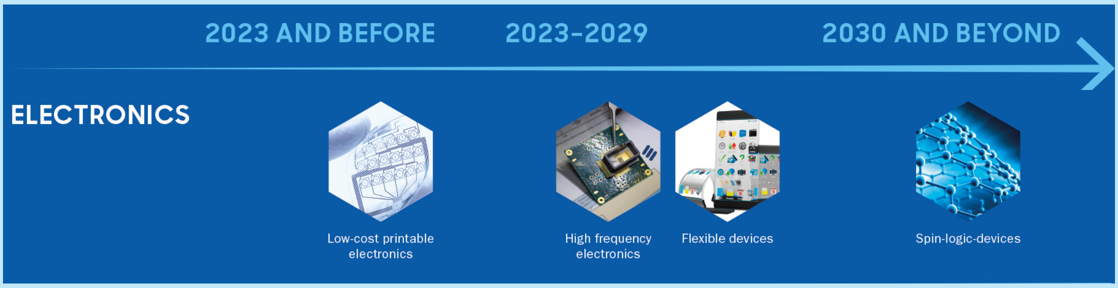
Electronics and Photonics

Due to the interesting electronic and optical properties of graphene and 2D materials, it is obvious that many different applications are possible in this field. This field often requires thin films and layered materials, which represents a paradigm change compared to bulk utilizations of 2D materials. The market perspective is generally very promising, as large and typically growing markets are addressed.

A major obstacle for many applications is economic feasibility of wafer scale integration and scalable high quality preparation of graphene and other 2D material films with sufficient quality and yield. On the other hand, if wafer scale integration succeeds, many applications suddenly become interesting and viable.

In terms of applications from a functional point of view, hybrid approaches with silicon appear promising, where graphene is added in the back-end-of-line or back end to deliver additional functionalities (e.g. optoelectronics, THz, sensors). Besides that, 2D materials appear particularly interesting for flexible applications where no leading incumbent technology readily exists (silicon does not perform well) and, thus, a strong need for new materials persists.

This is an excerpt from the complete Technology and Innovation Roadmap.



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5 Electronics & Photonics

5.1 Potential Electronic & Photonics applications

Graphene and 2D materials have interesting electronic applications:

- Varying electronic band structures as metal, semi-metal, semiconductor and insulator
- Varying optical and optoelectronic properties
- strongly nonlinear optical properties in the whole electromagnetic wave spectrum, from RF to optical frequencies
- High electron mobilities
- Two-dimensional character being optimal for layered devices
- Large surface area and strong influence of surrounding on electronic properties are good for sensing applications
- Flexibility for flexible electronics
- Interesting properties for spintronics (e.g. long spin diffusion length)

The electronics and semiconductor industry currently sees two major directions, i.e. "More Moore" (miniaturisation) and "More than Moore" (diversification), see Figure 68. Graphene and 2D materials can play a role in both areas and in the combination of both, although a higher potential is currently seen in the More than Moore path. The various potential application areas of graphene/2D materials are summarized in Figure 69. The several application areas are covered in separate chapters. The assessment starts with a few cross-cutting topics and issues that are to a certain extent relevant for all electronics applications.

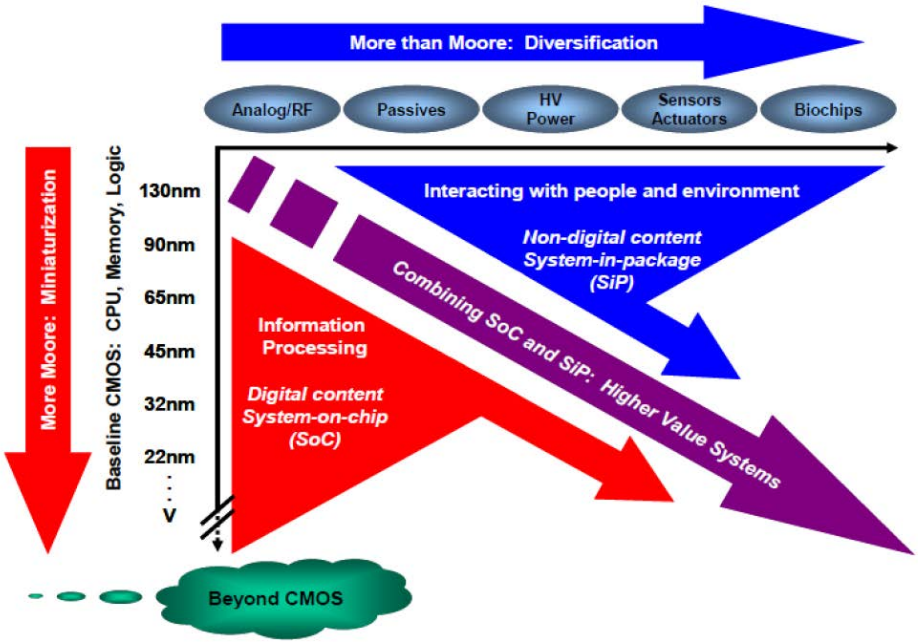


Figure 68: The major developments in the semiconductor industry towards miniaturisation and diversification as well as their combination in heterogeneous integration. [360]

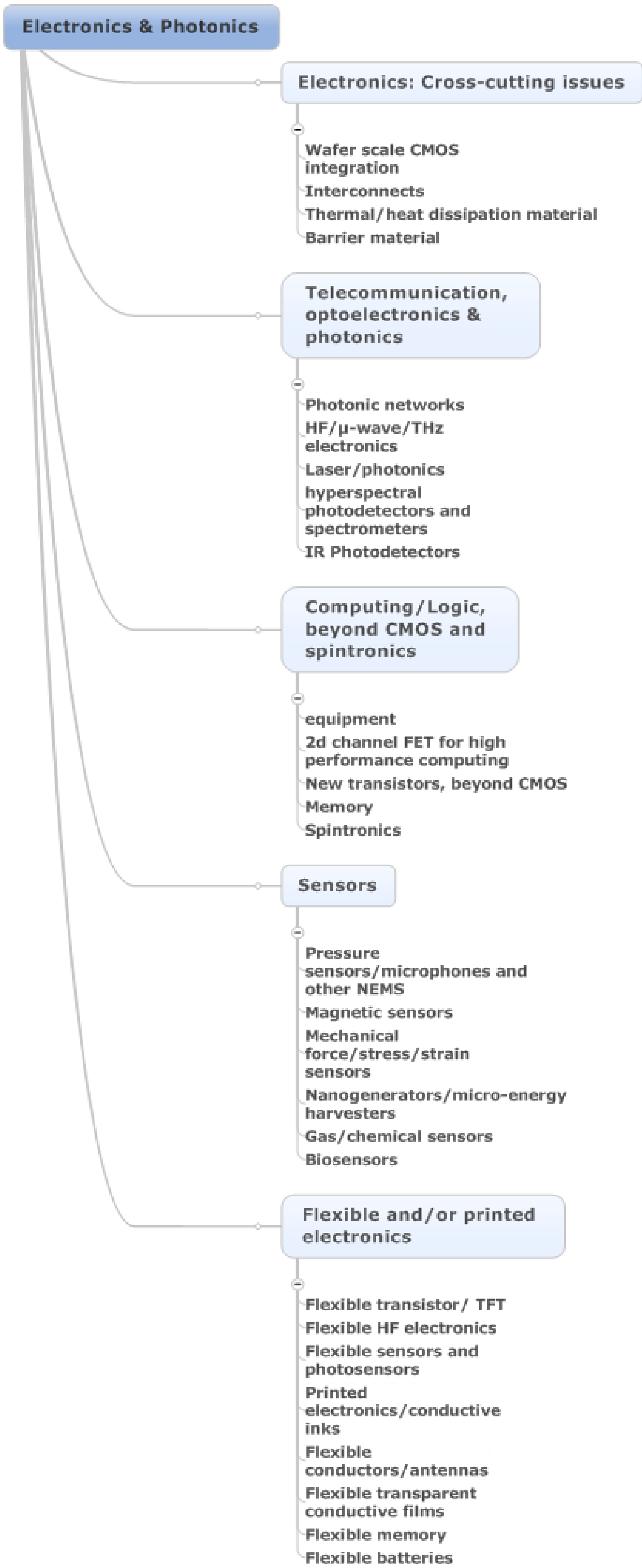


Figure 69: Application areas in the electronics and photonics domain.

5.2 Electronics: Cross-cutting issues

In the broad (Opto-)Electronics, Photonics and (Bio-)Sensing area several common issues with respect to the use of graphene/2D materials exist. This section covers the following identified common issues:

- General and common issues, i.e. issue related to the use of graphene/2D materials as (semi-)conductors and in the electronics industry in general.
- Wafer scale CMOS integration, i.e. integration of graphene/2D materials in standard CMOS processes, a prerequisite for many applications in the electronics industry.
- Interconnects, i.e. the use of graphene/2D materials in the back-end-of line for contacting between various semiconductor devices on a chip.
- Thermal material, i.e. use of graphene/2D materials as a thermal materials for heat removal and dissipation.
- Use as a barrier in electronics, i.e. to avoid diffusion of harmful substances into the semiconductors, e.g. metals from contacting.

The issues, opportunities etc. related to particular application areas will be presented in later chapters.

Table 36: Different cross-cutting electronics issues of graphene/2D materials and their functionalities.

Type of cross-cutting issue	**Functionality**
Wafer scale CMOS integration	• Laminate graphene on CMOS for specific functions, e.g. in optoelectronic transceivers, optical interconnects to reduce power consumption & increase speed • How to integrate graphene into MNE industry, large area, large scale
Interconnects	• Graphene as interconnects on chip and on package level
Barrier materials	• Graphene/2D materials as barrier material between different materials (e.g. via/interconnect and chip), probably combined with heat dissipation, interconnect or other active functionalities.
Heat dissipation material	• Graphene/2D materials as heat dissipation material for passive cooling, probably combined with other features such as barrier or interconnect or other active functionalities.

5.2.1 Market perspective: graphene/2D materials in the semiconductor and electronics industry

Worldwide semiconductor sales were $335.2 billion in 2015, expected to increase to $341 billion in 2016 and $352 billion in 2017 (CAGR of 2.5% 2015-2017). [361]

The product value generated in Europe with Micro- and Nano-electronics components was €17.8 billion in 2014 with a CAGR of –7.2% from 2012-2014. [155] In this area Europe is behind Asia and North America in terms of turnover (see Figure 70). European producers have roughly 10% of the global market share (USA 50%). [361] Looking at the broader picture of electrical and electronic engineering industries, including radio and telecommunications industries as well as wireless communication industries, the European gross output in 2012 was €703.3 billion, approximately 9.6% of all manufacturing gross output, and the industry produced €212.4 billion in 2012. It is recognized as one of the most competitive manufacturing industries in Europe by the European Commission. [362]

It is a goal of the European Commission to double the economic value of the semiconductor component production in Europe by 2020-2025. Europe has a strength in More than Moore technologies and special logic applications, e.g. for automotive and low power. It furthermore is strong in material, equipment, chip design and fabless activities, and system integration. 20% of the production of equipment and material is currently done in Europe and there is growth potential. [363] Only a very small share of classical PC and mobile phone processors and high performance processors are currently manufactured in Europe (Intel in Ireland and Globalfoundries in Germany, there are also some state of the art fabs in Israel), similar to storage media (RAM).

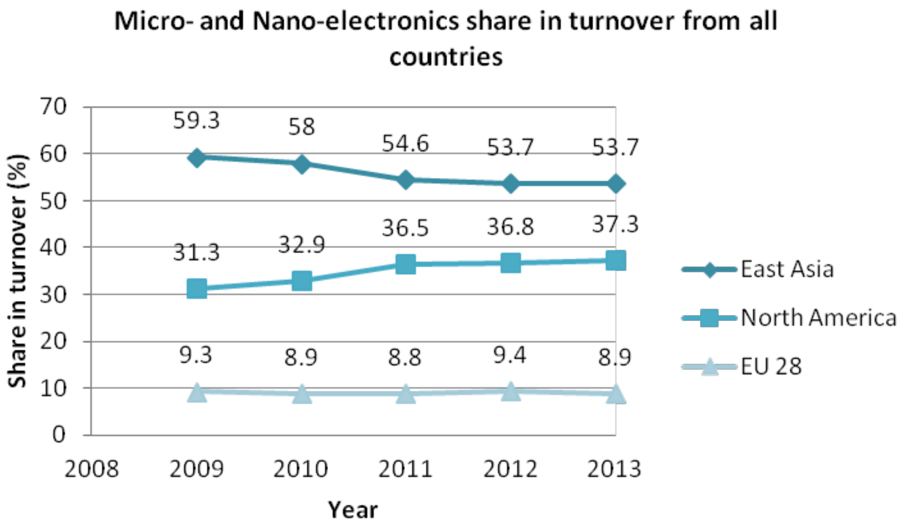


Figure 70: Share in turnover relative to all countries of micro- and nano-electronic goods. [364]

The value chains for semiconductor industry are truly global, which can be seen in Figure 71. The value creation is largest at the systems level. Graphene will be integrated at the semiconductor and material level, although it can have effects and enabling character along the value chain, see Figure 72. Europe is strong in vertically integrated markets, such as automotive, energy, security and smartcards. There are also certain strengths in industrial electronics and data processing electronics. [365] It possesses leading positions in sensors and MEMS markets (see 5.5.1 Market perspective: graphene/2D in sensors). Besides that, it has strengths in virtual components and low power processors, and in the supply of equipment, materials and IP (Intellectual Property) into the value chain. [363]

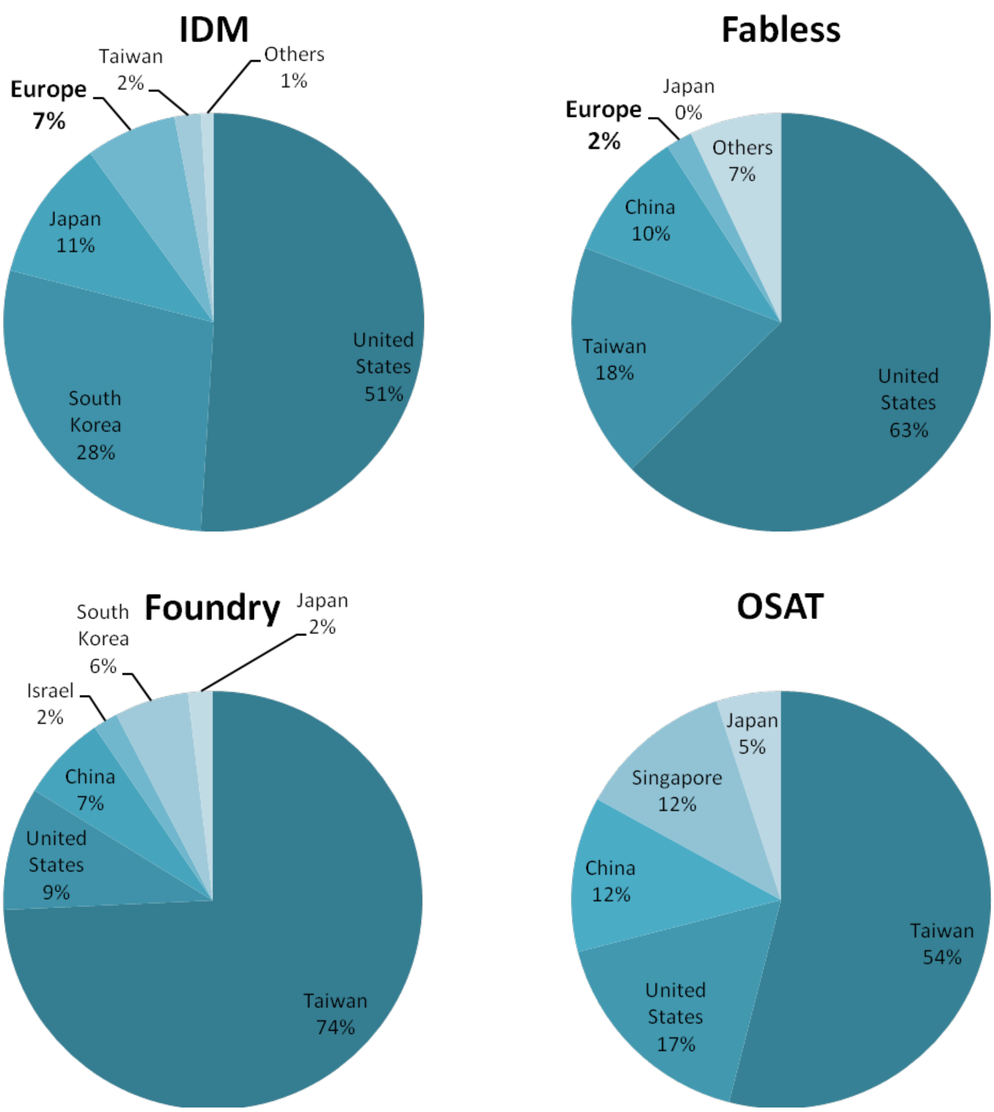
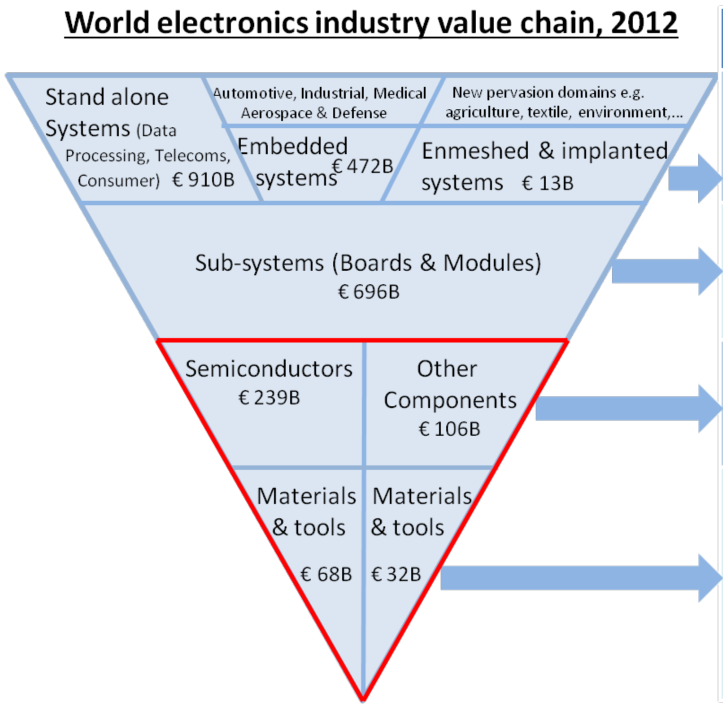


Figure 71: Percentage of global revenue. Europe plays a role in the semiconductor components industry with integrated device manufacturers (IDMs) and a few fabless companies. Outsourced semiconductor assembly and test (OSAT) and foundries play a negligible role. [366]

Figure 73 gives an overview, which in which end use markets ICs generate the greatest sales and growth rates. Automotive is the third largest market after computers and phones. Figure 74 highlights the type of semiconductor products sold in 2015. Logic and memory are the strongest products (“more Moore”), followed by analogue, MPU and opto components. The largest growth was observed for opto components and sensors. The semiconductor industry is among the most research intensive industries with expenditures reaching almost 20% of sales. [361]



	PROD. EUROPE (€B)	% EU/World
Level4: *Systems*	225	16 %
Level3: *Boards and Modules*	80	12 %
Level2: *Components*	30	9 %
Level1: *Equipment &Materials*	20	20 %

Figure 72: Value chain in the electronics industry and European share. Graphene can be integrated and used to the greatest extent in the highlighted areas, although it can enable downstream innovations and improvements. [363]

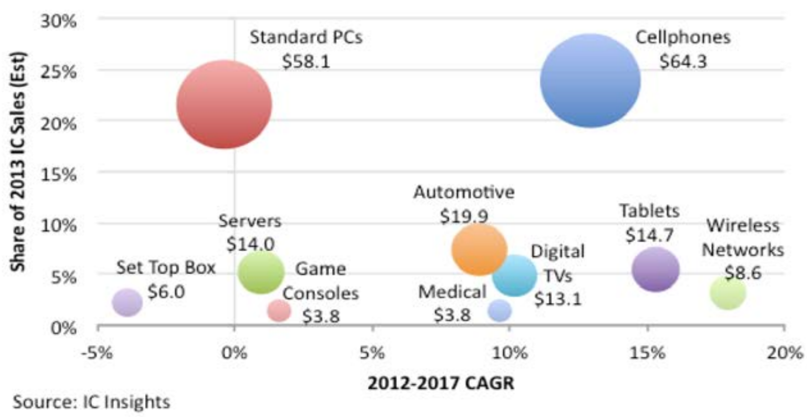
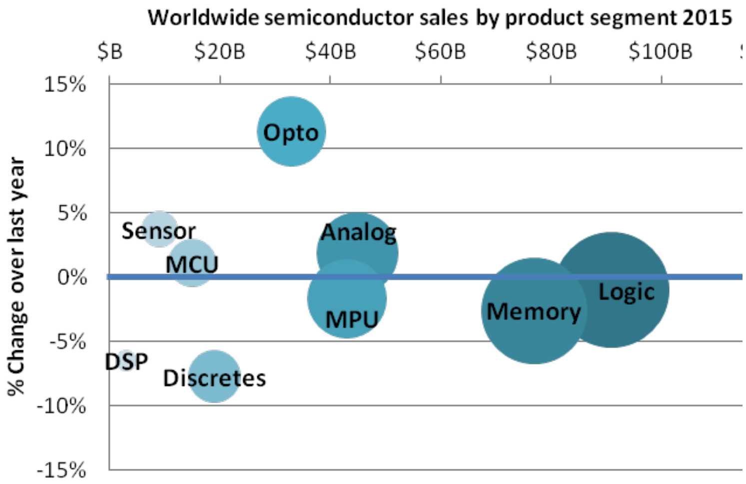


Figure 73: Global sales of ICs in end use markets in billion $ and growth rates 2013 [363]



Product	Sales	Growth
Logic	$91B	-1.0
Memory	$77B	-2.6
Analog	$45B	1.9
MPU	$43B	-1.7
Opto	$33B	11.3
Discretes	$19B	-7.7
MCU	$15B	1.1
Sensor	$9B	3.7
DSP	$3B	-6.5

Figure 74: Global semiconductor sales by type of product sold in 2015. [361]

5.2.1.1 Market Opportunities

5.2.1.1.1 Electronics and hybrid approaches with Si as an entry point for commercialisation

Purely graphene or 2D materials based electronics as well as “graphene as the new silicon” is not expected by most actors in the electronics field. However, there are opportunities to use graphene and 2D materials in hybrid approaches integrated with silicon (“more than Moore”). This can add active and passive functionalities (e.g. optoelectronic, sensor, analogue interconnect, nonlinear elements) whilst the benefits of the well known and understood Silicon platform can be used. Therefore, hybrid approaches with graphene/2D on Si (Si-on-Insulator, SiN, etc.) are probably the most promising and the most reasonable first entry point for commercialisation in electronics. Such an integration can enable further use of the technology and allows a proper industry assessment. But there are still major barriers to overcome until such a scenario becomes reality.

Moore’s law (higher transistor density and lower cost per transistor), as a self-fulfilling prophecy will at some point come to an end (some time between 2020 and 2025 according to most experts in the field [367]). However, this rather opens up the diversification of applications, as the field is already now becomes more and more diversified and at the same time many functions converge (software, SoC, SiP, networks, new architectures, etc.). The planability will decrease and the ITRS is already reacting with the initiative ITRS 2.0 [368]. Still, materials will remain at the core of new hardware developments in semiconductor industry and electronics. As such, new concepts and materials will be always sought.

5.2.1.1.2 Back-end-of-line and back end demand cost-effective technologies

The back-end-of-line (where individual devices produced in front-end-of-line get interconnected with wiring on the wafer) and the back-end (packaging and connectors of finished chip) are nowadays often more expensive and work intensive steps than the front-end-of-line. Therefore, these steps have a high pressure to become cheaper and any solution that delivers a performance increase whilst not increasing cost or process effort is welcome. Furthermore, back-end processes have less stringent constraints on integration compared to front-end-of-line. At the core of devices (front end), there are many constraints on quality, but if a material is added on top of something as added functionality, constraints are not so high, and the chance is higher for integration.

Especially for MEMS devices, the back end is very important and packaging is part of the innovation in MEMS. Therefore graphene use in MEMS technologies opens interesting opportunities, especially as Europe is strong in MEMS technologies and specialized medium sized companies are active in that field.

If a technology can be easily integrated into an existing line, it can lower the barrier for a new material tremendously. In that case, even the expectations on performance or cost advantage are reduced (not the 10x, see below) and integration can be feasible even for niche applications. The simplicity of integration alone can justify the incorporation of a new material in the back-end-of-line.

It might eventually become a great chance for graphene to play a role in these back end steps.

5.2.1.2 Additional market opportunities: wafer scale integration

5.2.1.2.1 When the technology and production is demonstrated, many doors are opened

Industry demands a (simple) demonstrator made with actually compatible CMOS processes and reasonable yield. If this is successfully shown, spill-over to other applications is possible and broad adoption can begin. Only if wafer scale integration works, many applications will be possible to realize on commercial scale.

Especially if it is shown that graphene/2D materials can be incorporated into existing foundries with good material control and are compatible with the existing tools, there is a great opportunity that it will be used for variety of applications.

At some point later in time, other very cost sensitive applications might also become feasible when the price of integration declines.

Currently, there are a few promising applications that already demonstrate the “10x” potential experimentally, e.g. in hall sensors, photodetectors or optical modulators. However, the integration challenge is still too high, that a single company takes over the integration challenge.

5.2.1.2.2 First implementation possible without foundries

The diffusion of the technology to foundries can trigger broader implementation, as many fabless companies could also implement graphene and many downstream industries (such as automotive, datacomm and telecomm) can benefit on a broader basis. However, European strength lies in IDM companies (see Figure 71) and integration could be possible there, especially for know-how sensitive products (in the beginning). So some applications do not need foundries, even for broader implementation.

5.2.1.2.3 Spill over effects to other 2D materials

Graphene is a good entry to pave the way for further 2D materials. It is the pioneering 2D material and if an integration scheme works, other 2D materials can follow easier in the slipstream. TMDs are more complicated, as stoichiometry is an additional degree of freedom playing a role for the properties, so in principle they are trickier to integrate. On the other hand, if graphene integration does not succeed, other 2D materials can be in discredit.

The same logic is true for spill-over effects of TMDs: If you can make one TMD, others follow the same principle and the whole class of materials might be accessible.

5.2.1.3 Additional market opportunities: interconnects

5.2.1.3.1 Limits of current Cu-based technology

Interconnects are a major bottleneck and there is an opportunity for new materials and systems, such as high quality repeaters. Below 20nm Cu interconnects suffer from strong increase of resistance and electromigration. Novel materials are needed to overcome this limitation. The need arises starting from 2020 and increases to 2028. [369] RC of interconnects started to dominate the delay and power dissipation already from 10 nm CMOS. Already today interconnects account for >60% power dissipation and 20% of circuit delay and are thus an ever growing challenge. [370, 371]

Interconnects become more and more important for heterogeneous integration as systems on chip (SoC) and (3D) systems in package (SiP), especially for 3D integration. Multilayer graphene might be a valid alternative for interconnects and could be worth exploring further from the technological point of view.

5.2.1.3.2 Opportunities when graphene integration works feasibly

For technologies where graphene is used anyway (e.g. as active material), graphene can be easier integrated as interconnect. Graphene becomes furthermore very important as interconnect, the day other 2D materials are used, but this is far out in the future, if it occurs at all.

5.2.1.4 Additional market opportunities: Barrier materials

5.2.1.4.1 Need for ultrathin and conductive Cu barrier layers

As long as Cu interconnects are used (possibly beyond 2028), a barrier layer is needed between interconnect and transistor. This layer conducts the charges but prevents Cu from diffusing into the active device. It further acts as an oxidation and corrosion resistant layer. The barrier layers need to become ultrathin and conductive, so that graphene is one of the potential candidates to replace barrier metals such as Ta(N) and Mn(N). [369]

5.2.1.5 Additional market opportunities: Heat dissipation material

5.2.1.5.1 Thermal management is an important issue

Thermal management is a general issue, from film/chip-level to system-level solutions. System level materials are also covered in chapter 3.2 and chapter 3.3. Power dissipation and heat removal of components are important challenges for energy efficiency. For current chip technologies temperatures <100°C are the limit and <65°C are the desire. This should be achieved with compact and lightweight solutions. Passive cooling is therefore the desired solution, however passive cooling is a problem as it may be not efficient enough.

Already a slightly better performance than incumbents or competing solutions could well be sufficient for a stronger market interest, as 10% lower temperatures results in 10% higher efficiency and double the lifetime of electronic components. A better cooling can help to push existing technologies further due to smaller footprints, higher possible currents and harder driving. On transistor level local thermal issues are becoming more and more a limiting factor, especially when going to power density increases in ever smaller scales and higher integration.

On system level, a better and more expensive thermal management can probably lead to an overall cost reduction as the core technology can be further exploited (though harder driving, larger currents…).

Cooling is crucial for all ICs and active components including high power electronics. If graphene/2D based solutions are demonstrated to work and an integration scheme is feasible, it can be used for many different products, from low cost to high value. A first entry would probably be advanced packaging for high value products.

5.2.1.5.2 Active cooling disadvantageous and not desired

Active cooling is maintenance intensive, consumes energy, has usually a larger footprint and some solutions have moving parts (fans). This is not desirable and therefore passive solutions are more appealing.

5.2.1.6 Market Threats

5.2.1.6.1 Conservatism regarding new materials: expectations for new materials in terms of cost/benefit are enormously high

The conservatism to stick to known technologies and materials and fully exploit them leads to unwillingness to bring new technologies/materials into a fab, following the idea of: If it works today, why change?

The experience with Silicon, CMOS and other bulk semiconductor technologies is very strong and everything that can be done with further improvement of existing technologies will be done with them.

The market demands either much cheaper solution with same performance or much better performance (very good cost/benefit). Therefore new materials/technologies have to present benefits of 10x better performance or 10x cost advantage (or something in between both cost and performance advantage) to be regarded as interesting. If this is not met on a demonstrator level, it is likely that a technology is disregarded. This results in a hesitation to include new machinery and processes presenting a barrier for new material systems. If a 100x increase in performance or power consumption is achieved for transistors or basic platform technologies, industry will solve the integration almost independent of the related challenges.

The effort/cost for qualification of a new material is tremendous and therefore, not many materials will be able to change the electronics industry on broader basis. New materials therefore see large barriers and need a long time until they are recognized and implemented in a fab (incubation time is 12-15 years [360]). However, the semiconductor industry faces challenges due to ever higher integration and the mantra of Moore’s law, so that the will to go for new computing and beyond CMOS technologies, as well as to go for new materials within CMOS was never as high as today.

5.2.1.6.2 Paradigm shift from 3D to 2D materials

It requires a paradigm shift in the semiconductor industry when going from 3D materials to 2D materials. Whereas the bulk material determines the properties in 3D materials, properties of 2D materials are determined by their surface. Therefore, every process step can have consequences on the 2D material properties and the cross-correlation of different process steps is much higher than with 3D materials today.

5.2.1.6.3 Overarching expectations that will hardly be met: threat of disappointment

The industry has high expectations on research results coming from fundamental research, especially in terms of timing of advances. If after a discovery no further improvements are seen and a technology/material does not live up to its expectations after 2-3 years, the industry becomes uneasy regarding the new technology. Graphene was strongly researched in recent years (e.g. IBM, Samsung, Texas Instruments) but it got quiet around that. This either points towards the fact that the research was unsuccessful and the interest is fading or that first real applications are under development in secrecy.

The impression at the moment is rather that the confidence in graphene is fading, especially from the application side and as the barriers for integration and production are still high and killer applications everybody sought for have not been found so far. The theoretical expectations were very high initially (“replace silicon”). This turned to the opposite effect when they were not met within recent years (trough of disillusionment in the hype cycle), leading to the perception of a “wonder material” that does not do anything. It is important to temper these attitudes and honestly and realistically manage the expectations for the material. This demands for instance analyzing the material holistically, i.e. in terms of electronics applications for low power, high performance and good reliability instead of studying one attribute at the time.

Furthermore, standardization becomes important to make sure what are we talking about, when talking about graphene.

If graphene is not successful in any application, it can be a threat for the application of other 2D materials, as they might also be in discredit.

5.2.1.6.4 Patent thickets

The initial strong interest of companies such as IBM[20] and Samsung lead to a patent thicket, especially in the electronic applications. This is particularly tricky for other actors and smaller companies, as it is hard to keep an overview of all patents. Especially for smaller players, negotiating license agreements can be very complex and expensive, creating a huge barrier particularly for small players.

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20 IBM patents are now with Globalfoundries since the acquision of IBM’s microelectronics business in 2015

5.2.1.7 Additional market threats: wafer scale integration

5.2.1.7.1 Wafer scale integration as key bottle neck for a variety of applications: if it does not work, many applications will be doomed

Wafer scale integration is key for many electronics related applications. If wafer scale integration does not work, many applications will be impossible to realize on commercial scale. It is the dominant bottle neck for: logic, RF/µ-wave, optoelectronics, telecommunication and partially for sensors and flexible electronics.

Wafer scale (CMOS) processes are based on films, coating technologies, patterning, etching and post processing. Graphene and other 2D materials are in principle compatible with these technologies, as it is a two-dimensional sheet. Graphene integration is comparable with MEMs production, where also many different materials are added to the semiconductor. Despite this compatibility, it is a long way to go and many open questions on the feasibility remain. One already perceives some scepticism in the industry regarding whether GRM integration will work properly at all (and in an economically feasible way).

No matter how the GRM integration will succeed, scalability and demand need to be matched, i.e. depending on the demand for particular applications, different scales (e.g. wafer sizes) might be sufficient. This might at some point lead to imbalance, as demand will come with scalability and further demonstrators. Still, it is most important that the economically feasible integration can be shown for interesting applications, where graphene delivers an actual technological USP.

5.2.1.7.2 Conservative semiconductor companies and reluctance to use new materials needing new processes

Semiconductor companies are conservative and shy away from new materials and tools. This is especially true for fabs and foundries: a new material in a fab is usually equivalent to huge costs, which introduces a huge barrier. Many innovations are done with existing tools to the extreme. As soon as new processes/tools are needed this induces a large acceptance barrier. The incubation time for new technologies and materials is usually 12-15 years [360]. Expectations are to either provide 10x performance increase and/or 10x better cost efficiency.

5.2.1.7.3 Expectations on new processes and materials are high

Due to the usually high costs to bring a new material into a fab, very clear cost/performance advantages are needed in an application to justify large investments in new machinery or materials. This also applies to graphene and 2D materials, although some of the processes are compatible or used semiconductor processes (especially in MEMs manufacturing).

Further barriers are related to expectations from industry on reliability and very high yields (typically >90%). Additionally, a semiconductor fab needs to have a high degree of capacity utilization (usually >90%) to be economically feasible. This also implements a barrier for low volume applications and highlights the demand for a critical mass of applications.

Incumbent materials (Si, Ge, III-V, etc.) are always a threat for new materials, as the processes are well understood and under control. Qualification of new processes and materials can take 1-4 years, which adds an additional barrier towards materials that are already used today.

5.2.1.7.4 Foundries needed to address large mass markets

To become relevant for fabless companies, foundries need to be involved and machinery needs to be developed together with foundries. This only works for large volumes, as foundries only address processes with high enough throughput and volume. It seems that large foundries currently do not work on graphene (only on basic research level). If new tools are needed, it is less interesting for foundries and the demand needs to be even higher. It is an open question, who pays the cost for graphene integration when a new tool is needed in a foundry.

5.2.1.7.5 Competition with US and Korea

Strong players in US and Korea patent graphene, especially with respect to electronics applications (Samsung, IBM, Apple). This creates a patent thicket (see 5.2.1.6.4 Patent thickets). It is yet unclear, whether the big players, who might be capable of graphene integration are still following this path (Samsung, Texas Instruments, TSMC).

5.2.1.7.6 Ecosystem development needed

The full integration of graphene/2D materials needs to be done by industry. Academia and research institutes can only push the integration and demonstrator development to a certain point, from which industry has to take the lead. It is indeed a problem, that the question when and how this point will/can be reached remains unsolved. Especially the currently high integration challenges and open questions together with the demonstrators that are not yet promising enough, are too much of a risk for a semiconductor company to stronger focus on graphene integration. Along with that, the new material needs a modified ecosystem and supply chain, open up another risk. The endeavour to reach a point where industry can take up the development, the demonstrators need to be further developed, also looking at scientifically less interesting parameters such as reliability, (temperature) stability as well as the holistic and full set of relevant parameters for the performance, so that a benchmark with other technologies is fair and possible. Equally important, processes need to be further developed and scaled for reliable and feasible production. This demands a lot of engineering knowledge and work. Furthermore, the whole value chain and eco system needs to be developed at the same time. This demands standards and joint efforts from research and industry.

5.2.1.8 Additional market threats: interconnects

5.2.1.8.1 Incumbent and competing materials

Besides the existing Cu conductors, other technologies are under investigation, e.g. Silicides, CNTs or CNT-Cu composites or in general making use of collective excitations in the conductors. [369] Furthermore, the thinness of 2D materials is not necessarily a big advantage, as the lateral dimensions are more important for further integration. The Cu layers are also already quite thin.

5.2.1.9 Additional market threats: Barrier materials

5.2.1.9.1 Incumbent and competing materials

The incumbent materials (Ta(N) and Mn(N)) are still sufficient for the next 10 years or so. Other researched material classes are for instance self-assembled monolayers. [369]

5.2.1.10 Additional market threats: Heat dissipation material

5.2.1.10.1 Existing technologies

On system level, metal and carbon pastes or bulk materials (Cu) work fine, although they have a typically large footprint. 30-40 other concepts are under investigation and to a certain extent similarly promising as graphene based heat dissipation materials.

5.2.1.10.2 Packaging as a cost driver

Packaging is a cost driver and costs usually need to go down. Only if on system level a price reduction through a better package is possible it will be worth it. For specialised applications, some added costs might be feasible, but only for small and high valued markets.

5.2.2 Graphene/2D materials perspective: current strengths, weaknesses and challenges for the use in electronics: cross-cutting issues

5.2.2.1 Current strengths for graphene/2D materials use in electronics: cross-cutting issues

5.2.2.1.1 Multifunctionality

The combination of electrical, mechanical, barrier and thermal properties is a USP of graphene. Especially for interconnects and in the back-end-of-line and back-end, these properties can be very interesting. Furthermore, it offers transparency and flexibility, interesting properties for flexible electronics (5.6 Flexible and/or printed electronics) and wearables.

5.2.2.1.2 Combination with other 2D materials

There is a high potential in combination with other 2d materials, e.g. using BN as passivating layer for graphene. These devices offer currently the best performances. 2D material stacks and all-2D material electronics can be interesting in the future, although the fabrication challenge increases tremendously.

5.2.2.2 Additional strengths: wafer scale integration

5.2.2.2.1 Monolithic 3D integration (BEOL or FEOL) is in principle technically possible

Monolithic 3D integration of graphene and 2D materials is in principle possible. This is one of the reasons, why graphene has been hyped as an interesting material for electronics (besides its electrical properties). The processes for fabrication of graphene layers are in principle CMOS process compatible and a co-integration with Si and other existing solutions is possible. 2D materials even have a better compatibility with SiN electronics/photonics than Ge and III-V semiconductors. However, there are still many open questions regarding quality of the prepared films, transfer, reliability, yield, etc. (see current weaknesses further below).

A CVD production tool is available for graphene on Cu foil for wafers [372] and roll-to-roll processes [373], capable of making large sheets available. There has been a huge progress in terms of quality in recent years; however, the quality is not yet high enough (e.g. due to grain boundaries). Furthermore, the transfer process is yet to be optimized in a scalable way.

For epitaxially grown graphene on SiC substrates, the quality of graphene is already reasonably high [374], however, this way of production is only economically feasible at the moment for products that need to be made on SiC anyways, due to the currently somewhat high cost of SiC wafers (~30x cost of a silicon wafer) [375]. This could be interesting for RF/HF applications (MMICs), LEDs or power electronics. However, the current processes for graphene growth on SiC are not compatible with common devices based on SiC due to the high temperatures needed. Therefore, it is not possible to grow graphene on SiC ICs without destroying the ICs. Epitaxial growth has also been shown on sapphire [376, 377] and germanium [378, 379]. The quality of the graphene grown on germanium and sapphire, however, is still inferior to the CVD methods on SiC and copper and thus not good enough for high performing devices.

A dissolution/precipitation sequence facilitating Ni films on SiO_2 has also been demonstrated, but this process is currently not reproducible enough, does not reach sufficient quality and has issues with the layer number control. [380]

A transfer-free CMOS compatible process would make graphene integration much more likely, although it is currently not foreseeable. For other 2D materials it is probably possible (direct growth on dielectrics).

5.2.2.3 Additional strengths: interconnects

5.2.2.3.1 Performance results are promising

The laboratory results so far to use multilayer graphene as interconnect are promising. 10nm wide MLG was shown to have lower resistivity than Cu at the same scale [381]. However, this also needs to be shown with larger scale integration schemes.

5.2.2.3.2 Not only high quality film possible to use (depending on application)

For larger interconnects, especially on flexible substrates, also the use as an ink could be possible. (see also chapter 5.6 Flexible and/or printed electronics).

5.2.2.4 Additional strengths: thermal interface materials

5.2.2.4.1 Ink or high quality film usage

5.2.2.4.2 Anisotropy

The heat transfer in 2D materials is directed and anisotropic. This can be beneficial to direct the heat transfer, where it should go. On the other hand, coupling of the heater (chip) to the dissipation material might be an issue. Furthermore, currently used materials conduct the heat isotropically, so a rethinking of conventional approaches would be needed.

5.2.2.4.3 Volume/footprint and mass benefit

Due to the 2D nature, potentially less space is needed than for common heat dissipation solutions, e.g. based on Cu. A lower mass per overall conducted heat is also possible. This is interesting due to ever smaller integration and the need to smaller footprints and space savings (e.g. in mobile phones, wearables).

5.2.2.4.4 First applications are expected on the market soon

Recently, functionalized graphene-graphene oxide films from flakes showed interesting properties in heat dissipation on package level [382]. There are also first products announced making use of graphene as heat dissipation and thermal interface material.

5.2.2.5 Additional strengths: barrier material

5.2.2.5.1 Use as barrier material for interconnects in back-end-of-line

High quality SLG or MLG graphene can be used as an ultimately thin and conductive barrier layer to replace barrier metals between Cu interconnects and transistors to avoid Cu diffusion into the active layers. It could also be generally used as barrier "metal" for other metals in the back end of line as well as for oxidation and corrosion resistance [369]. The performance is promising as barrier layer for Cu interconnects [383]. Flexibility as conformal coating are additional added values.

5.2.2.5.2 Graphene Oxide as material for packaging in back end

Graphene oxide based coatings and paints could be used as barrier layers in the packaging back-end. This would be a special application of paints and coatings or composites as barrier material, see chapter 1.4 The roadmap is subdivided into four major application areas (level 1)

5.2.2.6 Current weaknesses and challenges for graphene/2D materials use in electronics: cross-cutting issues

5.2.2.6.1 Mobility vs. bandgap in 2D materials

Most advanced and high speed semiconductor applications require a bandgap and high charge carrier mobility. In this respect, GRM offer no better performance than bulk materials (see Figure 75) and graphene cannot escape from this mobility-bandgap trend. It is an intrinsical disadvantage against 3D semiconductors (e.g. III-V), which have higher mobilities and a bandgap. Applications for graphene are particularly interesting if one can make use of the gapless and tunable nature and benefit from it, e.g. in non-linear applications. However, there might be 2D materials out there, which can compete (such as Germanane, MoS_2), but they have to be investigated further especially in terms of the manufacturability. Recent results on MoS2 as channel material appear promising for further developments. [384, 385]

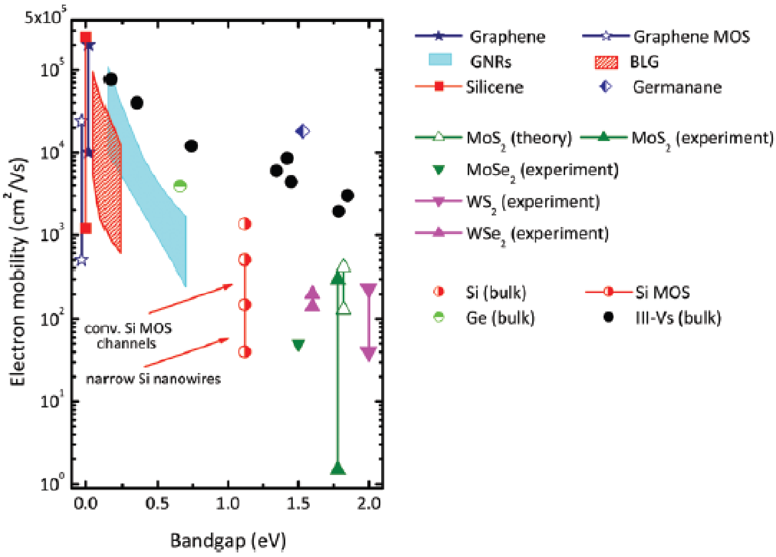


Figure 75: Electron mobility vs. Bandgap from several 2D and bulk materials. [386]

5.2.2.6.2 Performance lags behind initial expectations

For most electronics applications, the theoretically high promised performances are not yet shown experimentally (or only on basic lab level or with lab methods). This is a major disadvantage for the argumentation towards industry as too many risks and uncertainties currently exist. The lab-based demonstrators need to be prepared with more industrially relevant methods, or the methods have to be further developed to become industrially relevant to achieve breakthrough demonstrators.

As for all new kinds of nanomaterials, 2D materials in general receive a lot of attention and promise, but also have a lot of challenges. The integration and commercialisation is not straight forward.

5.2.2.6.3 Challenges in quality, reliability and degradation

Reliability is a very important factor for the semiconductor industry. Reliability models are crucial and necessary for a broader commercialisation. For 2D materials, these reliability models are unclear and need to be addressed at some point. For silicon, it needed 20 years until today's reliability models.

Therefore, degradation processes need to be understood. So far, it is seen that the graphene quality strongly depends on encapsulation. So more knowledge on encapsulation is needed.

5.2.2.7 Additional current weaknesses and challenges: wafer scale integration

5.2.2.7.1 Too low quality or yield of current high quality film methods

High mobility in graphene is a key factor to outperform the competition (e.g. in optoelectronics Si-modulators and Ge detectors). Therefore, a high quality, high purity, larger area production of GRM is needed and a prerequisite for many application areas.

There are several possibilities to grow high quality graphene films, examples are:

1. CVD on Copper
2. CVD on Ge (or Ge on Si)
3. CVD on catalytic material combinations at low temperatures (e.g Au-Ni) [387]
4. “Epitaxial” growth on SiC
5. dissolution/precipitation sequence facilitating Ni films on SiO_2

Usually and depending on the application, a transfer process is needed to get the graphene layer on the device substrate (e.g. SiO_2, etc.), see next subsection on the transfer process.

The quality of graphene on the substrates is at the moment not good enough to outperform competing technologies. For the most often used Cu CVD process only mm domains are synthesized due to thermal mismatch, resulting in a too high defect density. It is very important to find a suitable substrate (e.g. single crystal Cu or Ge), where the mismatch is better. The current process has issues with defects, wrinkles and metal impurities in graphene.

For graphene on SiC, the wafers are currently too expensive and the process is only economically feasible when components are made of SiC anyway.

At the moment, there is no existing high quality and low cost synthesis on dielectrics available. The Ni film route has problems with layer number control and poor reproducibility due to grain boundary effects. [380]

In some applications (e.g. modulators, sensors) bilayer graphene or two graphene layers with a spacer (e.g. of aluminium oxide) perform better due to interesting properties (tunable bandgap with an electric field). However, a controlled way of producing bilayer graphene on larger industrial scale does not exist yet, although some promising results have been achieved very recently. [388]

Another disadvantage is that there are large variations of graphene quality from supplier to supplier, which calls for standardized characterisation and labelling. This is a problem and barrier for the future ecosystem, as the second source principle could at the moment be not fulfilled.

The ultimate goal and Holy Grail for graphene integration would be a transfer free direct growth on Si or dielectric, but this is currently not in sight and rather unlikely to exist. Lattice matching would be very important for the quality; this also applies to TMDs growth.

5.2.2.7.2 Transfer process

As there is currently no high quality direct growth (transfer-less) process on Si or dielectrics in sight for graphene, the integration can only work with an upscalable transfer process to be compatible with various substrates. This transfer process is currently seen as the major barrier for integration and the hardest part, as it can strongly influence the quality of the graphene film.

The transfer process is not easy to control and scale up. Large area dry transfers create wrinkles, cracks, cleanliness, adhesion and flatness are issues influencing graphene quality tremendously and leading to lower mobilities. Furthermore, the CVD on metal processes introduce metal contamination, which is detrimental for CMOS processes and for the graphene itself (see 5.2.2.7.6 Contamination). Other transfer processes, such as in-situ transfer with a Cu wet etch process followed by adhesion to a dielectric through capillary forces creates less defects due to self alignment, but has long etch times [389], see also Table 37. Transfer processes are desirably dry, quick and on wafer scale to allow more efficient processing. Chip-scale transfer is probably easier but usually needs more effort and leads to higher cost, as the chips have to be processed one by one.

Table 37: Comparison of three common wet transfer methods. Credits to M. Lemme.

Etching method	Bubble method	Capillary method
Chemical process	Electrochemical method	Physical Process (capillary effect)
Cu is etched/dissolved Etchant: $FeCl_3$, Sodi-umpersulfate	Cu is removal by bubbles created at the interface Electrolyte: NaOH	Cu removal by water at the interface Reactant: DI water
Duration: 1.5h	Duration: 30s	Duration: 8h

If a transfer process is controllable and scalable, it also bears some advantages, e.g. the freedom of process parameters to achieve highest quality material during the growth process independent from final substrate or its constraints; it allows additional interface engineering and can be transferred on basically any substrate.

A transfer process could be compatible to MEMS transfer processes, so that the tools for such a transfer are partially standard back-end-of-line MEMs tools (e.g. for wafer transfer). But this is depending on the actual process and new tools might be eventually needed. This potential need for new tools with new working principles is a barrier for integration into fabs. It is most desirable that a process can be facilitated with existing tools, or the graphene films can be bought on the desired substrate with the needed quality (in case this is compatible with the component design).

5.2.2.7.3 Substrate interaction, encapsulation or self-passivation

The substrate material and surface treatment has a strong effect on graphene properties. This originates from the interaction with the substrate, from roughness, doping by dangling bonds or local charge inhomogeneities (see Table 38). Especially the atomic flatness of graphene seems to be a key factor to achieve extreme mobilities [390] needed to compete with existing technologies in many high performance applications. This atomic flatness most probably cannot be achieved on substrates where graphene corrugates, like on SiO_2. It might even be that defective graphene with fewer corrugations can achieve better mobilities than defect-free graphene with more corrugations, as corrugations might be key for mobility.

Best performances are achieved when using self-passivated layers, e.g a hBN-G-hBN stack embedded in dielectrics. As hBN is still at the exfoliation stage and production on larger scale is not possible at the moment, it is an even bigger challenge for upscaling but could contribute to the actual performance gain needed to outperform competing technologies. The economical feasibility for such a process is not yet assessable, as an industrially compatible process does not even exist on lab scale yet. The bottle neck in this case is the hBN production and the assembly of the stacks.

But different applications also demand different substrates, e.g. Si, Si/SiO_2, SiN, SiGe, quartz or AlN as well as flexible substrates (polymers, foils). In that case the mobility will be most probably limited, if graphene cannot be embedded in a passivating layer as hBN.

Table 38: Charge carrier mobilities of graphene on different substrates. [391–394]

Substrate	Mobility [cm²/Vs]
SiO2	4400…25000
h-BN	25000…140000
SiC	27000

Furthermore, encapsulation is also important to protect graphene from adsorption of contaminants. It is a challenge, that the encapsulation materials also effects the performance. For such an encapsulation it would be interesting if those encapsulating materials could be directly grown on graphene, e.g. through ALD. So far the nucleation of ALD materials on graphene, however, seems to be difficult. There are, however, ways to encapsulate graphene with a system of materials, such as Parylene, on which Al_2O_3 can be grown with ALD easily. This is particularly interesting for chemical sensors and biomedical applications.

5.2.2.7.4 Delamination, reliability and yield

Delamination is one of the most important challenges for graphene integration. It can appear during process steps, for instance due to temperature differences, stress in a stack, chemical-mechanical planarization or during wet processes. Already 1% of delamination is a problem in a pilot line, where delamination can lead to contamination of equipment eventually reducing the cycle time and yield. Irregular adhesion/delamination is also a problem in operation of a graphene-based device, as it can lead to failures and malfunctions reducing durability.

There is also an intrinsic tradeoff: On the one hand, weak adhesion forces are needed due to the required minimal graphene/substrate interactions, which can influence the graphene performance. On the other hand, a stronger adhesion bears a lower risk of delamination. So a balance between adhesion and substrate interactions needs to be found and an adequate and suitable integration scheme.

Most of the basic processes leading to delamination are unknown, so a better understanding of the adhesion limitations is needed (size and substrate dependent). This needs to be investigated for each process step and in operation, leading to more confidence in the window of stability and thus to a better process control and more reliable operation. Depending on the application, knowledge is needed for different substrates (Si, Si/SiO2, quartz, SiN, AlN, even polymer or foils for flexible applications) and wafer and sheet sizes.

However, the generic question and challenge remains currently still open, whether large scale high quality graphene be grown and laminated on top of a wafer with controlled defects. It is still unclear how to achieve reliable and constant quality over the wafer and batch/wafer to batch/wafer.

Related to the delamination in operation as well as other potential defects is the reliability failure model of a new material and technology, which is unclear for graphene. Device reliability failure models were important for silicon semiconductor success as they can be used in design factors and testing to improve the reliability of integrated circuits. Reaching this high standard and level of understanding needed 20 years for silicon. For reliability of graphene/2D materials based devices, other processes, such as delamination or encapsulation might play a role. For future mass production it is important to consider these effects for a reliability model during scale-up to avoid missing the high standards of the semiconductor industry.

Last but not least, the yield of wafer scale graphene processes needs to be considered, as yield expectations are very high in CMOS processes. It is to be investigated how high this yield can be pushed for graphene and if the needed yields can be achieved at all.

All these processes (delamination, reliability and yield) demand intensive engineering efforts and knowledge (what are the parameters, process control, impurities, etc.), which probably will not lead to highest ranked publications. Still this knowledge is essential for industrially compatible wafer scale integration.

5.2.2.7.5 Contacting

Reliable and low resistive contacting of 2D sheets is another important challenge. A reproducible and production compatible electric contacting with low resistance is not available to date. Classical and rather simple top contact shows resistance degradation due to work function mismatch, chemisorption of the contact metal [395], doping by the contact metals, induced stress or a contaminated interface. A possible solution are one-dimensional side contacts or combined architectures [396]. Here, reproducibility (top vs. edge) and scalability are major challenges. Most importantly, the metals used need to be compatible with the existing processes and used materials, compare Figure 76.

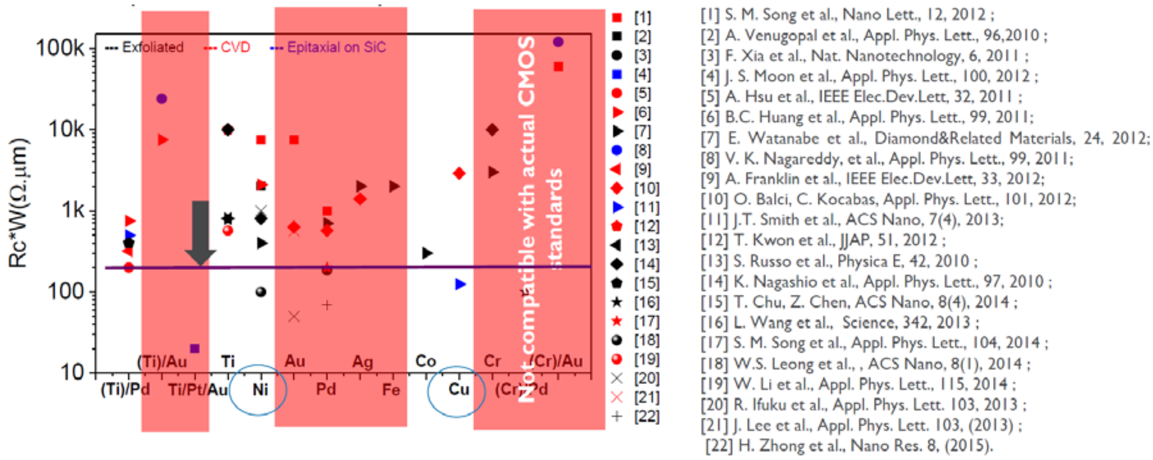


Figure 76: Graphene/Metal contact resistivity values – state of the art. Different results for contacting of graphene depending on metal and type of graphene used. Several metals are not compatible with CMOS processes (red). Credits to C. Huyghebaert, IMEC 2016.

5.2.2.7.6 Contamination

Contamination problems through metals or polymers exist for graphene itself (e.g. unwanted/uncontrolled doping) and for CMOS processes in general. Metal contamination in CMOS processes is undesirable (CMOS specification: <10^9 at/cm^2 metal contamination). This is particularly important for font-end-of-line processes. High metal contaminations of >10^{13} at/cm^2 of Fe and Cu have been observed in CVD prepared graphene [397]. This demands optimized cleaning processes or growth on non-metallic substrates. Furthermore, delamination during a process can also lead to contamination of equipment.

5.2.2.7.7 Deeper basic understanding needed

From the above mentioned challenges it becomes obvious, that a deeper understanding and better control of the interfaces is very crucial. This applies for interfaces and grain boundaries of graphene sheets, but also the interfaces with substrates or encapsulation. A fundamental understanding of grain boundaries is absolutely necessary for further process and device optimization: This includes the investigation of the influence of grain boundaries on electrical and mechanical properties as well as reproducibility.

5.2.2.7.8 Post process compatibility

Due to the 2D nature of graphene and the danger of delamination, all processes taking place after graphene deposition can influence the device performance and reliability. Thus, it is currently unclear how compatible and robust graphene devices are towards post-processes (patterning, litho, encapsulation, thermal treatment, packaging…). Graphene is sensitive to O_2 at high temperature, O_2 and H_2 plasma and prone to carbide formation with other elements at high temperatures. So it needs to be investigated whether it can survive the post process steps in typical integration schemes.

5.2.2.7.9 Design tools

Graphene-based components are new materials and concepts in the semiconductor area. As for all new materials and concepts, design tools are needed to allow system design and later foundry processes. The design tool are important at the interface between system planners and manufacturing. The development of design tools for graphene based components is an ongoing challenge and needed as another step towards CMOS integration.

5.2.2.7.10 In-line quality control and monitoring and standardisation

An industrial manufacturing compatible metrology is needed for process monitoring, reproducibility and quality control of graphene/2D films. As graphene is currently at a scientific metrology stage, new or adapted methods are required for industry compatibility. Some techniques are already investigated, e.g. based on raman scattering, ellipsometry, THz or eddy current. Industrial measurement techniques need to provide the desired measure (e.g. graphene quality, number of layers…), whilst being non-destructive, working on large area (full wafers up to 300mm), being high-throughput (inline compatible) and in best case being substrate independent.

Furthermore, if graphene wafers are sourced from a supplier, it is inevitable to exactly know the quality of the graphene product. Therefore, a certain degree of standardisation is necessary to ensure product quality and allow comparison between different graphene products and manufacturers and second sourcing. This especially requires standardised characterisation methods and measures. Therefore standardisation is required to a certain extent to drive the commercialisation of graphene.

5.2.2.7.11 Open question: Is it worth the effort?

Looking at the open challenges of graphene integration, the missing process demonstration for industrial manufacturing and the needed effort and uncertainties to resolve this, the barrier and risk for industry to take up the development seems to be still too high. This is especially the case, as there is currently no trustworthy realized opportunity (functional demonstrator, proof of concept application) on the horizon that justifies this whole risky endeavour for a single company. The benefits for different application areas in electronics appear to be just not yet clear enough. The incentives in terms of performance and cost are currently not high enough to justify the risks of successful integration.

Furthermore, a crude assessment of potential cost leads to the notion that prices for graphene/2D based/enhanced technologies might not come down enough or be competitive.

It remains an open challenge how far research needs to go until big industries will pick up the development to bring graphene electronics to the market. There are two major parameters influencing that:

1. Show benefits and potentials of the technology against competing and existing technologies to justify the investment
2. Reduce the risk for process integration by demonstrating the feasibility on a R&D level

Both issues need to be addressed to bring graphene/2D materials closer to the market. If the potential of demonstrators is high enough and the risk for integration at the same time is lowered, the point will come where industry will take up the development. It is, however, not known yet, whether and when this point can/will be reached.

5.2.2.8 Additional current weaknesses and challenges: interconnects

5.2.2.8.1 Integration scheme and worthiness of effort

Although multilayer graphene based interconnects already show some potential, the difference to state of the art Cu interconnects currently appears too low to justify a system change. The actual competitiveness with Cu has not yet been fully demonstrated. Cu and other incumbent metals have an integration scheme and are in fabs, whereas graphene has neither a solid integration scheme for interconnects nor currently shows the benefit to justify the evolution to this new material. Expert assessments currently say that in silicon-based electronics graphene will probably never be used as interconnect. However, it is still considered as potential candidate in ITRS publications. [369] Currently, there is no feasible method available to produce and implement multilayer graphene. If (multilayer) graphene integration works for other applications in CMOS back-end-of-line processes, the interconnect use case could get a revival and be developed based on the other developments (or vice versa).

5.2.2.8.2 Potential pollutant at interconnect interface

Due to the high pollution with metal [397], graphene may be a pollutant at an interconnect interface, which would require a barrier layer, similar to Cu. The advantage of getting rid of a barrier layer would in that case be cancelled out.

5.2.2.9 Additional current weaknesses and challenges: thermal interface materials

5.2.2.9.1 Total heat removal scaling

The total heat removal of single layer graphene might be too small, as the total heat transfer is limited by the small volume. Thicker layers do not scale up the thermal conductivity so well, so the challenge remains how the overall heat flow can be increased.

(FLG, multiple separated layers, how are they attached,…). A functionalization approach for GO seems to be interesting and has been demonstrated on lab scale. [382]

5.2.2.9.2 Unknown reliability

The functional benefit of graphene-based heat spreader have been shown and are promising. [382] But the reliability and heat radiation properties in the application remain to be tested further. It is clear that for system level, the influence of surfactant, functionalization or binder on properties are important and need to be studied.

5.2.2.9.3 Unknown substrate interaction and contact improvement

Thermal heat spreaders need to have a good contact to the heat source. It is unknown, how graphene interacts with substrate/matrix and how the phonon-coupling can be extended. It is important to study how to establish good contact between the material and the heat source/heat exchanger.

5.2.2.9.4 Anisotropy and implementation differ from state of the art materials

Today isotropic materials are used (e.g. Cu or Al). For an anisotropic material a paradimg shift and a rethinking is needed. The anisotropy can be both beneficial or detrimental. As soon as the handling/implementation is different compared to state of the art, an additional barrier is introduced. The simpler the implementation is, the better.

5.2.2.9.5 Wafer scale integration needed on transistor level and unknown contamination issues

For transistor level heat spreaders, CMOS integration or at least CMOS compatibility is needed (back-end-of-line). Poisoning of graphene and the transistors below from metal catalyst residues similarly applies to this application as to all wafer scale applications. Also for heat spreader materials, the question remains how to attach the material on transistor level so that a good thermal conductivity between the materials is guaranteed and long lasting. Is physical adhesion sufficient or some kind of bonding or functionalization needed?

5.2.2.9.6 Application dependent: Electrical conductivity of graphene

The inherent combination of thermal conductivity with electrical conductivity in graphene is not always needed or might even be detrimental. It thus cannot be used universally for all applications. hBN or other insulating 2D materials might be an opportunity for applications where thermal conductivity without electrical conductivity is needed.

5.2.2.10 Additional current weaknesses and challenges: barrier material

5.2.2.10.1 Differences to competing materials in integration

At the moment graphene is not so much better as a barrier than some other materials that can be integrated with lower temperature at interconnect scale, e.g. self-assembled monolayers. At the moment integration of graphene is not compatible with standard integration at back-end-of-line, whereas other materials are. But as soon as graphene integration at BEOL is available, maybe due to other applications that are driving the integration scheme, also the use as barrier can become feasible.

5.2.3 KPIs for electronics: cross-cutting issues

5.2.3.1 Wafer-scale integration:

Table 39: KPIs for wafer-scale integration

Specification	Required for CMOS
Wafer size	200/300mm
Charge carrier mobility / cm²/Vs	>25000 to compete in most applications, the higher the better
Yield	$\gg$90%
Impurities (metals)	< 10^9 at/cm^2
Contamination (e.g.PMMA)	< 0.1 %
Mechanical defects	< 0.1 %
Inclusions (e.g.water)	< 0.1 %
Uniformity along 300 mm wafer (with acceptable edge exclusion)	< 0.1 %
Scattering time	1 ps
Contacting	CMOS or process/material compatible metal, RcW as low as possible, parasitics should be <10 % of transistor channel resistance

5.2.3.2 Use as barrier

- Resistivity of interconnect (Cu) over barrier: ~10 u ohm cm (depending on line width, usually ~10-100nm) (as low as possible)
- Capacitance (as low as possible)
- EM reliability
- O2 barrier, Cu diffusion barrier properties
- cumulative failure probability vs. Time to failure (TTF)

Some KPIs are taken from [398]

5.2.3.3 Use as interconnect

- CU resistivity: 1.7 µOhm cm (bulk)
- Dimension (critical dimension CD<20nm)
- Line resistance RL=ρL/Wt (as low as possible)
- Voltage drop (IRL/V) (as low as possible)
- Line response time (RLC) (as low as possible)
- Line current density (I/A) (as high as possible)
- Resistivity ~10µOhm cm for line width ~10nm
- EM reliability
- Electron mean free path (<10nm)

Some KPIs taken from [398], For further KPIs, please refer to ITRS 2013:Interconnect Tables via www.itrs2.net or directly: [399]

5.2.3.4 Use as thermal material:

easy integration, good TIM pastes (silver) get 40W/mK for 10€/g; bulk Cu 400W/mK, Silver 430W/mK, graphite sheet in smartphones, e.g. 400W/mK (xy), 10W/mK (z)

5.2.3.5 Design tools

Compatibility with CMOS design tools

5.2.4 Roadmap for electronics: cross-cutting issues

5.2.4.1 Current maturity: 'Labscale demonstrators available, wafer scale integration R&D has started'

Promising lab scale demonstrators are available, although benchmarking needs to be intensified and the material quality needs to be increased to become competitive.

For SiC based graphene "epitaxially" grown graphene processes reach sufficient quality, but wafers are expensive and limiting the applicability. 3" wafers are quite uniform (99.9% coverage), 6" is also possible.

Wafer scale processes for other substrates (Si, SiO_2, etc.) are under investigation and often demonstrated, sometimes already on larger scale. However, the quality is still not good enough. Especially the quality of the growth process and the transfer processes are bottlenecks. Also the preparation of other semiconducting 2D materials (e.g. TMDs) and bilayer graphene (as a low bandgap material) is under development but much more juvenile than high quality SLG technologies. For graphene, especially hBN could play a decisive role, as best performances are achieved in combination with hBN.

TMD devices are currently still dominated by material quality (impurities, defects). hBN is currently still at the exfoliation stage and large scale high quality preparation methods are not yet known. Thin film growth processes yield either only small crystals or poly-crystalline films.

The potential as interconnect and barrier material has been shown. Manufacturability is currently the biggest issue.

For thermal material slightly better performances are observed compared to state of the art TIM. However, experts are slightly critical about experimental published results, which seem to be not easily reproducible and sound.

5.2.4.2 Barriers/challenges (summarized)

Fundamental understanding

- High quality transfer and growth processes
- Grain boundaries and their influence on performance
- Interplay of doping, contamination, flatness, substrate, interfaces and performance

Application:

- For which applications is the SiC process feasible? How far do prices of SiC wafers have to go down for further applications?
- High prerequisites of industry before they take up the development: 10x performance increase and/or 10x lower cost demonstrated and lowered manufacturing risk needed or 100x performance increase demonstrated for platform technology (e.g. transistor)
- Realized mobility for most applications not high enough (performance lacks behind expectations)
- Unclear reliability/degradation in operation (e.g. due to delamination, influence of package or heat)
- Wafer scale feasibility as key barrier

General manufacturing technology and graphene:

- Wafer scale: very large challenge to implement wafer scale integration within 2 years time. Almost impossible? Time expectation for a new material usually ~10 years.
- Manufacturability not proven yet for a simple device
- Transfer process
- Large area single crystals preparation method for needed substrate not yet available
- Mobility of large scale films way behind expectations and need
- Unclear quality, reliability, degradation
- Delamination problems and unclear optimal parameter space
- Yield
- Doping and defect control, defect density
- Interface control
- Stacking/lateral alignment (control)
- Contacting, contact resistance
- metal contamination (especially Cu)
- Post process compatibility
- Quality control and monitoring
- Missing design tools

- Substrate and encapsulation with hBN on industrial scale
- missing estimate of a cost for process integration + unclear prospects of a missing “killer application” that can be feasibly produced keeps semiconductor companies from taking graphene into the fab and making larger investments

hBN substrate/encapsulation:

- Thin film growth processes yield either small crystals or polycrystalline films: better ways are needed
- Precursors
- Growth mechanism
- Layer number control
- Grain size
- Can single crystals of a significant size be grown –controlled?

TMDs:

- Material quality (defects, impurities)
- growth on large scale, multi-layer
- Substrate selection: lattice matching, extended defect control, grain size control
- Growth technique selection: CVD, ALD, MBE, VPE, etc
- Precursor selection
- Contamination
- Nucleation and growth
- Point Defect Control: intrinsic doping (vacancies, extrinsic doping

Ecosystem:

- Companies seem to wait, because there are still too many questions: Is it worth the effort? This is not clear enough yet!
- How much does it cost to integrate graphene into a fab and what is the benefit? As long as this is unclear, a company will not go for it
- For larger company: 1-2 million pieces per year are interesting, but is that enough for a completely new material?
- Not only technologists need to be convinced, but also marketing
- Open manufacturing challenges and demonstration with adequate parameters, missing actual prospect for “killer app” & uncertainty of cost keeps semiconductor companies from taking graphene into the fab and making larger investments
- Scalability and demand need to be matched (currently ok)
- Challenge: how far does research need to go until pick up through big industries?
- Even if the KPIs are met for wafer scale it is yet unclear who will take it up in Europe (→hypothetical device)
- Single customer/single source issue: for a supplier a single customer is not interesting; for an end user a single supplier is not ok: whole ecosystem is needed, whole environment needs to develop at the same time
- Start ups can cover low volume production, but for industrialisation/mass production a whole infrastructure needed. Start with start-up to get first demonstrators (who will finance them?) on a smaller scale for low volume niche applications to show the potential. Getting the whole ecosystem for mass production forward will take much more effort and is probably not feasible at the moment.
- Patent thicket

5.2.4.3 Potential actions

If the area of graphene/2D in electronics and cross-cutting applications is seen as promising for Europe and the topic is further pushed, the following potential actions, derived from the challenges, are suggested:

Fundamental understanding

- Grain boundary and interface investigations
- Investigate new growth processes and substrates
- Further investigations on interplay between material (doping, substrate, interfaces, contamination) and performance

Applications:

- Benchmark with existing technologies and other researched technologies in terms of functionality and figure of merit
- Focus on applications that promise to fulfil the 10x performance and/or 10x cost challenge

Manufacturing:

- SiC: engage with power electronics and PV who know how to work with SiC
- Lab-level and fab-level collaboration to address challenges
- Address the relevant process parameters and challenges in wafer scale integration (engineering knowledge), e.g. yield, contamination, etc.
- Demonstrate the process for a simple but convincing application, allowing cost assessments
- Elaborate design tools for integration
- Intensify hBN manufacturing research

Ecosystem:

- Develop a way how the innovation eco system can go ahead together (what is needed, in terms of customers and orders for a semiconductor company to do the investment); make an exercise/case study: how and if at all can that be achieved? What role can be taken by start ups/large enterprises? Even engage with marketing/management to get to know clearer prerequisites for uptake by (European) industry.
- Establish standardized methods to determine the quality of produced graphene and other 2D materials (“certification”)
- Create a group of classification criteria in order to evaluate the produced materials to help manufacturers and customers to
    - classify their material quality and customers
    - provide an expectation of the performance of the classified graphene and
    - decide whether or not the graphene or other 2D material quality is potentially suitable for various applications

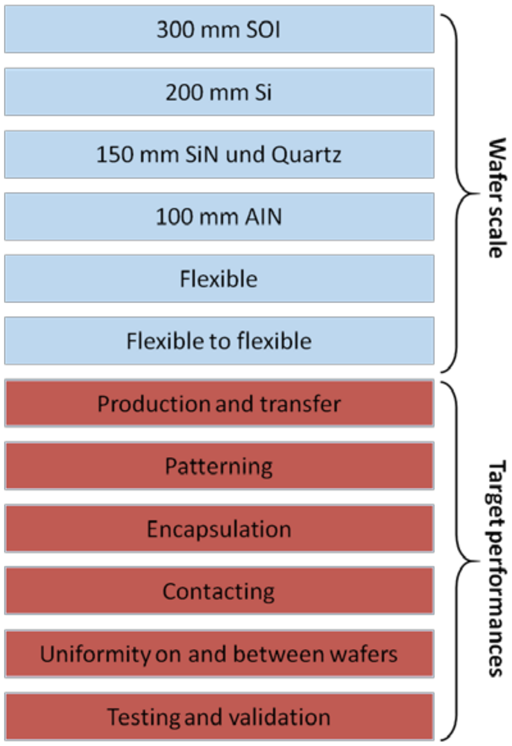
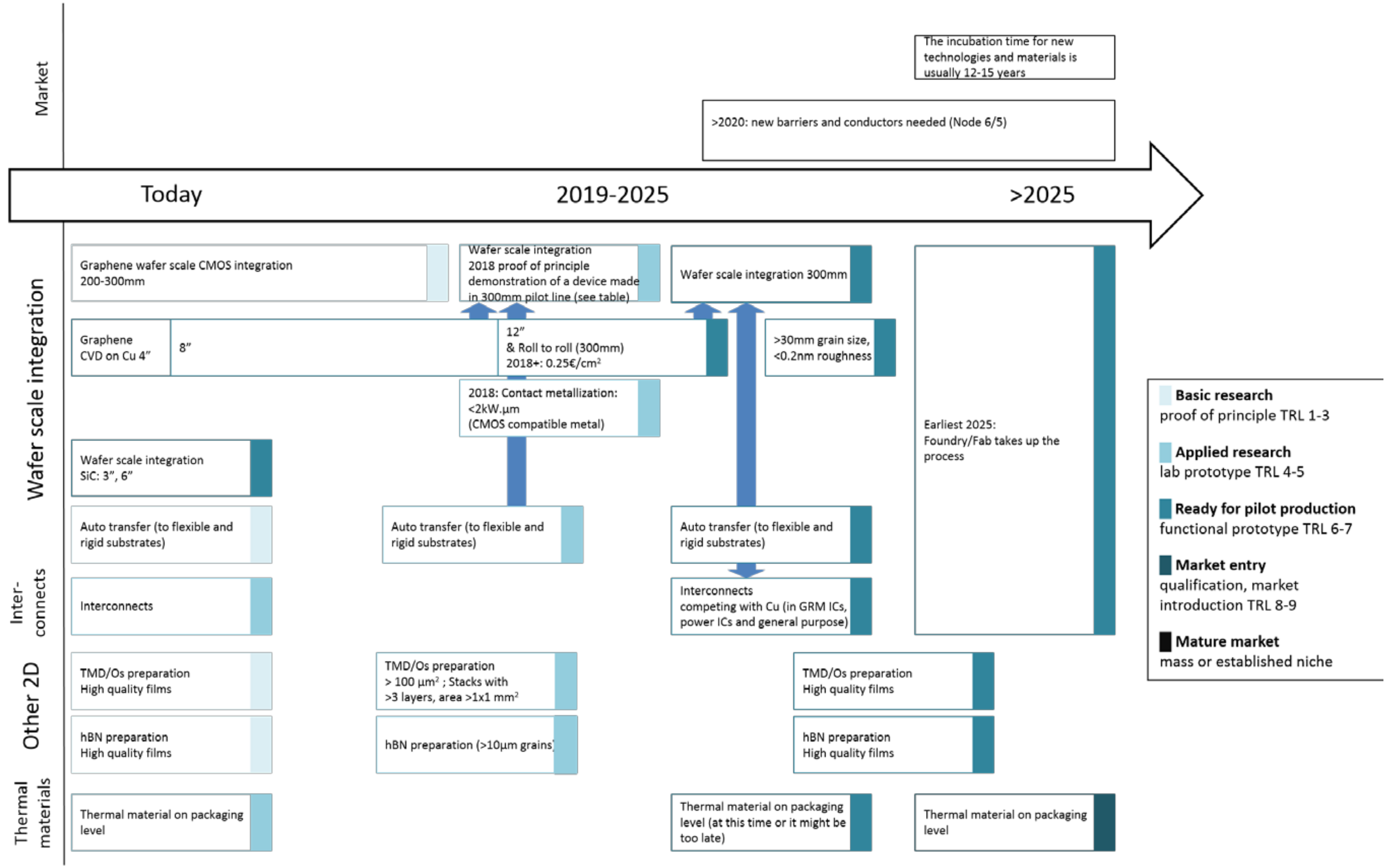


Figure 77: Areas of actions for wafer scale integration in the Graphene Flagship. Credits to C. Huyghebaert, IMEC 2016

5.2.4.4 Roadmap

The incubation time for new technologies and materials is usually 12-15 years [360]



Sources: [360, 369]

Table 40: Wafer scale parameters

Specifications	Target 2018 (prototype)	Required for product
Impurities	< 10^{12} at/cm2	< 10^{11} at/cm2
Contamination (e.g.PMMA)	< 10%	< 0.1 %
Mechanical defects	< 10%	< 0.1 %
Inclusions (e.g.water)	< 10%	< 0.1 %
Uniformity along 300 mm wafer (with acceptable edge exclusion)	< 10%	< 0.1 %
Scattering time*	100 fs	1 ps
Prototypes	Photodetector array, optical transceiver, …	

5.2.5 Conclusion electronics: cross-cutting issues

Cross-cutting electronics issues address common technology areas relevant for all electronics applications, e.g. common production related issues (wafer scale integration) or common technological issues such as electrical connection (interconnects) or thermal heat dissipation or barrier layers.

These areas typically address front-end-of-line and back-end-of-line as well as packaging in the chip/semiconductor fabrication. In this industry, Europe is behind East Asia and North America with a turnover share of 9.4% in 2012.

In particular the wafer scale integration is currently a bottleneck for many applications of graphene/2D materials in electronics. Positively seen, accomplishing a commercially viable wafer scale process opens up a wide area of applications and paves the way for a broad integration of 2D materials. On the other hand, if commercially viable wafer scale integration is not feasible, many applications will be not possible to be realized with 2D materials on a broader scale commercially. As these applications demand high quality films (mostly single or double layer), the integration will take more time as in composites or areas where flakes are sufficient. In order to justify the investment into new production technologies and 2D material integration, a clear and trustworthy demonstration is needed for a particular application, where the actual potential of graphene/2D materials is obvious in the device and the production.

For the back-end-of-line and packaging applications (interconnect, thermal and barrier material), the multi-functionality of electrical, mechanical, barrier and thermal properties as well as flexibility is again rather unique. There are definitely needs for new solutions, as this part of electronics manufacturing has a high cost pressure and physical boundaries are soon to be reached with the common materials. On the other hand there is a high barrier for materials needing a new process (conservative industry, higher investments needed).

For thermal heat dissipation applications on packaging level there are first products approaching the market, which make use of graphene flakes.

It is obvious that in general demonstrators are needed that show the potential in functioning devices prepared by production-compatible methods. Due to the long history of silicon and related materials and the strong experience, everything that can be done with Si, will be done with Si or incumbent materials, which introduces another barrier for uptake of new technologies.

Table 41: Assessment of market and technological potential of graphene/2D materials use in cross-cutting electronics issues on a scale - -, -, 0, +, ++

Cross-cutting electronics	Current technological potential (USP)	Market potential (EU perspective)
Electronics in general	+	+
Wafer scale CMOS integration	+	+
Interconnects	+	0
Thermal material	+	0
Barrier	+	0

5.3 Telecommunication, optoelectronics & photonics

This area deals with the broad application area of telecommunication, but also covers photodetectors and light sources/lasers for various applications. It essentially covers all technologies that deal with electromagnetic wave interaction and processing and analogue electronics. Figure 78 gives an overview of the electromagnetic spectrum and the spectral regions where 2D materials can play a role.

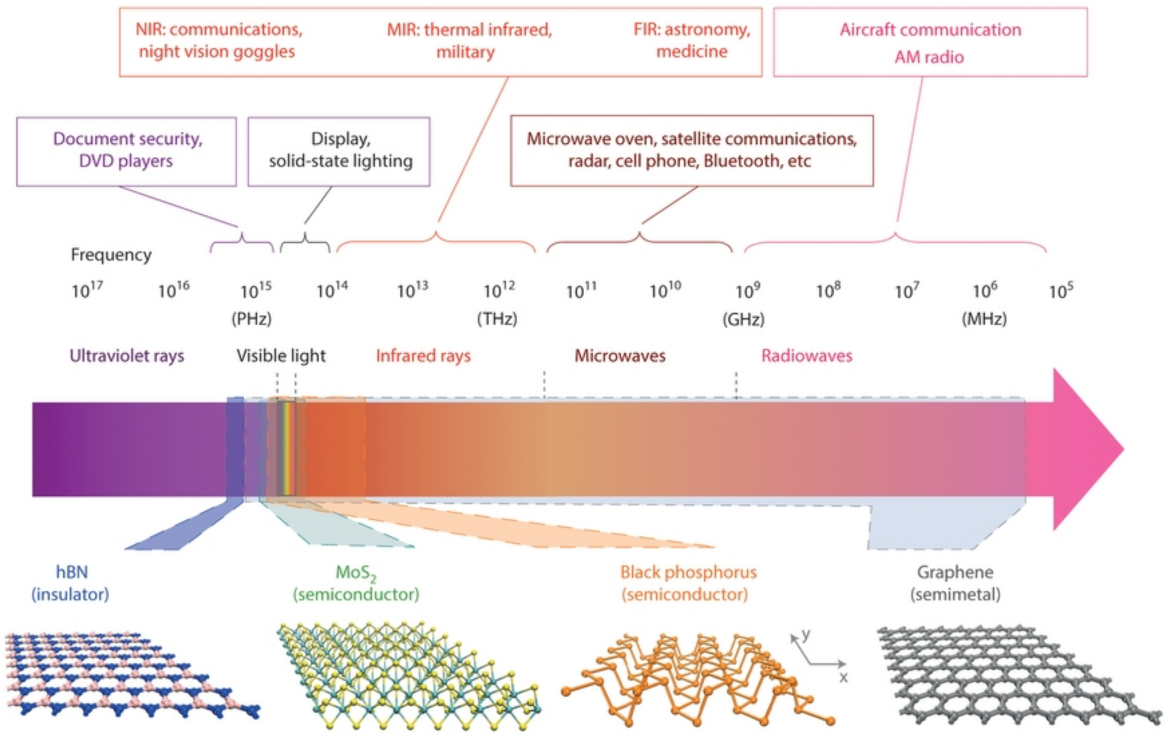


Figure 78: Optical spectrum and interaction with 2D materials. [400]

Telecommunication and networking covers all technologies that deal with high speed and low power data transmission and processing, ranging from optical networks, wireless networks, mobile applications/terminals to RF electronics. Graphene/2D materials are investigated due to their interesting optoelectronic and high frequency properties. Typical application areas are:

- **High frequency electronics deals with generation, acquisition and manipulation of high-frequency signals**, including RF, **microwave (MMICs) and THz/sub-mm waves** through analogue transistors, e.g. for amplification or signal processing. Radar/Telecom signal sampling/downconversion
    - **THz/sub-mm wave detection, imaging**
    - **Antennas and resonators**, i.e. passive HF electronics, e.g. for filtering (resonators) and reception (antennas), antennas for near-field enhancements for detectors.
- **Optical switches and modulators**, i.e. the manipulation of optical signals through electronic devices for high speed optical networks/optical fiber communications, e.g. (de-)multiplexing, modulation, switching. Together with photodetectors these components are important for photonic networks and optical data transmission, combined in optical transceivers and photonic ICs.
- **Photodetectors** for several uses, including high speed, high bandwidth detectors for optical networking, broad wavelength range (UV-VIS-IR) detectors for hyperspectral imaging/detection, x-ray detection, THz detectors.
- **Laser/photonics** for several uses and light sources, such as tuneable lasers, ultrafast lasers, THz light source.

The markets besides telecommunication (backbone network, radio cells for mobile communications, distribution network, terminals and end user devices) are in security, production/manufacturing (control and monitoring), biomedical applications and fundamental science. Table 42 highlights a few potential applications and scientific reviews dealing with the topics.

Table 42: Potential applications for graphene and 2D materials in telecommunication, optoelectronics and photonics as well as recent reviews.

Application area	**Use of graphene/2D materials as**	**Important markets**
High frequency components, analogue electronics (RF, µ-wave, THz, mm-wave) [256, 401–404]	Transistors, diodes, varactors and microwave-photonic devices for use in amplifiers, oscillators, frequency multipliers, mixers, receivers, transducers, MMICs, spin torque nano-oscillators as tunable µ-wave source	Telecommunication (incl. mobile), monitoring (industry, security), research
Resonators	electrode in BAW resonators	Mobile communications
Antennas [403]	Unobtrusive antennas, flexible RFID/NFC antennas, antenna for increased sensitivity (near field) of detectors	Mobile communications, RFID
Photodetectors for imaging and ultrafast detection [400, 405–410]	Electro-optically active material in imaging sensors and photonic ICs (VIS-IR)	Telecommunication, photonic networks, industrial monitoring and inspection, security, health, research
Optical modulators for optical networks [405, 411, 412]	Electro-optically active material for modulation of optical signals (VIS-IR)	Telecommunication, photonic networks

Application area	Use of graphene/2D materials as	Important markets
Laser/LED components [408, 413, 414]	Photonic component for ultrafast lasers/fibre lasers (e.g. saturable absorber); transparent conductive layer for LEDs	Telecommunication, photonic networks, research, industrial production, health

5.3.1 Market perspective: graphene/2D materials in telecommunication, optoelectronics & photonics

Various markets can be addressed by radio/high frequency, optoelectronic and/or photonic components, ranging from security applications such as radar, via the broad field of telecommunication and data transfer to inspection/monitoring methods and lasers.

In terms of telecommunication applications (optical and RF/HF/THz), mobile networks, network data centers, video broadcasting networks play important roles in driving the need for faster and more efficient solutions.

Optical network components

The overall optical transport network market was estimated to be ~$11.4 billion in 2014 and growing to ~$23.6 billion by 2019 at CAGR of close to 16%. [415]

Optical transceivers are at the core of optical network components. The datacom optical transceiver market is expected to grow to over $2.1 billion by 2019. 10-, 40- and 100-Gigabit optical transceivers for enterprise and data center markets created an estimated revenue of $1.4 billion in 2014 (growth of 21% that year), whereas worldwide revenue for client 10G modules stagnated. [416, 417] Other sources suggest even larger markets of $3.2 billion in 2013 growing to $9.9 billion by 2020 (CAGR 17.5%) driven by the availability and cost effectiveness of 40 Gbps, 100 Gbps, and 400 Gbps devices. [418] Optical modulators are part of these markets and the revenues for those are in the few hundred million $ range (~$230m in 2013). [419]

Looking at the photonic ICs market, the silicon photonics market is estimated at ~$330m in 2016 and expected to reach ~$1 Billion by 2022 (CAGR 22.1%). Highest CAGR is expected for active components, including optical modulators, photo detectors, wavelength-division multiplexing filters, switches, and lasers integrated within a single device, providing a smaller form factor with the help of silicon photonics. [420]

Photodetectors and imaging

Optical sensors are part of optical transceivers but also find applications beyond telecommunication, e.g. in imaging, inspection and all kinds of sensors facilitating light to measure a particular parameter (e.g. pulse sensors, proximity). Optical sensors go into many different areas ranging from consumer electronics, health to industrial monitoring and security, addressing low cost to high value products

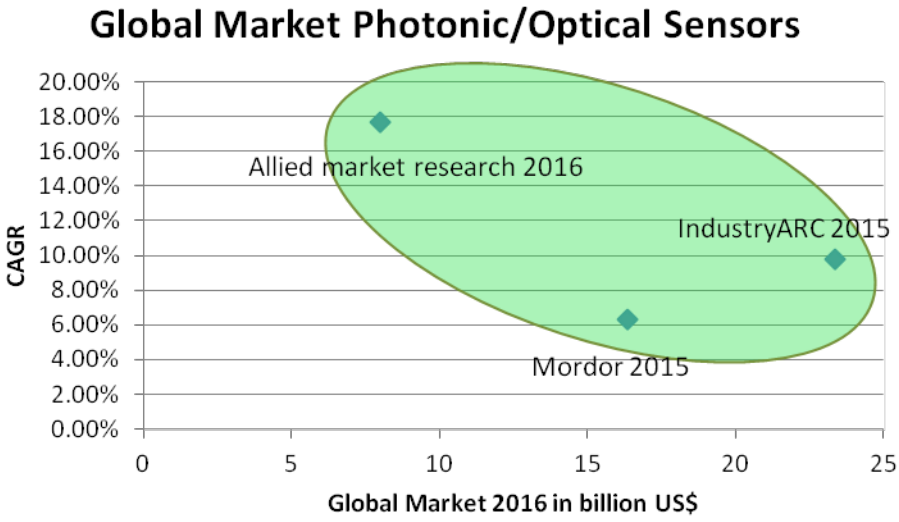


Figure 79: Global market overview 2016 for optical sensors from several sources. [421–424]. Another source estimated the optical sensor market at $5.3 billion in 2015. [425]

The market figures vary, which depends on the definition of the area of optical sensors and photodetectors and the uncertainty of such market expectations. Figure 79 summarizes three sources. Nonetheless it is a fast growing market expected to grow with rates between close to 10 and above 20% from $10-20b in 2016. [421–424, 426].

The global image sensor market, a subset of optical sensors, accounts for the largest share of optical sensors. Figure 80 summarizes several sources. This market accounted for revenues of around $10b in 2015 with expected growth rates between 4% and 8%. [427–430] CMOS sensors occupy more than 90% of the market. IR sensors were expected to have created revenues around $180m in 2013 growing to around $410m by 2018. [427] European based companies were responsible for about 10% of the world-wide production of image sensors. [431] For a more general sensor overview and to put it into perspective with other sensors, please refer to chapter 5.5.1 Market perspective: graphene/2D in sensors.

IR spectroscopy markets are today estimated to be valued close to ~$1 billion, expected to grow to $1.25 billion by 2020 (CAGR ~7%). [432]

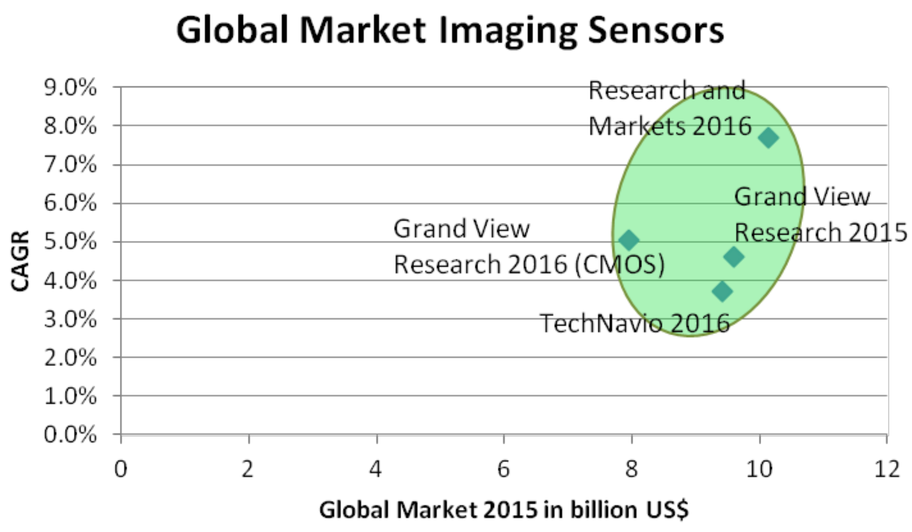


Figure 80: Global market overview 2015 for imaging sensors from several sources. [427–430]. Another source estimates the market to $10.6 billion in 2015. [425]

Optoelectronic semiconductors are the fastest growing semiconductor segment (11.3% growth in 2015) accounting for $33 billion. [361]

HF/RF/THz/sub-mm wave markets

RF power semiconductors revenues are estimated to grow heavily from USD 10-11 Billion in 2015 to USD >31 Billion by 2022 (CAGR 15.4% 2016-2022). In the last few years, new improved materials such as gallium nitride (GaN) are increasingly being used in RF power semiconductor devices [433] Of the RF Power revenues 2014 the main applications were: 65.9% cellular, 20% wireless communications, 4.7% military, 3.7% fibre-optic communications, 3.9% consumer, 1.8% automotive. [434]

The global Wi-Fi market is also expected to grow heavily with a CAGR of 17.8% until 2020 from USD 14.8 Billion in 2015 to USD 33.6 Billion by 2020. [435] Antennas, as an important part of its backbone accounted for a market of $15.1 billion in 2014, expected to grow to $19.9 billion in 2019 (CAGR of 5.7%) [436] The antenna, transducer, and radome (ATR) market for defense, aerospace, and homeland security was estimated to be close to USD 8 Billion in 2015. It is expected to reach USD 12.5 Billion by 2020 (CAGR of 9.53%). [437]

The market estimates for THz technologies are summarized in Figure 81. THz technologies are emerging and high growth rates are expected (>20% CAGR), although the market itself is not yet very large (~$100m in 2016). The high growth rates are attributed to a high adoption rate of THz technology-based products for laboratory research applications, as well as a growing demand from the defence/homeland security and medical sectors. THz imaging systems accounted for the largest market share of the THz market in 2015. The market for THz communication systems is expected to exhibit the highest growth in the years to come. [438] THz spectroscopy is projected to reach a $50 million market by 2020 market growing from ~$25 million today at a CAGR of ~20%. [432]

The millimetre wave technology market accounted for revenues of $208.1 Million in 2014 and is expected to grow at a high rate of 42.70% in the near future. [439]

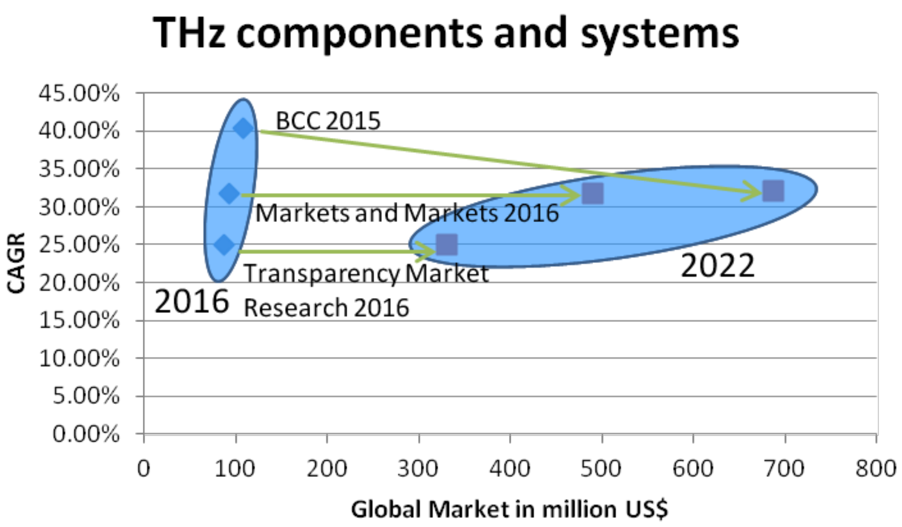


Figure 81: THz components and systems market overview from different sources. [438, 440, 441]

Analogue semiconductors accounted for a market of $45 billion in 2015, growing about 1.9%. [361]

The global signal generator market is projected to grow at CAGR 8-9% until 2022. It was estimated at ~$0.8 billion in 2014 growing to ~$1.2 billion in 2020. Signal generators are used for pre-production processes, e.g. designing, and post manufacturing, e.g. to check the conformance and accuracy of electronic devices. More and more "smart" devices enter the market and more and more industries are affected by digitalisation and sensor implementation, which drives the market need for signal generators. [442, 443]

Radar apparatus and parts product value in Europe was ~€4.5 billion in 2014 with slight downwards trend since 2012 (-2.5% CAGR). [155]

Laser/photonics:

The global market for lasers was on the order of $10 billion in 2014/15 with a split of 55% non-diode and 45% diode lasers. With annual growth rates of more than 6% the market is expected to reach $16b in 2020. Lasers for processing accounted for roughly over 50% of the market growing at CAGR of 6%. [444] Fiber lasers are expected to grow at a strong 16%.[445, 446]. The ultrafast laser market (15 picoseconds or less) is expected to climb past $1.4B by 2019. [446] Another study looking at titanium-sapphire lasers, diode-pumped lasers, fiber lasers and mode-locked diode lasers estimated a $2 billion market in 2014 expected to grow to nearly $5.5 billion in 2019 with a CAGR of 23.7%. [447]

Optoelectronics & photonics patents:

In terms of the innovative basis of the R&D and industry, some evidence can be gathered from the comparison of transnational patents between countries as depicted in Figure 82. The EU is behind the US and Japan and especially China is advancing. Figure 83 looks at the graphene/2D patents in optoelectronics, where Korea and US are leading followed by Europe. Japanese patent applications play only a minor role. The graphene share is increasing (see Figure 84) and particularly strong for Korea.

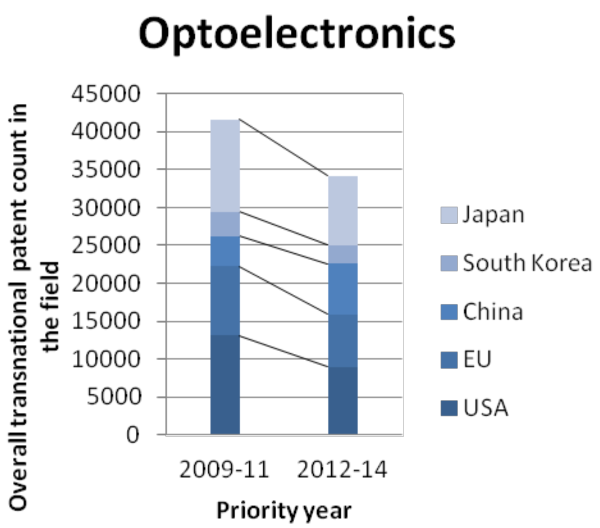


Figure 82: Overall transnational patent count in optoelectronics. 2012-2014 values are projected.[137]

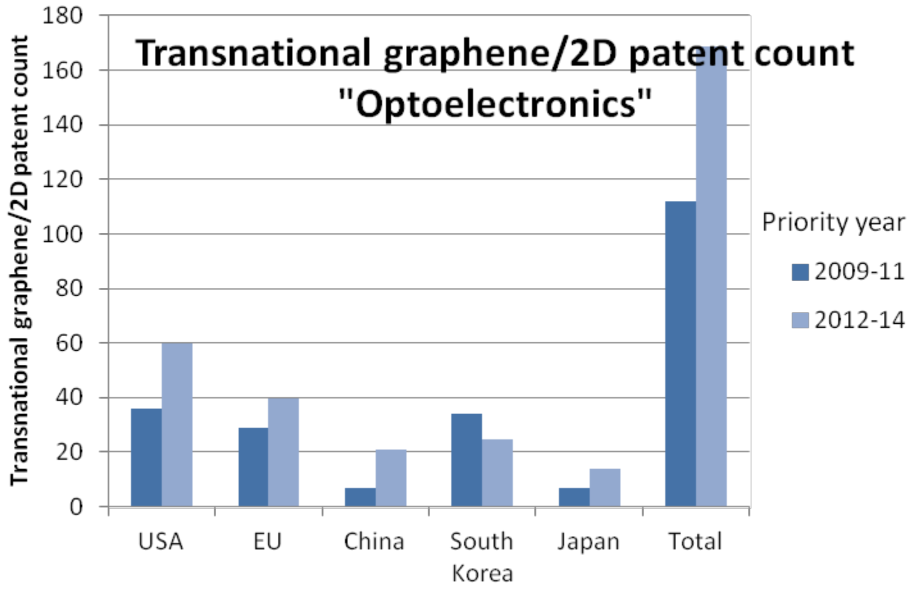


Figure 83: Patent analysis of graphene/2D materials in optoelectronics: Number of graphene related transnational patents in 2009-2011 and 2012-2014. 2012-2014 values are projected. [137]

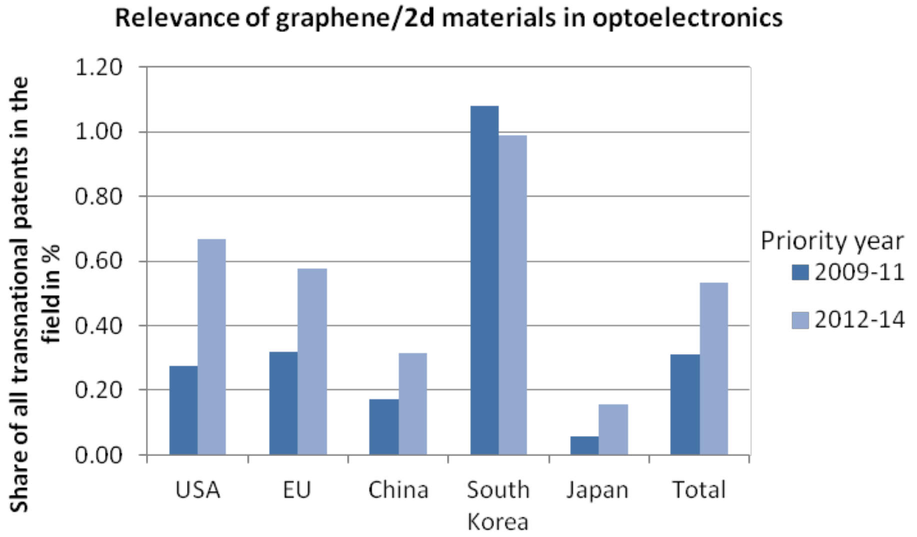


Figure 84: Patent share of graphene/2D related materials with respect to all transnational patents in optoelectronics. 2012-2014 values are projected.[137]

European industrial basis:

Table 43 gives an overview of product values produced in Europe in 2014 that are related to telecommunication, optoelectronics and photonics. Other sources claim that European based companies were responsible for about 10% of the worldwide production of image sensors, accounting for roughly 1b€ in 2016. [431]

Table 43: Production of manufactured goods value in EU-28 in 2014 and growth since 2012. [155]

Product	Product Value EU-28 2014 in billion €	CAGR 2012-2014
Logic/HF transistors, components and ICs	15.78	-1.7%
Telecommunication equipment	12.50	-22.6%
Photodetectors (incl. solar cells), spectrometers	3.37	-23.3%
Other Optoelectronics (Optical instruments, UV/IR for medical, optical fibre cables)	2.87	3.6%
Antennas	1.37	-1.5%
Light sources (semiconductor) & Lasers	1.20	4.1%
Signal measurement devices	1.01	-8.2%
Mounted piezo-electric crystals (including quartz, oscillator and resonators)	0.21	12.8%

The overall European photonics industry (including light sources, optical systems, solar cells, optoelectronics, etc.) has a global market share of [448]

- 55% in production technology
- 40% in optical components & systems
- 35% in measurement & automated vision
- 30% in medical technology & life sciences
- 30% in safety & defence systems

However, depending in the sources, the overall turnover share of EU-28 is smaller than for East Asia and North America, compare Figure 85.

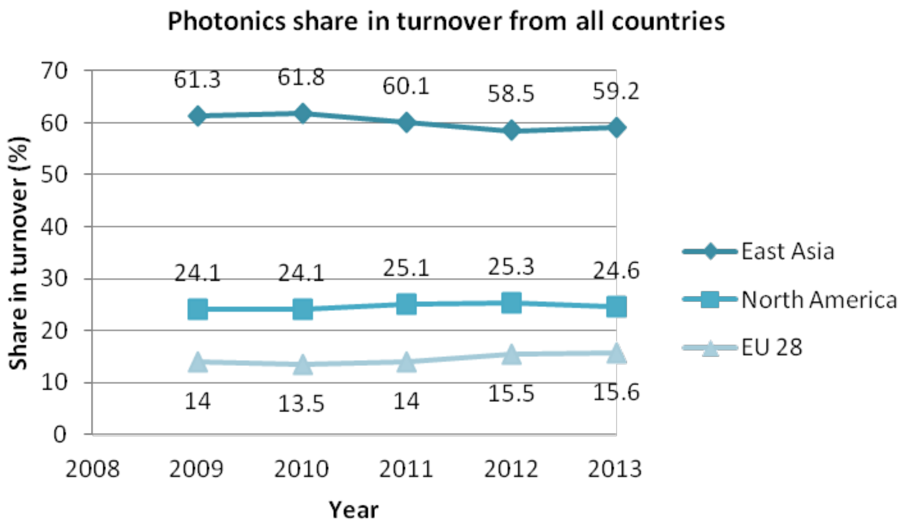


Figure 85: Share in turnover relative to all countries of photonics-related products. [449]

5.3.1.1 Market Opportunities

5.3.1.1.1 Strong and ambitious plan for 5G and beyond creates pull for new technological solutions

The internet of things and consumer markets drive needs for low cost, high volume wireless solutions. 33 billion devices are expected to be connected to the Internet in 2020 [434], almost 40 billion connected mobile devices are expected by 2024 [450]. The increasing use of cloud services and big data call for connectivity with high bandwidth and low latency everywhere.

The evolution of the mobile network standards to address these demands is ongoing and the next generation mobile network 5G is under full development. Key differentiators from earlier networks are: faster and higher-capacity broadband internet (100x-1000x capacity of 4G), lower (real time) latency, multi-access, multi-layered. [450] Although most of the 5G developments will be driven by software [451], there are also hardware related challenges: especially the backhaul (optical networks) and higher frequency (above 6GHz) wireless communication require new technologies or the heavy exploitation of existing ones (such as CMOS, SoI, SoS, GaN, SiGe, InP, Ge on Si, Si photonics). 5G plans involve developing networks at frequency bands of 5 GHz to 86 GHz [434], or even towards 300GHz waves for data transmission and backhaul. Besides, the power consumption challenge creates a need for new technologies: the increased bit rate must come without increasing power consumption (although bit rate is proportional to power consumption) and without increasing cost.

5G therefore generates needs in terms of hardware technologies for ever higher integration of functions and chips, low energy consuming small radio cells and terminals or photonic ICs beyond 600Gbit/s for backbone. To accommodate the new frequencies and higher number of bands, a better linearity and a lower R_{on} x C_{off} is needed for terminal RF power amplifiers and switches besides a better efficiency (currently realized with GaAs, RF-SOI or RF-CMOS). But for higher frequencies a big jump in improvement is needed at some point (most probably beyond 5G). [452]

5G Network development is already happening, but deployments may not be until 2020. Still, most technologies are already settled today. But after 5G there will be some sort of "6G" or at least further incremental developments for lower power consumption and higher bandwidth at lower cost necessary beyond 2020.

5.3.1.1.2 Broad market available (from high to low cost, low to high volume)

The telecommunication equipment market offers a broad variety of applications of RF and optoelectronic components. There are high cost components, e.g. in the backbone/main network with lower cost constraints but high constraints on durability and performance, as well as low cost components with shorter life cycles, high integration, increasing performance needs for user equipment, terminals and (optical) network units. The market competition is very high.

Besides the potential telecommunication markets, there are also high valued applications for RF/HF electronics, e.g. in defense and safety applications, so higher performance for some low cost increase is possible (but will only serve niche markets). For these markets, competition is moderate.

5.3.1.1.3 Race is still open for new technologies in and beyond 5G

5G hardware technologies and materials are not yet fixed, especially when it comes to wireless transmission beyond 6GHz and optical networks for the backbone. Beyond 2024 ("6G" or 5G evolution) it is to a great extent unclear which technologies can meet the needs. So even if 5G specifications are not met in time, there will be further future needs opening up another window of opportunity.

In terms of wireless transmission beyond 6GHz, technologies (e.g. CMOS) living up to the expectations are already demonstrated and quite mature. However, above 80GHz, there are not many technologies capable and feasible.

In terms of optical networks, ultra-low energy (optical) transceivers are required. Competing new technologies in development are either costly or do not live up to the needs yet. As such, crystalline Ge and III-V semiconductors are (currently) rather exotic and too expensive for massive integration, Si-based photonics are juvenile but emerging and expected to be cheap, Ge on Si is already mature and rather cheap and a main competitor. There is a particular need for new wavelengths beyond 1.3 and 1.55µm, e.g. 9xx nm, which could allow cheaper lasers to be used as light sources. Furthermore, current optical network components are not highly integrated and still quite bulky. There is a clear need for higher integration, e.g. an optical transceiver on one chip (including laser, modulator, multiplexer, demultiplexer photodiodes, ADC and digital signal processing). In this respect, there might be potential synergies with the rise silicon photonics, where graphene could be used as active material. [453]

Large players in the telecommunication/optoelectronics area are looking at graphene as one potential technology. It has the potential to be a special differentiator in optoelectronics creating a competitive advantage (at least it is partially seen like this).

5.3.1.1.4 Importance of optical networks steadily increasing

As mentioned above, optical networks are gaining more and more importance and also the markets are growing with annual rates beyond 15%. Optical high bandwidth communication is playing an important role also for server farms, on chip communication, etc. Also for the last mile in telecommunication networks, passive optical networks (PONs) are increasingly interesting with demands for 1530-1560/65nm variable light source and resonators. The latter application addresses a high quantity, low cost application (last mile).

5.3.1.1.5 European strength in photonics technologies

Europe is a strong international player in photonics technologies with a broad industrial basis. The focus, however, is more on production related technologies, on optical system level, in measurement & automated vision, in medical technology & life sciences and in safety & defence systems. [448]

5.3.1.2 Additional market opportunities: optical switches and modulators

5.3.1.2.1 Optical switches and modulators one of the key components of advanced optical networks

Fast and efficient optical switches and modulators are one of the key components and issues for mobile networks optical backbones, besides photodetectors. There is a strong need for broadband optical modulators with low switching voltage and high bandwidth. These components are high up in networks and high valued products with prerequisites of high switching speed ($\gg$50Gbaud), low power consumption, low driving voltages and low loss. Addressing new wavelength ranges comes as an additional opportunity.

5.3.1.2.2 Lack of alternatives for high speed switches and modulators

In terms of optical modulators there is a gap between future demands and technological offers. There are not many competing technologies with similar potential as graphene/2D materials: Si, SiGe and III-V semiconductors need higher switching voltages. LiNbO modulators have a size of 10cm or more, need high switching voltages and are expensive. InP performs well but is expensive and currently has no integration scheme on Silicon. It is yet unclear which technology can help to meet the ambitious market demands beyond 2024. No competitor has a solution at the moment for modulators that are economically feasible and meet the demands. This is a great opportunity for graphene-based modulators beyond 2024.

For optical switches, free-space MEMS and liquid crystal switches are competitors, but an integrated and compact switch with low-cost and high reliability is not available at the moment.

5.3.1.3 Additional market opportunities: Photodetectors

5.3.1.3.1 Need for high bandwidth optical detectors for communication

Optical networks demand high bandwidth and broadband optical transceivers and one key component of these transceivers are photodetectors. Most important properties are sensitivity, speed, reliability and cost. However, for optical long distance transmission, components can cost up to several thousand dollars, so performance and reliability is more important. The shorter the distance, the cheaper the products need to get, because volume increases. The opportunity for a first entry in higher valued products is possible, followed by a later entry in end user components (low cost).

5.3.1.3.2 High cost of competing technologies and SOTA

Although performance and reliability are more important for early adopting applications, cost can be an advantage on the long run. Depending on the integration scheme and further development of graphene/2D materials, costs are probably better than the established and rather expensive Ge and III-V crystals. Cost reduction could actually become a USP towards other, similar or better performing technologies.

5.3.1.3.3 Need for cheap and broadband NIR and hyperspectral (fast) imaging

Photodetectors are not only relevant for telecommunication applications, but also for photosensing and imaging. In particular hyperspectral imaging/sensing is an interesting field, as the cheap Si based technologies usually cut off at about 1100nm due to silicon’s bandgap and other technologies are more expensive.

There is a clear need for VIS+NIR/IR imaging, e.g. for industrial inspection and monitoring, e.g. in the food sector, but also in the health market and for wearables. Large and diverse markets are addressable with hyperspectral sensors, consisting of many available niche markets for early adoption:

- Consumer market: digital imaging, surveillance, remote sensing
- Wearable devices: pulse oxymetry and other health monitoring
- Biomedical industry: biomedical imaging and diagnostics
- Automotive industry: thermal, passive night vision
- Environmental monitoring: x-ray, infrared, UV and hyperspectral imaging
- Safety: imaging, explosives and threat detection
- Metrology: scientific metrology, space applications
- Process monitoring: agro/food, product inspection
- Machine vision: industrial manufacturing, autonomous vehicles

For competing technologies price is a major issue, which either comes from the production cost of materials or from the need for cooling. For instance, InGaAs is too expensive and sensitive (600-2000nm) for certain applications, such as food quality inspection. In that case a lower sensitivity for lower cost would be sufficient and allow a broader market uptake. In particular cheaper and uncooled solutions are interesting, as often InGaAs solutions are price prohibitive. A lower functionality is often justifiable with lower price. Such lower performing but cheaper products could open up new and diverse areas of application/markets (particularly when lower cost is combined with a broader spectral range). The NIR analysis already accounted for 9.6% of the total analytical instrumentation market in food testing in 2014, which corresponds to $175 million. [454]

European based companies were responsible for about 10% of the worldwide production of image sensors (~$1b), so there is an industrial basis. [431] In particular in the hyperspectral range competition is moderate.

5.3.1.4 Additional market opportunities: laser technologies

5.3.1.4.1 Early adopters with lower cost-sensitivity

Many specialised laser technologies address low volume, high value niche applications, such as science and health. These are important early adopters for new technologies and can be addressed by new laser technologies. For these high performance lasers, cost is not so prohibitive. However, when it comes to industrial applications (laser machining), telecommunication (optical networks) or consumer products, cost sensitivity increases.

UV-LED transparent film and substrate, Crayonano [455]:

Further applications are possible in special areas such as deep UV LEDs. Here graphene can be used as a combined epitaxial substrate and transparent electrode to make AlGaN nanostructured UV LEDs. These types of deep UV LEDs can be used for e.g. water and air disinfection purposes. The current LED technology is struggling with low performance and high cost, e.g. due to expensive AlN substrates (commercial graphene transferred wafers are already 10 times cheaper today). ITO is not an option as transparent contact as it is not transparent in deep UV. Furthermore, AlGaN nanostructures on graphene are dislocation free, whereas conventional deep UV LED are growing AlGaN thin films with very high dislocation densities resulting in low performance. Current barriers are availability of graphene wafers and Cu contamination to comply with AlGaN MOCVD requirements.

5.3.1.4.2 Need for tuneable sources in telecommunication

Optical networks demand photonic-assisted signal processing technologies (e.g. optical modulators, switches and photodetectors) or directly modulated light sources, currently provided by diode lasers. Tunable lasers are needed in telecommunication for WDM and passive optical networks (PON) in the NIR range: C-Band (1530 – 1565nm) / O-Band (1260 – 1360nm) 15-20nm tuning range. But these technologies are typically high volume, low cost, so for these products a high volume production method (e.g. wafer scale integration) is necessary.

5.3.1.5 Additional market opportunities: HF/microwave/THz generation, detection and processing

5.3.1.5.1 Market needs and opportunities for improved resonators

In terms of RF resonators for filters, there are market needs to increased the Q factor, reduce losses and increase energy efficiency. Besides, another important need is to downsize the package and reduce the total height by increasing the package density. The latter is especially important for mobile applications such as smartphones. For 5G and beyond there is also the need to increase frequencies and make higher frequencies available, whilst not increasing or even reducing cost (some added costs allowed for added value/functionality). Resonators address broad application areas in mobile communication from mobile handset to stations. For broad market diffusion, high volume is needed (billions).

5.3.1.5.2 Market needs and opportunities for antennas

Antennas are another passive element important for any wireless data transmission. There is a need/wish for unobtrusive (transparent) antennas in the frequency range 2-

5GHz for mobile broadband communication to increase acceptance, especially when more and more small cells are established. Conformal antennas are another important field, also for RFID and NFC (see 5.6 Flexible and/or printed electronics). Miniaturized and integrated antennas are important for mobile devices (e.g. integratable with SiGe RF components).

5.3.1.5.3 THz opportunities in imaging, detection and data transmission

THz-frequencies and sub-mm waves are a more a more exploited frequency range that previously has been neglected in terms of electromagnetic radiation. THz band communication is seen as one of the possibilities addressing the spectrum scarcity and capacity limitations of current wireless systems. [438] It is discussed for high speed communication at low distances (dense environment, buildings with many terminals and users, onboard of aircrafts, ships) or in pico cells with big bit rates and spatially constraint information.

Furthermore, THz radiation can be used in imaging, detection, remote sensing, e.g. for explosives, in security and defence applications but also in industrial quality control and monitoring or diagnostics.

There are markets that allow higher costs for better functionality (e.g. defense, security), but also consumer markets are possible at a low enough cost (telecommunication). The diversity of such a technology can be quite high.

5.3.1.5.4 Existing THz technologies rather expensive and/or over-performing

THz applications are currently not possible with Si. GaN and SiC are typically used, but those materials are quite expensive and at the moment not feasible for mass integration. Furthermore, the performance of these technologies is also partially too high, making it too expensive and over-performing for many mass applications. If graphene turns out to be integratable and economically feasible, THz applications could be interesting even if the performance is lower.

For instance, some current THz detectors (bolometers) are expensive because they need heavy cooling. The cooling also leads to a poor usability. There is thus the need for new lower or un-cooled technologies (room temperature device or 70K standard IR cooler compatible) device needed. A 10x lower sensitivity (NEP) than bolometer would be acceptable. Such a technology would be more compact, less energy demanding and cheaper, leading to a broader implementation and new application possibilities. On the other hand, Schottky diode based detectors are operating well at room temperature.

Other candidates to address this demand are based on semiconductors, but also still difficult to make. The cost of the current systems is so high that even single chip fabrication may be feasible. Additionally, the competition for THz components is not so high at the moment.

5.3.1.5.5 THz modulation and polarization insufficient with existing technologies

Besides THz detection, also modulation techniques are interesting. Intensity modulation is interesting to enhance, via a lock-in detection, the sensitivity and eventually the speed in mainstream THz applications, such as material characterization/quality control, medical diagnostics, remote sensing and security [456] as well as in THz wireless communications [457]. Polarization modulation is an approach for measuring the linear and the circular dichroism. The linear dichroism can be used, for example, for the evaluation of the homogeneity and internal strains of plastic films and papers. The circular dichroism is a key to distinguish absolute configurations of organic chiral molecules and as such is an important analytical tool in biology, chemistry, medicine and pharmacy. [458, 459]

One of the obstacles for advancing various THz applications (especially between 1-5 THz) is the lack of efficient and fast intensity and polarization modulators. Mechanical and thermal modulation techniques are possible in the THz range [460] but intrinsically slow (< a few kHz). The use of all-optical modulation is limited by the cost of ultrafast lasers. Many conventional techniques, used in the visible, near infrared and microwave ranges are difficult to apply in the THz due to the lack of proper materials. As a result, measurements of both types of dichroism that require such modulators are rare and not commercialized in the THz range.

The market is currently rather small but has high growth rates and a new development which makes the applications simpler or cheaper could even further push this growth. There are also a few companies active on THz spectroscopy in Europe (e.g. Menlo Systems, Toptica Photonics, EKSPLA, Hübner and others).

5.3.1.6 Market Threats

5.3.1.6.1 Highly competitive and international telecommunication market with high price pressure but performance focus

The large telecommunication equipment market is a highly competitive and international market. Competition and price pressure is high on system (networks) and operator level, and even higher on terminal/consumer level. This is price pressure is passed on to the components and parts of the systems.

But, for new technologies, performance comes before price: not performing better but being cheaper is no successful entry point. A potential cost advantage is only secondary, as material cost is less of a concern for data centres, high speed links and high power computing. There are also applications in defence or special applications with low volume that accept higher prices.

So the market has its space for high quality, high performing and high priced products, but especially in the backbone, the price pressure is high. As soon as it comes to high volume end-user equipment, terminals or optical network units (ONUs) low cost is even crucial and decisive.

5.3.1.6.2 Value/supply chain for telecommunication equipment exists and emerges in Europe but with a weak link and strong competition

Companies from each part of the value chain are in Europe. Telecommunication equipment manufacturers (such as Ericsson, Nokia including Alcatel Lucent) are mostly multinational companies within a strong international competition (Huawei, Cisco,…). Although the value of telecommunication equipment in Europe declined by 22.6% per year from 2012-2014, still a value of €12.5 billion has been created in 2014. [155] These companies can be enabled by graphene development. However, these companies will most probably not directly integrate graphene themselves, as they buy the components from their suppliers. On this supplier level, graphene integration needs to take place technologically. This is where the value chain is possibly weakest in Europe: The majority of component producers and fabs for optical communication are not in Europe, however, there are a few actors active (mostly integrators or fabs, e.g. ST Microelectronics, BAE Systems, NXP in Si photonics). For HF components the European position is better, as larger companies like Infineon, ST Microelectronics, NXP and medium sized companies such as AMS, X-Fab and others produce semiconductor components for RF/sub-mm applications. However, if graphene can make a difference, these manufacturers can be enabled and get a competitive advantage.

But there are several barriers to be taken and prerequisites that can hinder the uptake of a new material in this industry:

1. Sourcing: The sourcing of graphene materials on wafers need to be clear. Second sources need to be available.
2. The supply chain for the integration into a functional system needs to be clear
3. Single user/single customer conundrum: a supplier will say that a single customer is not interesting; the end user/customer will say: a single supplier is not ok. Therefore, a whole ecosystem and a whole environment is needed for successful and broad integration.
4. Larger companies need at least markets of 1-2 million pieces per year
5. For a broad use, foundries need to be involved. Currently, foundries do not investigate graphene for optoelectronics. Unless a mass market is addressed, foundries will not react.
6. Not only technologists need to be convinced, but also marketing

The possible early market entry scenario is via start-ups and researchers showing the actual potential in close-to-reality devices on low volume and smaller scale in niche applications. For industrialisation/mass production: a whole infrastructure needed, which will only be established when the added value is large enough ("10 times"). Getting the whole ecosystem for mass production forward will take much more effort and is probably not feasible at the moment, especially taking into account the second supplier, second source issue.

If this mass market is established for one applications, others will follow. It was assessed that optical switches and modulators for long range, high value market will most probably be available later, after a first mass market is established.

5.3.1.6.3 Stringent market requirements for reliability and durability

Reliability and durability are always major problems for a new and not established technology. The durability/stability needs for network infrastructure are 5-20 years, -40-70°C, depending on applications. The operational lifetime in telecommunication systems for instance can reach 30 years guarantied life time. There is a high demand for reproducibility and quality standards. Thermal stability is also very important, especially as thermal changes might induce changes in 2D materials. If the requirements are met, it is a huge opportunity for 2D materials.

5.3.1.6.4 Medium-term success unlikely as the window of opportunity is closing

As the graphene-based technology is still too young and especially the large scale production is not yet solved, it is very unlikely that graphene can play a role in the first generation of 5G components. The 5G window of opportunity is closing, standardisation is happening now and until ~2020. Solutions need to be there soon to be fully recognized for 5G. However, even if first technologies are fixed for 5G now and until 2020, there will be an evolution of 5G or 6G will follow afterwards, demanding higher bandwidth with lower power consumption and lower cost.

Besides, competing technologies and common technologies can be still used through optimization and higher level of processing. Additionally, Si-photonics is arising as a competing technology and bears large potentials. Graphene on the other hand could also find its way into Si-photonics and use this new technology as an enabler. [453] Si-photonics is capable of 100 Gb/s optical transceivers without graphene, using four laser wavelengths, each operating as an independent 25 Gb/s optical channel at low cost. [461]

The typical timeframe for new technologies in this area are >10 years from initial experiments to full market entry. For instance, Si photonics needed >10 years from early stages demonstration to maturity in a foundry (which is not yet reached).

5.3.1.6.5 Without wafer scale integration no success

For a broader market roll out of graphene-enabled technologies in telecommunication and optoelectronics, especially for larger markets and lower cost products, wafer scalability and CMOS integration is a prerequisite. A convergence of graphene technology and semiconductor technology is needed for most products (e.g. graphene on read-out of focal plane arrays for imaging sensors). Without economically feasible integration, graphene based technologies in this overall area will only be available for small niches and special very high valued products where other production schemes can be used, e.g. in lasers or simple photodetectors, if at all.

Refer to 5.2 Electronics: Cross-cutting issues for the SWOT analysis of wafer scale integration.

5.3.1.7 Additional market threats: optical switches and modulators

5.3.1.7.1 Competing technologies catch up rapidly

Although graphene is very promising and incumbent technologies currently do not meet the future demands (see 5.3.1.2.2 Lack of alternatives for high speed switches and modulators), the incumbent technologies still have further potentials for development and also other competing technologies catch up rapidly. The race therefore is still open.

5.3.1.8 Additional market threats: Photodetectors

5.3.1.8.1 Competing technologies for photodetectors

For high speed photodetectors, III-V, quantum well and resonant tunnel diodes are competing technologies with interesting performances. Those technologies are more mature in terms of production.

For NIR/IR imaging, many different technologies exist and are established, such as III-V semiconductors, Ge, PbS/PbSe, InSb, InGaAs, InAsSb, Mercury Cadmium Telluride (MCT) or other ternary compounds. III-V is well compatible with Si technology. These technologies mostly have proven to be reliable and have an adequate operational lifetime. The major drawback of those incumbent technologies is that they all are quite expensive, need cooling or are rather slow. Furthermore, the resolution is usually not good for given wavelength regions.

There are even already LWIR applications available for consumer electronics, such as the un-cooled VOx microbolometer Lepton® from FLIR, which is used in a CAT smartphone. [462]

5.3.1.8.2 Some markets require low cost

High cost markets are already served by other technologies, e.g. NIR in health addresses a high value, but rather specialised niche market with only few end products and high competition from competing and mature technologies. For these markets, the performance advantage must be rather large and be needed or the prices should be considerably lower for the same performance.

Applications with stronger cost constraints present interesting opportunities, e.g. food safety or consumer markets. But if the lower cost targets are not met, these markets are not an option. The first smart phone with LWIR imaging is already available on the market, see chapter 5.3.1.8.1 Competing technologies for photodetectors.

5.3.1.9 Additional market threats: Laser technologies

5.3.1.9.1 For large markets: cost constraints

Larger markets usually served by laser diodes and integrated lasers have strong cost constraints. For example, in telecommunication passive optical networks (PONs), high volumes are needed at a low costs of ~1$ per piece. For these high volume markets, laser applications needs efficient wafer scale integration.

5.3.1.10 Additional market threats: HF/microwave/THz generation, detection and processing

5.3.1.10.1 Mature competing incumbent technologies

MMIC technologies (GaAs, SiGe, GaN, SiC) are mature and established for 4G and first 5G applications. GaAs is currently the dominant technology. CMOS/SOI-based amplifiers and switches capture market share from GaAs. [434] Highest performing material is InP (with the highest f_{max}), but InP is very expensive and currently not integratable easily. Only SiGe has an integration scheme on silicon at the moment. For RF switching MEMS solutions are also possible and might replace RF SOI in the future.

For THz detection, Schottky diode based detectors are operating well at room temperature and are the reference and most important established competitor.

All in all, there are several advancing technologies which also build on a longer history that can technically outperform current graphene/2D based demonstrators. However if graphene is integratable and if it can be shown that the performance can be even better, this might turn into an advantage.

5.3.1.10.2 THz disillusionment

THz technologies were hyped in the 2000s and are now approaching something like the slope of enlightenment. Back in 2000 the technology was oversold and now expectations are low and interest vanished. However, it is again discussed nowadays for small cells and short range communication in 5G. Also for imaging and inspection (e.g. for production monitoring), it is still very interesting.

Although the growth rates of THz markets are strong, the overall market is still relatively small.

5.3.1.10.3 Resonators: Process/application addressed by graphene is very cost sensitive

In particular the use as an electrode in BAW resonators is a very cost-sensitive process, as it is nowadays realized with rather simple metal evaporation (SOTA: metal/alloy sheets of 200-300nm). The addressed products are prone to high competition and address large volume market (billions).

5.3.2 Graphene/2D materials perspective: current strengths, weaknesses and challenges for the use in telecommunication, optoelectronics & photonics

5.3.2.1 Current strengths for graphene/2D materials use in telecommunication, optoelectronics & photonics

5.3.2.1.1 Outstanding potential of graphene for optoelectronic applications

Due to the missing/tunable bandgap and high charge carrier mobility, graphene is an interesting candidate for optoelectronic applications as active material for light-matter interaction. Other 2D materials with varying band gaps and mobilities could also play a role in this area.

Graphene absorbs broadband light ranging from visible to IR to THz. The combination with the high speed (bandwidth), tunability, low noise and flexibility make it a quite unique candidate for optoelectronic applications. In principle, it can be also integrated on waveguides and on fibres and thus be used for fibre communications. It is also compatible with typical optical communications bands in the 1200-1700nm range, like the C-band and beyond.

The broad optical absorption and tunability (band gap engineering) render it further interesting for hyperspectral detection and imaging. For most applications more or less integrated lab scale demonstrations are available showing the potential. The high charge carrier mobility (electrons) make it an interesting candidate for high bandwidth fast photodetectors used in optical networks.

Besides this technological substitution, graphene and 2D materials can also be enablers for new optoelectronic devices, e.g. mixers at high frequency and microwave. Due to the linear energy dispersion of electrons and holes graphene demonstrates a strongly nonlinear electromagnetic response in a broad frequency range from microwaves to visible light. Resonance frequencies and the nonlinear response can be controlled by the electron density, i.e. the gate voltage. This can be used in different nonlinear electric-field controlled optoelectronic and photonic devices, including saturable absorbers, fast and compact electro-optic modulators, optical switches, frequency multipliers and mixers, parametric amplifiers, etc. If wafer scale integration work economically, all these nonlinear graphene devices could be implemented on silicon-based chips, thus opening up new opportunities for the realization of nonlinear integrated Si-based photonic circuits.

The multifunctionality, performance, flexibility for conformal electronics and potential integratability therefore make graphene and 2D materials rather unique candidates with that potential. Only few other materials have similar optoelectronic potentials, depending on applications (e.g. some III-V sc's).

Besides the technological performance, the probability that it can be even cheaper than competing technologies is there, although this remains to be proven. In that case, a cost advantage towards other technologies, such as Ge could become a USP (but this is still not clear). The technological potential is already there, but in particular for cost effectiveness an integration scheme is crucial. Devices could also be made simpler by using graphene for instance because less complex circuits or less transistors are needed (e.g. for demodulators), also leading to a potential cost reduction.

At the moment, optoelectronic applications are seen as a realistic and feasible application of graphene/2D materials, also from industrial point of view.

5.3.2.1.2 Compatibility with Si/SiO2, SiGe and SiN platforms

Wafer scale integration would allow adding active functionality though graphene on passive Si-photonics, Si/SiO2, SiN platforms. It would make it possible to integrate graphene on SiGe or Si CMOS (VLSI) as optical modulator. The convergence of graphene technology and semiconductor technology is still possible and might be feasible (see wafer scale integratiion in chapter 5.2 Electronics: Cross-cutting issues).

5.3.2.1.3 Possibility for fully integrated optoelectronic devices

The evolution of the prior integration potential is to integrate different active components made with graphene with similar processes to allow preparation of fully integrated optoelectronic devices on Si or other semiconductor materials. For instance to integrate a photodetector, switch and modulator on a VLSI chip to make an all-integrated optical transceiver.

5.3.2.1.4 Mechanical flexibility and conformability

2D materials are naturally flexible. This opens up interesting applications such as flexible RF electronics (see also 5.6 Flexible and/or printed electronics).

5.3.2.1.5 New types of spin-based data communication might become possible in the future

Graphene's long spin diffusion length (see chapter 5.4.2.2 Additional strengths: spintronics) offers a potential to be used within completely new data communications scheme in the future which relies on the modulation of the electrons' spin polarization [463]. If spins are used to encode information, then the charge current is used to drive the information instead of to carry it. This spin based scheme is expected to be free of transmission line effects, electromigration problems, and the need for wire shielding. Graphene could offer better performances in this type of data communication towards other semiconductors. This may open ways for spintronic applications beyond information storage.

Furthermore, the long spin coherence length in graphene could be used to drive spintronic nano-oscillators at microwave frequencies. This would be a new and economically interesting way how wideband (1-100 GHz) microwave signals can be generated, modulated and detected in future graphene based microwave devices. [464]

5.3.2.2 Additional strengths: optical switches and modulators

5.3.2.2.1 Electro-optical properties of graphene well suited for optical switching and modulation

Graphene exhibits interesting optical switching/modulation capabilities, especially a theoretically low switching voltage, low loss and high speed. It can be used for integrated switches and modulators with smaller package size compared to Mach-Zehnder type modulators. The experimental demonstrations have not yet reached these high levels, but are promising. The design of graphene-based optical modulators is available. It has been shown that the devices exhibit reasonable speed, are optically broadband and temperature insensitive. The switching voltage is already acceptable and lower than for SiGe-based modulators.

Besides reproducibility, lower insertion loss and higher extinction ratios are needed as well as higher speeds, leaving still room for improvement. Only few other materials have a comparable potential for optical switching and modulation (some III-V sc's or the large footprint Mach-Zehnder modulators). So graphene is quite unique and promising for this application.

5.3.2.3 Additional strengths: Photodetectors

5.3.2.3.1 Broad optical absorption has a huge potential

Graphene absorbs electromagnetic waves from the UV to THz. Furthermore, the material can be optically tuned with plasmonic effects. This broad optical absorption has a huge potential for hyperspectral applications and tailored applications for any wavelength range.

Furthermore, graphene can be used as very thin antennas strongly focusing radiation in small near-field areas (the thinner the conducting layer, the larger is the field amplification factor, see also 5.3.2.5.3 Potential to be used as transparent antenna or absorber for certain wavelength ranges and 5.3.2.10.4 Antenna performance still too low). This can be used in detectors and mixers.

5.3.2.3.2 Potential for high bandwidth detectors and first lab results are promising

For high bandwidth photodetectors, simulations suggest a much higher possible speed (>600GHz) than existing technologies (roughly double the speed as III-V, Ge) [465]. Experimentally shown frequencies in the laboratory are close to III-V based frequencies (~262 GHz, III-V are >300GHz) [409] and performances of laboratory scale integrated photodetectors on Silicon (SoI) show a promising of 50Gbit/s. Up to 100 Gbps (at 850 nm and 1310 nm optical wavelengths) should be possible. [466] Furthermore, an improvement of 1-1000x bit/power (lower energy consumption) seems possible. The bandwidth and detection speed is already superb (in simple lab prototype) and the wavelength flexibility is very interesting. Sensitivity/responsivity is a current challenge, but there are concepts addressing this issue. [467]

Another key advantage is that graphene based ultrafast photodetectors can operate without the power-hungry transimpedance amplifier, which reduces power consumption of the system.

There is no specific intrinsic disadvantage. However, as the high potential needs to be actually demonstrated to show the actual technological benefit, it does not mean that graphene will evidently be the “winner” concept.

Another advantage is that the process for photodetectors is compatible with graphene modulator processes. The latter have similar promising characteristics, so that important parts of optical transceivers could be available and integratable from graphene with similar processes.

The combined properties of graphene for photodetection are quite unique (it is one out of a few candidates for future detectors). Other concepts are III-V semiconductors, quantum well or resonant tunnel diodes. The competing technologies are also quite costly, so if integration works and turns out to be rather cheap, graphene based detectors could become cheaper and easier to handle. Thus, cost can become a USP for photodetectors based on graphene.

5.3.2.3.3 Potential flexible detector solutions allow simpler optics

Graphene photodetectors can be made flexible on conformal substrates. This is an added value and quite unique (one out of a few candidates), especially for simple photodetectors (e.g. for fitness wrist bands pulse measurement, proximity sensors or imaging). Furthermore, the robustness is higher compared to e.g. InGaAs, which is brittle.

Flexibility and conformability can be important depending on the targeted market. For imaging it can for example simplify the optics leading to cheaper optics or smaller packages.

5.3.2.3.4 IR imaging allows higher resolution

IR imaging is an important application area for graphene. Graphene based IR imaging sensors can in principle lead to a better spatial resolution than InGaAs possible (resolution somewhere between InGaAs and Si). The overall performance of graphene based NIR/IR sensors today is already close to Si and InGaAs and there is still room for improvement. There are at the moment no specific or intrinsic disadvantages of graphene based sensors, besides the CMOS integration issues, which does not mean that it would evidently be the “winner” concept. But there are still many challenges to be addressed and an economically feasible wafer scale integration would be very beneficial. This in the end could lead to even cheaper sensors, especially as the competition is rather expensive. There is a market for poorer performing but cheaper IR/NIR sensors.

5.3.2.3.5 For non-integrated photodetectors and single pixel wafer scale integration is not necessarily needed

For very simple (single pixel) not-integrated detectors or flexible detectors, wafer-scale integration is not necessarily needed and roll to roll or sheet to sheet direct transfer is sufficient. This might still be cost competitive (probably already today), as many existing solutions in the IR are quite expensive. With working and feasible wafer scale integration, the cost reduction potential for these simple detectors would be very high potentially opening up wide markets.

5.3.2.4 Additional strengths: laser technologies

5.3.2.4.1 Saturable absorber and non-linear properties of graphene

Ultrafast carrier dynamics combined with large, spectrally broad and fluence dependent absorption due to Pauli blocking make graphene an interesting ultrabroadband wavelength independent and fast saturable absorber (SA) for ultrafast lasers (typically nano to sub-ps pulses). [256] The dominant SA technology for commercial (fibre) lasers is based on semiconductor SA mirrors (SESAMs), suffering from narrow tuning ranges and complex fabrication and packaging. Graphene SAs are an alternative to low-temperature grown GaAs (LT-GaAs).

Graphene based SAs enable broad tunability and can be realized with LPE and CVD graphene and the fabrication is relatively easy. They have been demonstrated for the important telecommunication wavelengths (e.g. ~1.5µm) but can be also used for mid-IR photonics.

Furthermore graphene exhibits higher order nonlinearities ($\chi^{(3)}$) for frequency conversion. In general, it should be possible to reach small form factors for graphene based photonics, e.g. in ultra short pulse laser diodes, especially if wafer scale integration technology is available.

Other nonlinear optical properties of graphene, such as second harmonic generation, difference frequency generation, four-wave mixing have been predicted and experimentally observed. It has been found that the nonlinear graphene parameters are substantially larger than in many other nonlinear materials and graphene might be more practical/robust to be used in applications. This opens new opportunities for design and development of different nonlinear graphene-based optoelectronic and photonic devices, controlled/tunable by the gate voltage.

5.3.2.5 Additional strengths: HF/microwave/THz generation, detection and processing

5.3.2.5.1 Physical properties are beneficial for HF/microwave/THz electronics transistors and realized advances are promising

The main motivation to use graphene for high frequency and analogue electronics is the ultra high carrier mobility, which allows high speed. Additional benefits are the very short life time of the photo-carriers, and the availability of 2D gas of electrons (plasma properties, plasmonics). This leads to realised graphene transistors with promising cut-off frequency f_T of 427 GHz (for a 67nm channel) [468] already reaching cut-off frequencies of competing technologies at similar wavelengths (e.g. GaAs, Si MOSFET). Furthermore, devices exhibit a low noise and allow for ambipolar electronics, leading to lower amount of needed transistors, leading to less chip area and lower energy consumption. f_{max} of competitive 200GHz at 60nm gate length have been demonstrated, which is not yet enough to outperform incumbent technologies but further shows the potential. [469] However, voltage gain A_v still lags behind. For a comparison of f_T and f_{max} with other technologies see Figure 86.

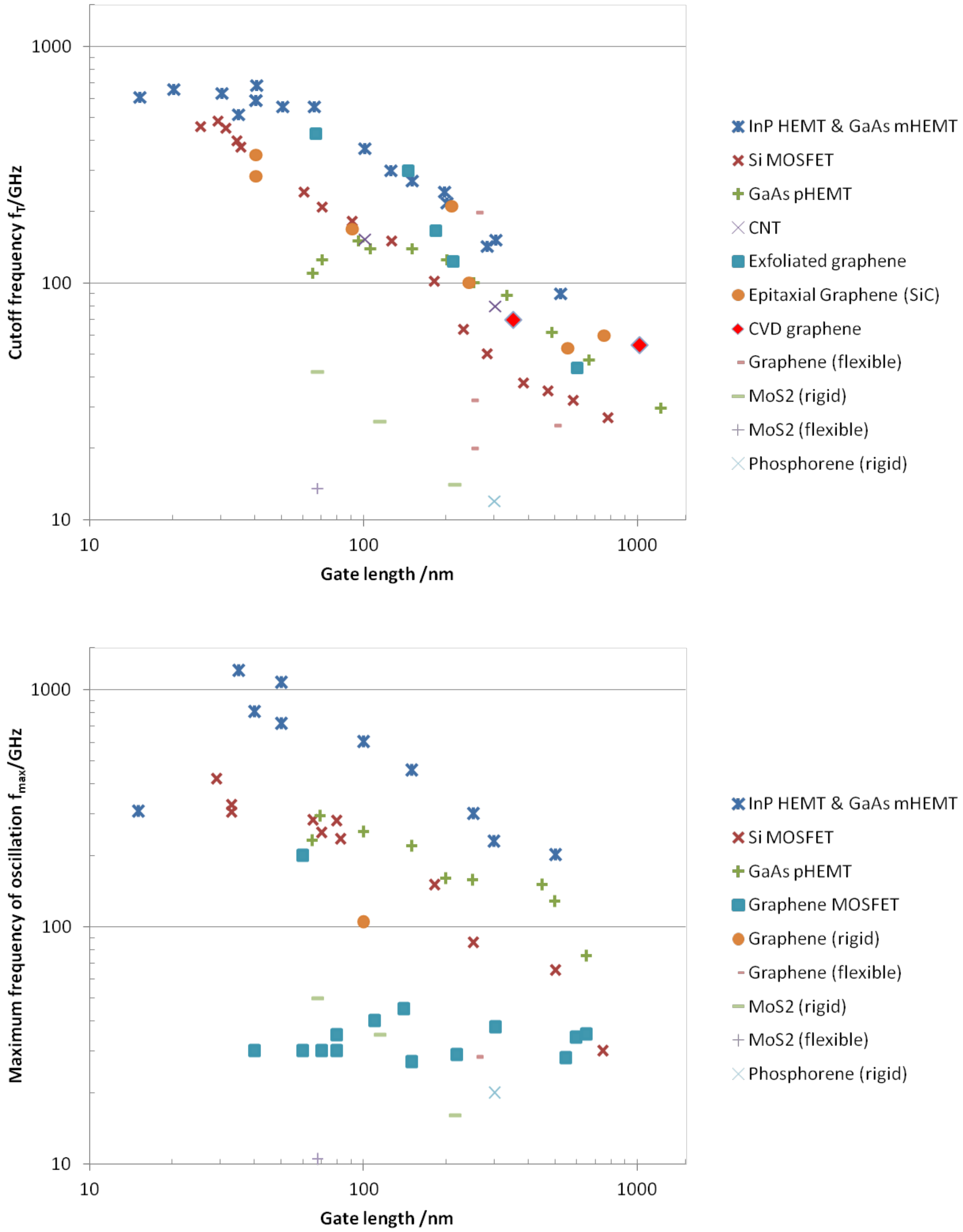


Figure 86: Comparison of cutoff frequency and maximum oscillation frequency depending on gate length for incumbent technologies, graphene and other 2D materials. Adapted from [386, 469, 470]

Graphene based modulators, demodulators, mixers and power detectors, key components for microwave and millimetre wave (wireless) applications, have extraordinary high linearity, possibly better than other semiconductors. First proof-of-concept measurements show a great potential for spectral efficient, very high data rate wireless communication interesting for systems for 5G and beyond for backhaul communication.

A larger mobility is also interesting because the larger the gate can be for a given frequency, which makes coupling easier, as the gate length gets closer to an antenna. Furthermore, optoelectronic functions and optoelectronic mixing can be addressed at the same time leading to an interesting multifunctionality. This is even further interesting due to the tunable optical properties. Tunability can even be achieved through stretching.

In principle, the technology is scalable and integratable with existing technology on wafer scale (see chapter 5.2 Electronics: Cross-cutting issues). It is also possible to integrate graphene in MMICs.

Also large arrays can be made for THz detection or radar application and flexibility is also interesting for RF applications. Due to the heat transfer properties, power dissipation can also be addressed at the same time.

An interesting novel transistor type is also the hot electron graphene base transistor, which uses gapless graphene and has some promising properties, although it is currently still difficult to seriously assess its potential for logic applications.

5.3.2.5.2 Graphene is the ultimately light and conductive electrode for BAW resonators

Graphene could be used as an ultimately light conductive electrode to replace metal/alloy sheets of 200-300nm on BAW resonators. The perfect electrode has low weight (very thin) and high electrical conductivity to allow a high q factor and low energy consumption. The theoretically calculated q-factor of graphene resonator is not achievable with other materials. However, the experimental validation of potential performance is still open (high risk, can also be a complete failure).

5.3.2.5.3 Potential to be used as transparent antenna or absorber for certain wavelength ranges

Graphene can be made tunable and optically transparent. At the same time it can have absorbing characteristics in the RF or microwave range. [471] Therefore it is potentially usable as a transparent and unobtrusive antenna, potentially in buildings or wearables. It can be also used as optically transparent radar absorbing material. On the other hand, it could be possible to tune it so that it is RF transparent and DC conductive, e.g. for radomes.

Graphene and GRM can serve as efficient micro-antennas of RF, MW, THz and IR radiation. The local AC electric field near sharp edges of thin conducting layers can be orders of magnitude larger than the field of the incident wave, with the field enhancement factor being stronger for thinner layers. Since the mono- or bi-atomic graphene layers are one or two orders of magnitude thinner than typical metallic layers, the graphene-based antennas can much more efficiently focus the incident wave field in very small areas. To reach that, higher mobility samples need to be available (with the scattering time of longer than ~ 1ps) with industry compatible manufacturing techniques. For this scattering time, the surface resistance is ~36 Ω/□. Thus, monolayers of graphene with the electron density ~3x10^{12} cm^{-2} and the scattering time ~ 1ps could serve as very thin antennas and replace metals.

Such antennas can be also used in RF, THz, IR detectors strongly focusing radiation in small areas and hence increasing the detector sensitivity.

5.3.2.5.4 Potential in low cost room temperature THz detection (also for RF, MW, IR)

Due to the plasmonic effects, the absorption of THz, RF, MW and IR radiation can be much higher than 2.3%, especially allowing access to these frequency domains for detection and manipulation. There are investigations towards the potential for low-cost room-temperature THz imaging/detection and ultrafast THz detection. Although the sensitivity may not be as good as with other techniques (at least with the current graphene quality), the speed is high. This has potential for ultrafast THz detection, even for quantum information applications, covering a broad frequency range from 3 THz to1 GHz. Uncooled THz detectors are already demonstrated at lab scale with NEP and fast speed approaching competing technologies [404, 472–474]. With wafer scale integration, also the cost could become competitive or even better for room-temperature THz imaging. Currently, the complexity of integration is more tricky than for semiconductors, which are prepared by MBE, but easier than for CNT. If room temperature performances are reached, which are comparable with cooled solutions, the indirect cost reduction potential is high, because the cooling system is not needed any more or can be weaker and at the same time power consumption can be reduced.

Other strength could lie in THz modulation, where graphene-based mixers were demonstrated up to 600 GHz.

Further investigations address MW, RF and IR detection based on plasmonic enhanced detectors.

5.3.2.5.5 Graphene interesting for THz modulation

Graphene allows an ultrafast modulation of its optical properties (absorption, reflection, transmission) by applying a periodic electric potential to the gate in a field-effect transistor (FET) configuration. Maximum cutoff frequencies of 100 GHz and higher in graphene-based FETs were shown. In the THz frequency range the modulation can be especially strong, due to graphene's high Drude conductivity, the dominant mechanism of electromagnetic absorption in this frequency range. As compared to its already high intrinsic value, the Drude absorption can be further enhanced by using plasmonic effects, external Fabry-Perot cavities and applying magnetic field.

It could be used as free-standing modulator, in the THz source or in the detector. In quantum cascade lasers (QCL) as THz sources, graphene showed promising properties and achieved 100% modulation on the lab scale (concentric-ring QCL) [475]. For THz detectors, it could be used with bolometers and/or semiconductor photodetectors (e.g. InAs, GeGa etc.), where the amount of THz radiation impinging on the detector could potentially be modulated by electrically gated graphene. In this case, the small detector size allows using small area (and therefore high-mobility) graphene.

A unique feature of graphene is a strong magnetic circular dichroism (MCD) and the Faraday rotation (FR) in the THz range [476, 477]. It appears that the MCD is especially significant (30% and higher) and that it can be inverted electrostatically by the gate at a fixed magnetic field. This feature allows switching between the LHC and RHC polarizations electrically with the maximum modulation speed allowed by a given GFET. The magnetic field intensity generated by compact and cheap permanent magnets and thus suitable for practical applications is limited to about 1.2 T. Preliminary estimates show that for high-mobility graphene this field can be sufficient to achieve a significant MCD, required for a proper modulator functioning.

5.3.2.6 Current weaknesses and challenges for graphene/2D materials use in telecommunication, optoelectronics & photonics

5.3.2.6.1 Quality and maturity of demonstrators

Many lab demonstrators show proofs of principles/concepts and the technological potential, but not on industrial scale. The graphene/2D material based technology is still rather young and thus a concise and solid business assessment is not possible at the moment. However, the potential is there and further investigations, especially in terms of actual demonstrators used in relevant environments and benchmarking with other technologies will help to reduce the uncertainties and assess the actual technological potential and unique selling propositions.

Besides that, the manufacturability is the most important topic, where especially reproducibility and the reduction of the scattering of the performance need to be addressed, as those issues are crucial for manufacturability and broader usage (see below).

Current key limitations are therefore a reliable large scale production, contacting of the material, energy efficiency and the overall performance in relevant systems and its benchmarking.

5.3.2.6.2 Integration challenge (wafer scale)

Undoubtedly, wafer scale integration is a crucial challenge for most telecommunication, optoelectronics and RF electronics applications. For some areas, such as simple photodetectors, laser applications and flexible applications wafer scale processes and integration with existing electronics is not needed and the already quite mature roll to roll or sheet to sheet transfer might be sufficient in quality. Using graphene and 2D materials as optoelectronically active material on Silicon or other substrates is very promising but also very demanding. If this is not feasible, many applications will not be able to address broader markets and will be relegated to a niche existence, if at all. For more information on wafer scale integration see chapter 5.2 Electronics: Cross-cutting issues.

In the following, the most important aspects of wafer scale integration for telecommunication, optoelectronics, photonics and RF electronics are addressed. Reliable large scale production is a key concern of many interested companies. The best case and desire would of course be a transferless process.

These applications mostly demand and benefit from the high charge carrier mobility in graphene films. Further needs are related to tuning the graphene homogeneously over the whole substrate (e.g. to introduce a bandgap, increase light interaction, etc.). Production of films exhibiting the needed electrical properties over the whole substrate is not yet possible. For instance, there is currently no reliable large scale technology to fabricate devices integrating a graphene film exhibiting carrier mobilities above 20000cm^2/Vs and strong carrier velocity saturation (using e.g. dry transfer, BN/Graphene/BN structures,…) over the whole substrate.

Besides the films itself, also the contacting and post-processing are key challenges not yet resolved: Contacting limits the performance of many devices due to parasitic effects such as capacitances and/or resistances. New concepts are needed to address these issues on wafer scale. This is not a physically limited challenge, but effort is needed to resolve that by proper engineering.

Independent of the actual challenge, the production reliability and yield play important roles in a fab and for the final price of a product. Especially as graphene exhibits a high sensitivity of properties to defects, so that small defects can have large effects. This calls for very stringent and precise processes. To address that, a stronger focus of research on process understanding and metrology is needed.

Furthermore, the substrate and encapsulation can influence the devices and long term reliability. Currently, there is knowledge missing about the most suitable substrates and the need, potential and influence of encapsulation.

The package of the unresolved integration scheme and limitations in current demonstrators (actual device-like demonstrations are needed) limits the overall advantage and will for companies to get stronger engaged and interested in the topic. Obviously, the unclear cost and effort of the production process can become a killer for broader graphene use. This applies to more or less all integrated solutions (laser, detector, …).

The remaining question is how much investment is needed to improve prototypes and manufacturing to a level that industry takes up the development. It is believed that especially for the manufacturing larger investments and patience are still needed.

5.3.2.6.3 Unproven long-term stability and robustness

Long term stability and robustness (2-5-10-20 years qualification period depending on application) are crucial for market acceptance. Although it is clear that this topic cannot be in the focus from the early beginnings of a technology, especially when the actual performance gain is not yet fully proven, it needs to be addressed as soon as the technological potential is seen. Especially when it comes to manufacturing and large scale production methods, long term stability/behavior need to be investigated and proven.

5.3.2.6.4 Graphene most probably too late for 5G, but there will be further evolutions

It is not realistic that graphene or other 2D materials will play a significant role in the beginning of 5G. High enough maturity and qualified graphene-based 5G solutions might come too late (needed before ~2020). Still the demand for efficient and fast data transmission components will increase after the launch of 5G creating the need for new solutions in further evolutions of the standard. To go further down this path, more industrially relevant and still better performing proof of principle/concepts are needed.

5.3.2.7 Additional current weaknesses and challenges: optical switches and modulators

5.3.2.7.1 Need for high doping and speed-drive voltage trade-off

Current demonstrators need a high and homogeneous doping to reach the performances. It is yet unclear how this doping can be implemented in a feasible and large scale process. Furthermore, the trade-off between speed and drive/switching voltage (influencing the energy efficiency) could be an intrinsic disadvantage of graphene and needs to be addressed and balanced, as both parameters are important for the application.

5.3.2.8 Additional current weaknesses and challenges: photodetectors

5.3.2.8.1 Imaging hardly possible without wafer scale integration

For imaging application a convergence of graphene technology and semiconductor technology is needed, e.g. to provide the read-out of focal plane array. Especially for imaging the production yield is crucial to avoid pixel defects and higher rejection rates which can drive the costs although initial savings are possible in the production due to for instance lower temperatures or faster and simpler processing steps.

For flexible and lower performing applications, already established roll to roll or sheet to sheet transfer might be sufficient, if it becomes cost competitive.

5.3.2.8.2 Still rather juvenile technology with open questions on sensitivity, reliability, stability and device linearity

As the technology is still rather juvenile and only lab type first proof of principles demonstrators are available, several next steps need to be addressed. A major challenge of ultrafast photodetectors for telecommunication is the poor sensitivity. A heterogeneously integrated graphene on Si detector for instance exhibits very fast speed, but a poor sensitivity due to the setup. The IQE is in principal good enough and it is an engineering task to increase the overall sensitivity. [466]

Further key issues are increasing and proving the combined performance in terms of insertion loss, sensitivity and speed as well as contacting and energy efficiency. At the moment, it is still unclear whether the realizable advantages are sufficient for broad use and to justify the investment in the production challenge.

5.3.2.9 Additional current weaknesses and challenges: laser technologies

5.3.2.9.1 Still unclear where graphene provides a winning application

Winning applications have not been clearly identified yet, although some results are promising. There are still open questions in terms of actual USPs and benchmarking with existing technologies. In this respect it is not sufficient to compare with graphene-based laser but to compare with actually competing technologies (incumbent and under development), which are mostly not based on graphene.

5.3.2.10 Additional current weaknesses and challenges: HF/microwave/THz generation, detection and processing

5.3.2.10.1 Currently experimentally realized benefits for telecommunication and high performance applications do not yet justify the needed risk and effort for integration

In order to be interesting enough, a one order of magnitude improvement needs to be offered by graphene towards integratable/mass manufacturable competing technologies to justify the needed investment to solve the manufacturing problem. Alternatively, it needs to be shown that integration is easy and does not require large efforts and costs. This is currently not fully obvious, particularly for high performance and telecommunication applications, and needs to be further investigated. Therefore, the current promising but not good enough performance is a major barrier, especially in the HF and microwave field. A similar efficiency, speed, etc. as, for instance, SiGe or Si will not justify the use of graphene.

Major disadvantages for RF transistors are at the moment the poor output power, voltage gain. The maximum oscillation frequency f_{max} is already competitive with Si and GaAs, but to justify the integration effort, it needs to be higher. (see Figure 86).

First proof-of-concept measurements of Graphene based modulators, demodulators, mixers and power detectors, key components for microwave and millimeterwave applications, have extraordinary high linearity, possibly better than other semiconductors. This, however, needs to be further investigated to actually proof the added value.

Alternative approaches than the GFET might lead to additional benefits for RF/microwave transistor, e.g. the barristor or graphene base transistor (GBT).

For other applications, e.g. THz technologies, a lower performance can be acceptable if total system cost is reduced. In terms of THz technologies, for sources the output power is an issue and for detectors the sensitivity might be too low compared to other room temperature technologies, but speed is already an important advantage.

5.3.2.10.2 BAW resonator electrode: Current processes more complex than metal electrodes

The processes for the preparation of the graphene based electrode are definitely more complex process than for metal electrodes, which are just evaporated. Furthermore, the RF conductivity in experimentally realized sheets is still too low. The industrial scale deposition on substrate is not available yet. With current transfer processes, it will be hard to reach the utmost spatial precision that is needed for BAW electrodes. The cost of the final product will be most probably higher (as the metal electrodes are very cheap), so that the benefit needs to be reasonably high in order to be feasible.

5.3.2.10.3 Missing basic understanding of (micro-)acoustic properties of graphene for BAW resonators

At the moment, there is no BAW resonator adequately experimentally realized yet. Furthermore, a basic understanding of (micro-)acoustic data of graphene (stiffness, density, mechanical tensor) and how to influence that is not yet experimentally confirmed, currently only theoretically estimated data is available. This is a challenge that needs to be addressed in order to gain further basic understanding of graphene in the device (to optimize, design and simulate the performance).

Further open questions are related to the unclear behaviour at higher power, e.g. in terms of delamination. This is strongly related to the question of how well it attaches to the piezo (AlN, quartz).

Last but not least, after first potentially successful experimental tests in simplified structures, a realization and investigation in optimized resonators with state of the art geometries is needed. Therefore this application is rather high potential, but also high risk with the chance to become a complete failure.

5.3.2.10.4 Antenna performance still too low

For the use as RF antenna , the antenna performance is still too low. Only for NFC and RFID the antenna performances are currently sufficient from printed materials, which are not transparent.

For better antenna performance, the resistivity at RF of graphene is too high. If this applications area is further investigated, it needs to be researched to which extent this RF resistivity can be influenced, e.g. through structuring, defect-healing, doping or other modifications.

For the use as micro-antenna instead of metals, the mobility and quality of industrial manufacturing compatible graphene is not good enough. To be a good plane "two dimensional" antenna, the surface static resistance of graphene/GRM should be (much) smaller than the free space impedance of ~376 Ω. Surface resistance of <50Ω/□ would be sufficient to reach that. For graphene layers with an electron density of ~3x10^{12} cm^{-2} and relatively low mobility, as reached from todays industrially compatible processes (with the effective scattering time ~100 fs), the surface resistance is ~360 Ω/□, which is not sufficient. If higher mobility samples are available (with the scattering time ~ 1ps), this changes, and graphene becomes interesting for RF, THz, IR detectors strongly focusing radiation in small areas and hence increasing the detector sensitivity.

5.3.2.10.5 Realized gain in HF circuits is not good enough at the moment

As mentioned above, there are still limitations of graphene use in RF applications, especially as GFETs, such as the low voltage gain A_V which lags behind incumbents. This is mostly due to the poor conduction band of graphene and the missing bandgap, so that there is essentially no “OFF” state available through a gate electrode bias. Furthermore, for RF power applications, although the current density is highest among all semiconductors, the total power is low due to the low voltage. But recent demonstrations of high f_{max} [469] appear promising for low power HF applications.

Doping is needed to address the bandgap issue and the doping possibilities of graphene available today are not so good.

In terms of ultrafast DAC/ADC and LNAs with high bandwidth, good resolution and operation efficiency, low power losses there is currently no economically feasible graphene-based solution on the horizon, because these devices require wafer scale integration.

5.3.2.10.6 Other 2D materials not yet promising enough

Other 2D materials are still too immature to do a proper assessment. However, the results so far suggest that there is no 2D material based film/ribbon with a proper bandgap and high carrier mobility. However, as the amount of potential 2D materials is very large, it cannot be excluded that a better performing material can be found.

5.3.2.10.7 Mobility vs. bandgap trade-off

Especially for RF and high frequency applications, a high mobility and a bandgap is needed. Chapter 5.2.2.6.1 Mobility vs. bandgap in 2D materials elucidates, that these parameters are intrinsically not better than for 3D materials, such as III-V semiconductors. There is an intrinsic cleft between band gap and charge carrier mobility, as opening of bandgap reduces the mobility in graphene and the mobilites of 2D materials with a bandgap are not very high compared to bulk semiconductors. In contrast, CNTs have the combination of high mobility and reasonable bandgap, whereas bulk graphene and GNR have issues with that.

5.3.2.10.8 Substrate dependence of performance

The performance of graphene based electronic devices is heavily depending on the used substrate layers. Best performing devices usually use 2D boron nitride as substrate layer to encapsulate the graphene. So far, there is no industrially scalable process for graphene-BN stacks available, so all applications that perform only well with BN layers will have a very long time to market, if the integration challenges can be solved at all.

5.3.2.10.9 THz applications need high mobility

To develop graphene-based intensity and polarization electrically driven modulators for THz applications, large-area high-mobility graphene (>20.000 cm^2/Vs) is preferred, since this increases the peak intensity of the electromagnetic absorption and consequently enhances the modulation depth and speed. Depending on the integration level, this quality is needed on >3mm (free space propagation modulation), ~500µm (waveguide modulator) or <100-200 µm (modulator integrated into small THz sources or detectors). The latter is easiest to be achieved currently.

5.3.3 KPIs for telecommunication, optoelectronics & photonics

In this chapter several important key performance indicators for applications are highlighted. In some cases specification of competing technologies (state of the art or under development) are presented for comparison. This chapter shall simplify and motivate benchmarking of graphene/2D material based technologies with competing technologies by means of functions and not technological principles.

5.3.3.1 Telecommunication in general

- General: 5G: 100x-1000x capacity of 4G, standardization until 2016-2020
- Terminals 1Gbps – 10Gbps, Small (Micro) Cells 100 Gbps
- General specs: 1-1000x lower bit/power
- Reliability and durability (qualification period): 2 years (consumer) – 20 years (backbone)

5.3.3.2 Antennas and resonators:

Antenna:

Unobtrusive, transparent

- 50Ω/□ at mm-wave and µwave-frequencies needed

For micro-antennas and detectors (focusing radiation in small areas and hence increasing the detector sensitivity):

- Mobility good enough to allow a scattering time >1ps (at electron density of ~$3x10^{12}$ cm^{-2} to reach ~36 Ω/□

Resonator: (G as electrode on piezo BAW)

- Q-factor/insertion loss (≤1dB?), small footprint, frequency (2-40GHz?), temperature stability
- Electrodes: <0.1Ω/□

5.3.3.3 HF & microwave:,

For analogue HF transistors high mobility and I_{ON}/I_{OFF} ~10-100 needed.

Table 44: Desirable properties of ideal high performance RF FET channel materials. From [386].

Property	Desireable
Bandgap	sizeable, probably lower limit below 0.4 eV and optimum above 0.17 eV
Carrier effective mass	very light, $m_{eff} < 0.05\ m_e$
Mobility	very high, > 10 000 $cm^2\ V^{-1}\ s^{-1}$
Peak/saturation velocity	very high, ≥3 × 10^7 cm s^{-1}
Heat transport	Thermal conductivity: High Thermal boundary resistance: Low
Contact resistance	Low ≤0.03 Ω mm
Scale length, channel thickness	Small

mmWave **transceiver** MMICs/TMICs (30-40dBm)/analogue transistors, modulator, demodulator with high bandwidth

Low Noise Amplification

use of a broader spectrum up to mm (30-300GHz) waves for data transmission and backhaul

See Figure 86 for f_{max} and f_t values.

For further KPIs please refer to the ITRS 2013 tables www.itrs2.net or directly via [399] (RFAMS2013tables).

5.3.3.4 Optical Switches/modulators

Important figures of merit: Optical Insertion loss, switching speed, responsivity and switching voltage

Needed KPIs for optical backbone communications devices are:

- Optical Wavelength: 1530 nm ... 1610 nm
- On/Off Switching Voltage: $V\pi \leq 0.5$ V (Ge-based EA modulator: 2V, LiNbO3: >2V; $V\pi L$>0.2Vcm)
- Low energy consumption (currently < 0.4 pJ/bit)
- Input Impedance: 50 Ohm
- Optical Input Power: ≥ 10dBm
- Insertion Loss: ≤ 5 dB (Fiber to Fiber) (Ge-based EA modulator: 4.1 dB, LiNbO3: >2.6 dB)
- Extinction Ratio: ≥ 20 dB
- Bandwidth: ≥ 30/35 GHz (Ge-based EA modulator: 50 GHz, LiNbO3: 10s of GHz)
- Chirp Free
- Small form factor (cf. today‘s LiNbO3 Modulator ~ 10cm)

Si-photonics capable of 100 Gb/s transceivers without graphene (4x 25Gb/s) [461]

Table 45: KPIs of electro-optical modulators. [478]

Modulator Type	Footprint [μm²]	Drive voltage [V]	Optical BW [nm]	Temp. Range [°C]	ER [dB]	IL [dB]	Dyn. Power [fJ/bit]	3 dB freq. [GHz]	Bit Rate [Gb/s]	Ref.
Si Mach-Zehnder	~3000x5000	1.5	> 80°	> 80°	3.4	7.1	450	30	50	[479]
Si Ring	~10x10	0.5	< 0.1	< 1	6.4	1.2	~1	21	44	[480]
SiGe EAM	~55x10	2.8	35 5	< 1 < 40	~5	~4	60	> 30	28	[481]
Graphene-Si EAM	~40x10	3	>180	n/a	2.4	n/a	n/a	1.2	n/a	[482]
Graphene-Si EAM	~50x10	2.5	>80	> 29	2.5	< 4	350	2.6 - 5.9	10	[478]

5.3.3.5 Photodetectors (high speed)

Needed KPIs are:

- Fast speed (100GHz) (current semicon based tech >50Ghz) (met already for material, not component, rest is integration)
- 100Gbit/s are necessary; photonic ICs capable to reach 600Gbit/s
- High Efficiency
- Responsivity of >0.5 A/W
- Low Noise
- Robustness→valid for all components (integration)

Handling different wavelengths: nice to have to span to other wavelengths ranges besides standard wavelengths (bands). (met already); beyond 1.3 and 1.55µm, e.g. 9xx nm

Graphene needs to achieve a contact resistance of <50Ohm µm, mobility 10000Vs/m² (µ) on wafer, then KPIs will be met (currently µ=7000Vs/m²)

Table 46: Parameters of some fast photodetectors. Credits to D. Neumaier.

	Data Rate	**Sensitivity**	**Wafer-Scale Integration on Si**
Graphene [466]	50 Gbit/s	0.1 A/W	in principle possible
Graphene [483]	42 Gbit/s	0.36 A/W	in principle possible
Ge [484]	40 Gbit/s	0.8…1A/W	OK
Ge-APD [485]	10 Gbit/s	~10 A/W	OK
InP [486]	160 Gbit/s	0.6 A/W	NO
Phosphorene [487]	3 Gbit/s	0.7 A/W	Not yet

5.3.3.6 Broadband photodetectors and broadband hyperspectral Imaging

Needed KPIs are:

- High Detectivity (Jones D*) (depends on noise, typical values for competing technologies: @1-1.7µm: 10^{12} cm$\sqrt{Hz}$/W @1.7-10µm 10^{10} cm$\sqrt{Hz}$/W, ultra high sensitive InGaAs detectors reach 10^{13} cm$\sqrt{Hz}$/W) but cut off at 1.7µm;
- High speed (fast response); Standard mid-IR detectors have D*=3x10^{8} cm$\sqrt{Hz}$/W with a speed of ~1 kHz (non tuneable)
- High resolution (256x320 available for IR)
- Price: InGaAs 2k€/sensor for 256x320 pixels; with high spatial resolution for imaging: 15-50k€, "lower quality, better price" could facilitate new markets, e.g. food quality sensing: InGaAs has too high sensitivity (600-2000nm; 256x320 pix) and is too expensive

(2k€) →compromise needed/possible; LWIR bolometers 10-100€ (e.g. FLIR detector for mobile phones)

- Hyperspectrality (wavelength range covered)
- Low dark current (for ultra-sensitive applications and single photon counting: <nA (InGaAs)), or high gain, as e.g. realizable in graphene-QD phototransistors
- Flexibility

Table 47: Comparison of THz detectors taken from [404].

Detector Type	Temperatur [K]	Response Speed	Integration	Responsivity [V/W]	NEP [pW/sqrt(Hz)]	Frequency	Remarks
PC LT-GaAs	300	Slow (ms-s)		-	~10	Broad band	Indirect
EO GaAs	300	Slow (ms-s)		-	~100	Broad band	Indirect
EO DAST	300	Slow (ms-s)		-	~10	Broad band	Indirect
Golay Cell	300	Slow (~50ms)		10^4-10^5	100-1000	Broad band	
DLATGS	300	Slow (~10ms)		~10^5	1000-3000	Broad band	
Si Bolometer	0.3-4.2	Slow (~1ms)	320 x240	~10^4/~10^8	0.01 @0.3 K	Broad band	
QW	4.2	Fast (50ps)		-	7x10^{-8}	0.5~3 THz	
QD	0.07-4.2	Slow (20 µs)		-	10^{-10} @70mK	0.5~3 THz	
NbN STJ	0.3-9	Fast	36-1000	~10^9	10^{-4} @0.3 K	Nb: <700 THz	
TES	0.3	Slow (~50 ms)	1024	-	10^{-5}	Broad band	

Detector Type	Temperatur [K]	Response Speed	Integration	Responsivity [V/W]	NEP [pW/\sqrt(Hz)]	Frequency	Remarks
Nb HEB	4.5 K	Fast (~50ps)	64	-	~50	<30 THz	
SBD GaAs	300	Fast (~20ps)		0.3~1K @150-400 GH	5 ~ 20	~900 GHz	
SBD ErAs/InAIAs	300	Fast (~20ps)		6.8 K @100 GHz	1.4 at 100 GHz	~2.6 THz	
SBD In-GaAs/InP	300	Fast (~20ps)		~1K @300 GHz	0.4 at 100 GHz	<1 THz	
Graphene FET (NR-Plasmon)	300	Fast		14 @0.6 THz	515 @0.6 THz	Broad band	
Graphene (PV/PTE)	300	Fast		700 @10-100 GHz	16 @10~100 GHz	Broad band	pulsed meas.
Graphene Bo-lometer	0.1-4.2	Slow (~1ms)			$5*10^{-8}$ @0.1 K @1 THz	Broad band	
Si-CMOS (NR-Plasmon)	300	Fast	32^2	57k @0.9 THz	470 @0.9 THz	0.3~3 THz	amp. Inte-grated
InP HEMT (NR-Plasmon)	300	Fast (~10ps)		23k @0.2 THz	0.5 @0.2 THz	~5 THz	

5.3.3.7 Optical transceiver system

Competing typical systems are:

- Luxtera Blazar 4x10 Gb/s QFSP+
- Avago MicroPOD 12x10Gb/s
- Cisco: All modules 100GE (CFP4, CPAK, QSFP28)

5.3.3.8 Passive and Active Lasers

Saturable absorber (SESAMs) for ultrabroadband tuneable mode-locked lasers and Integrated fibre, semiconductor, waveguide and solid-state lasers. Conventional technology KPIs:

- Wavelength tuning range: 680-1080 nm (Kerr-lens mode-locking)
- Output power: ~300 W (SESAM)
- Repetition rate: 1.2 THz (NPR)

Tunable light source for communication for passive optical networks (PONs):

- Wave Length: C-Band (1530 – 1565nm) / O-Band (1260 – 1360nm)
- Tuning Range: 15 - 20nm
- SMSR (side mode suppression ratio): >30dB
- Optical Output Power: > 1mW (0 - 5dBm)
- Electrical Input Power: < 1W
- Bitrate: ≥ 1.25Gb/s (bis zu 10Gb/s)
- BER (bit error ratio): < 10-10 (ITU)/10-12 (IEEE)
- Extinction Ratio: > 6dB (IEEE)/10dB (ITU)
- Good Noise Performance
- High Volumes, lowest Cost! (Mpcs, 1$ range)

5.3.3.9 Components for THz applications

Detector (KPIs of competing technologies)

- Uncooled or 70K THz detector, 10x lower sensitivity than bolometer is ok (typical NEP are ~2pW/Hz1/2 and few kV/W)
- Response speed of conventional high-speed THz detectors on the order of 10-100kHz
- THz arrays of 1024 pixels
- Bolometers (aSi or Vox): TCR: 2%/K-1; Response time 20 ms, Absorption: > 80 % broadband)

Modulator:

- Mobility >20.000 cm^2/Vs; depending on the integration level, this quality is needed on >3mm (free space propagation modulation), ~500µm (waveguide modulator) or <100-200 µm (modulator integrated into small THz sources or detectors)

5.3.4 Roadmap for telecommunication, optoelectronics & photonics

5.3.4.1 Current maturity: 'Lab demonstrators'

For this applications area, most research is currently at the lab demonstrator stage when it comes to graphene. Other 2D materials are less mature. The lab demonstrators usually show some promising parameters, but the overall benefit and proof in a relevant environment is not yet there. A major obstacle for further maturity improvements is related to the manufacturability. Wafer scale integration is necessary for most applications in this area to gain a higher relevance for industry. However, the current overall demonstrated performances appear to be not good enough so that industry would easily pick up the lead for solving the integration problems.

5.3.4.2 Barriers/challenges (summarized)

A major challenge is wafer scale integration, as it is a must have for most applications. The barriers highlighted in chapter 5.2.4.2 apply similarly. For the integration challenge related to telecommunication, optoelectronics and photonics applications, the following challenges are of particular relevance:

Demonstrators and technology

- Performance gain (or less likely: cost reduction) must justify wafer scale efforts (seems to be not yet the case), quality and maturity of demonstrators and how they are produced do not yet provide the needed certainty to profoundly assess that
- Benchmarking with technologies that address the same applications in terms of functionality (and not within graphene or with a device concept that is also far away from the incumbent or competing application-addressing technology)
- Reliability, energy efficiency and durability requirements (delamination)
- Contacting
- Substrate and package interactions, understanding of properties of graphene in MMICs, opto-electronic and acusto-electronic devices (for proper design and simulation)
- Other 2D materials even too early to assess

Ecosystem development:

- Dead-lock situation: OEMs are interested in the technology (such as Nokia, Ericsson). This is important, but they buy components and the integration of graphene is done elsewhere.
- Missing link at least in Europe? Who will integrate graphene into components? Developments are currently mostly done in the (public) labs, nobody is capable or willing to take it up at the moment.
- Foundry/integrated device manufacturers (the ones who have own fabs) need to be convinced of the potential of graphene via realistic demonstrators to act as a middleman between OEMs and labs. To achieve that, convincing KPIs need to be reached to justify the probably high investment needed.
- Single user/single customer conundrum: A supplier will not change for a single customer, a customer will not by from someone who is the only supplier (second source principle)

Antennas & Resonators:

In terms of antennas and resonators, the following challenges are particularly relevant:

- Unclear RF conductivity of (transparent) graphene films for efficient antennas, especially 2-10-20GHz and how this can be influenced through manipulation (tunability, doping, …)
- Highly precise, yet economically feasible (and thus not complex) transfer on dielectrics (piezos)
- Missing basic understanding of (micro-)acoustic properties of graphene

Optical Switches/modulators:

Major challenges related to optical switches and modulators are:

- Open question: Who will integrate the technology into components in Europe (from the current partners in the flagship)? Or is integration in Europe actually needed? Should it be licensed?

Technological challenges

- Trade-off speed vs. drive voltage (depends on quality)
- Homogeneous doping over large substrates
- Bilayer or double-layer graphene with a spacer (e.g. aluminium oxide)
- Need lower insertion loss –Higher extinction ratio
- Better quality large area graphene with mobility >10.000 cm^2/Vs (performance limited by graphene quality after processing)
- Need higher speed (28GBit/s, 56 Gbit/s …)
- More compact devices: shorter devices need higher interaction with graphene film
- Lower contact resistance (speed limited by RC-constant)
- Better reproducibility, need reliable and reproducible integration process
- Demonstration of full transceivers (multi-channel devices, also detectors)

Photodetectors (fast speed):

Technological challenges:

- Sensitivity needs to be improved (while insertion loss and speed remain or improve)
- Current speed of graphene based components limited by contacts and assembly (65GHz overall performance vs. >200GHz for material)
- Limits of the system integration/ assembly
- Key limitations: Reliable large scale production, performance, contacts

Imaging:

Major challenges related to photodetectors for imaging/high sensitivity are

- High priced, high performance market is already existing and an actual added value must be shown through working demonstrators
- Medium to lower priced markets are very interesting, but price and performance competitiveness must be shown
- Integration with silicon on wafer scale for highly integrated sensors needed (e.g. to combine with read-out focal plane arrays). But: single pixel and flexible do not necessarily need wafer scale
- Contacting of the graphene
- Sensitizing/plasmonic enhancement to increase sensitivity without sacrificing hyper-spectrality

Laser:

For laser applications the integration issue is important for low cost/laser diode applications. For fibre lasers and high performance ultrafast lasers, especially benchmarking with existing well performing technologies is needed.

HF/microwave/THz electronics:

For microwave/RF/sub-mm applications

- Current realized RF performance in transistors not good enough (does not justify the effort): especially voltage gain A_V
- Promising proof of concepts need to be further developed to be able to benchmark with competing technologies
- Bandgap issue in graphene not good for transistors, but can be also exploited for other interesting applications and also seen as a benefit
- Reliable large scale production, requirement of high mobility, contacts are key issues

Major barriers for THz applications

- Missing proof of principle of potentially (and theoretically) good THz performance in devices
  - Proof of principle for actual THz detector and THz mixer
  - Proof of principle of detector arrays for THz detection
- For bolometer: proof of principle and improvement of temperature coefficient of resistance TCR response time and absorption

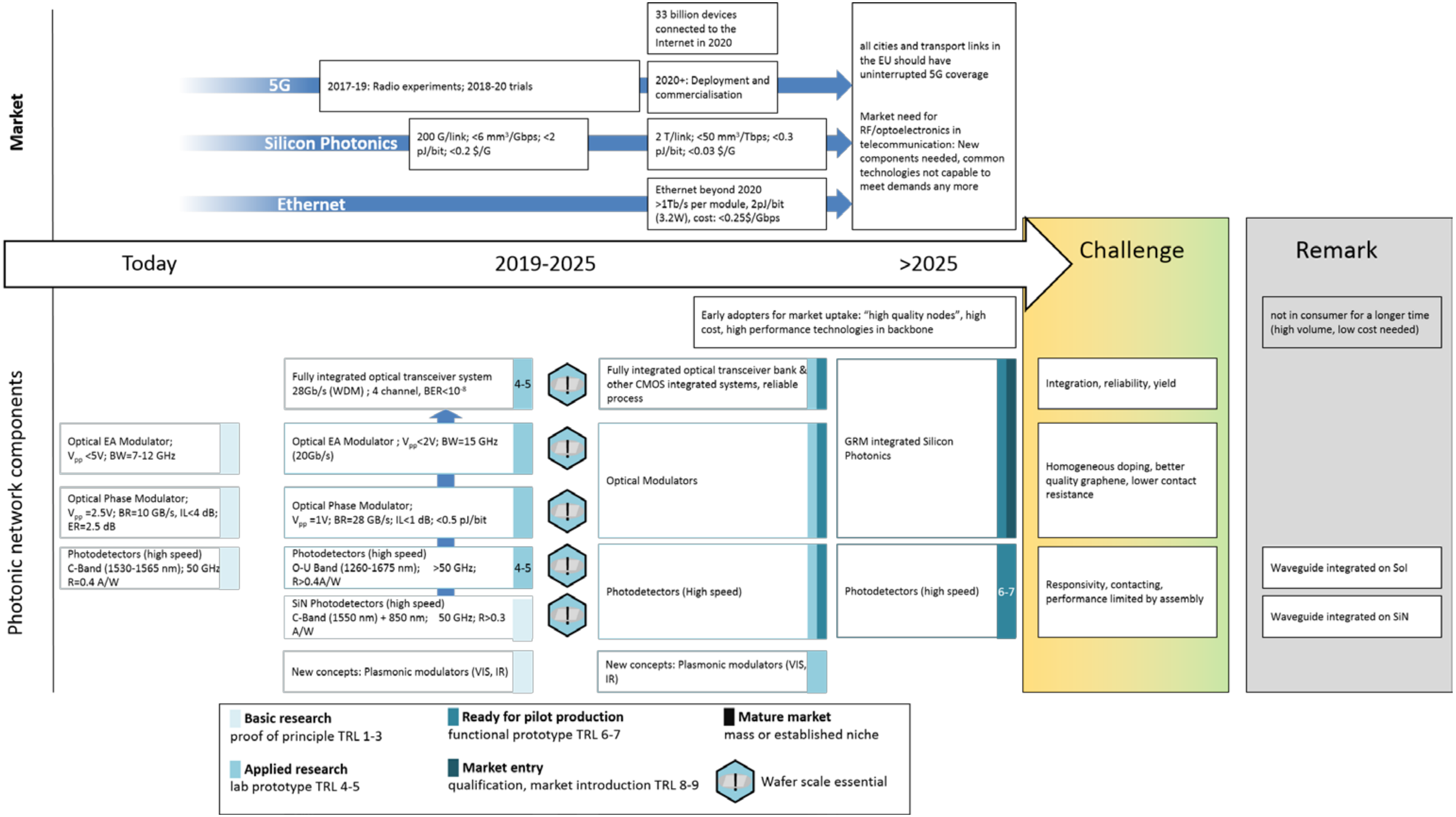
5.3.4.3 Potential actions

If the area of graphene/2D in telecommunication, optoelectronics and photonics is seen as promising for Europe and the topic is further pushed, the following potential actions, derived from the challenges, are suggested:

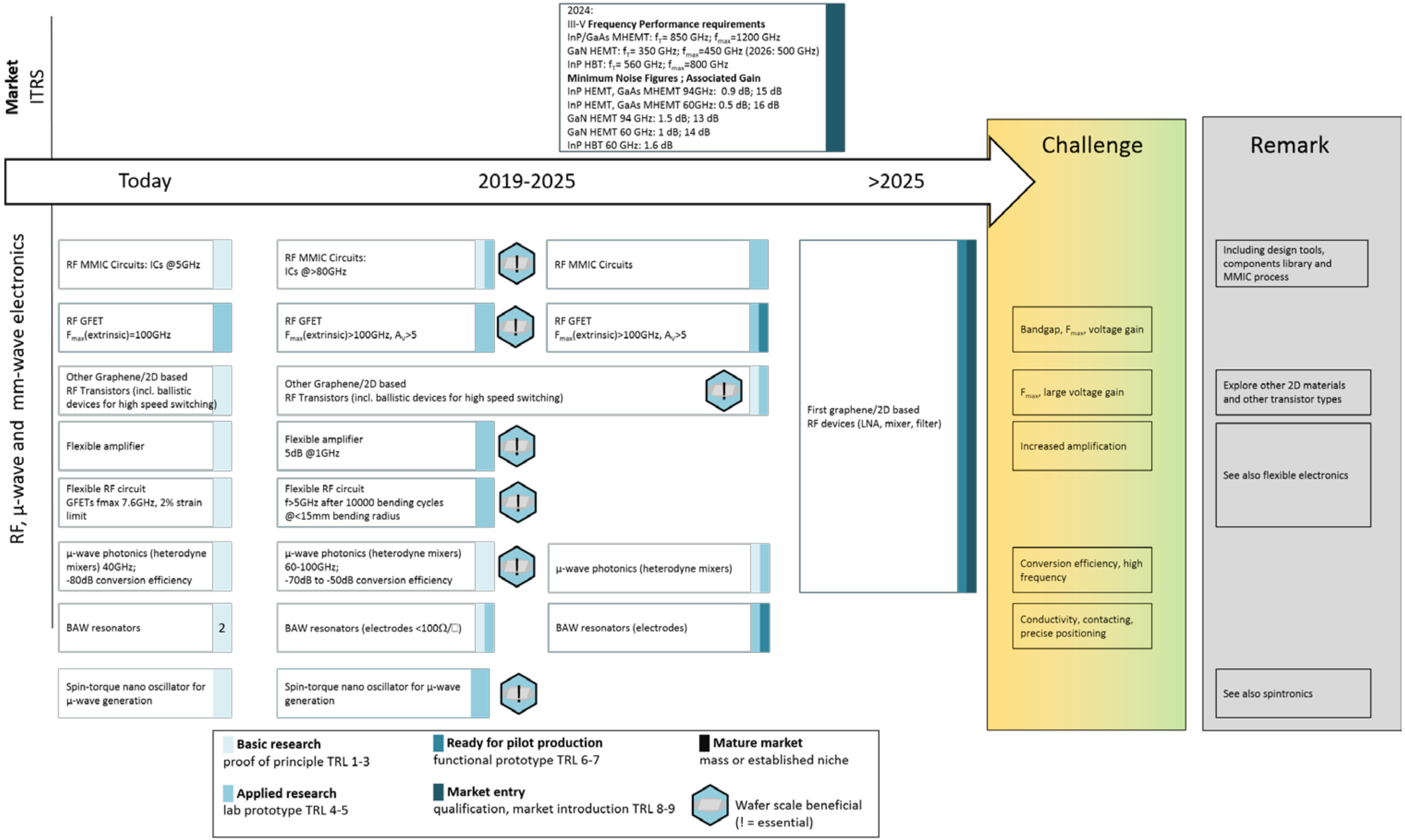
The following potential actions are identified as addressing common issues:

- Go from idealised or simplified proof of principle demonstrators with promising performance to actually relevant designs and demonstrators for actual benchmarking (create "engineering knowledge")
- Explore other 2D materials
- Look at full relevant set of parameters when comparing to other technologies (including reliability, temperature stability, long term performance, energy efficiency)
- Explore and intensify the ecosystem to get ideas on how to overcome the dead-lock situation when the time is ripe.
- Explore alternative approaches tailored to graphene (GBT, etc.)
- Explore substrates, lamination and passivating layers for the applications
  - With AlOx(wafer scale devices)
  - With HBN (exploratory, small scale devices)
  - Towards double layer graphene devices (allows shortening of optoelectronic devices)
  - On silicon or silicon nitride waveguide

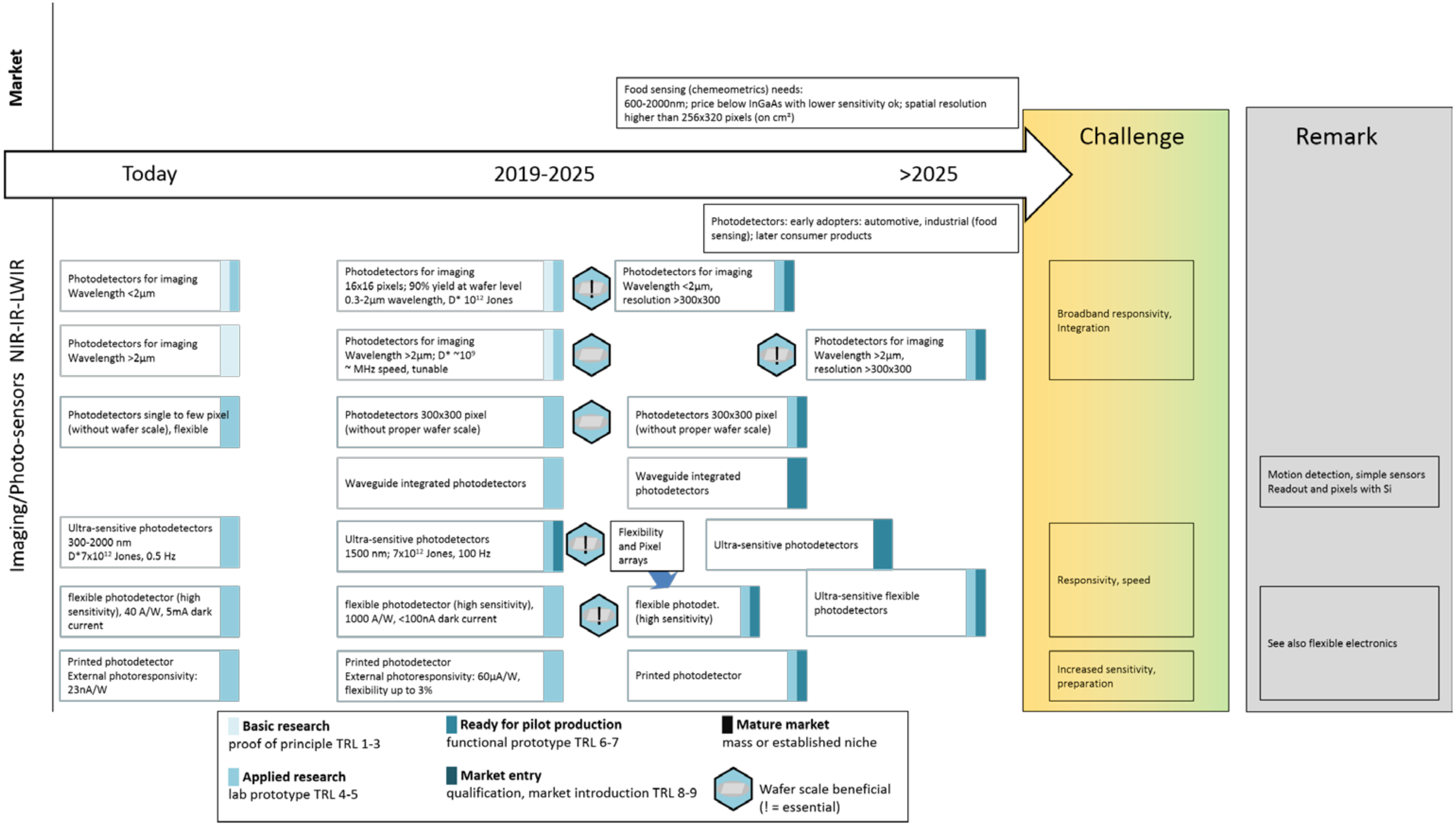
5.3.4.4 Roadmap

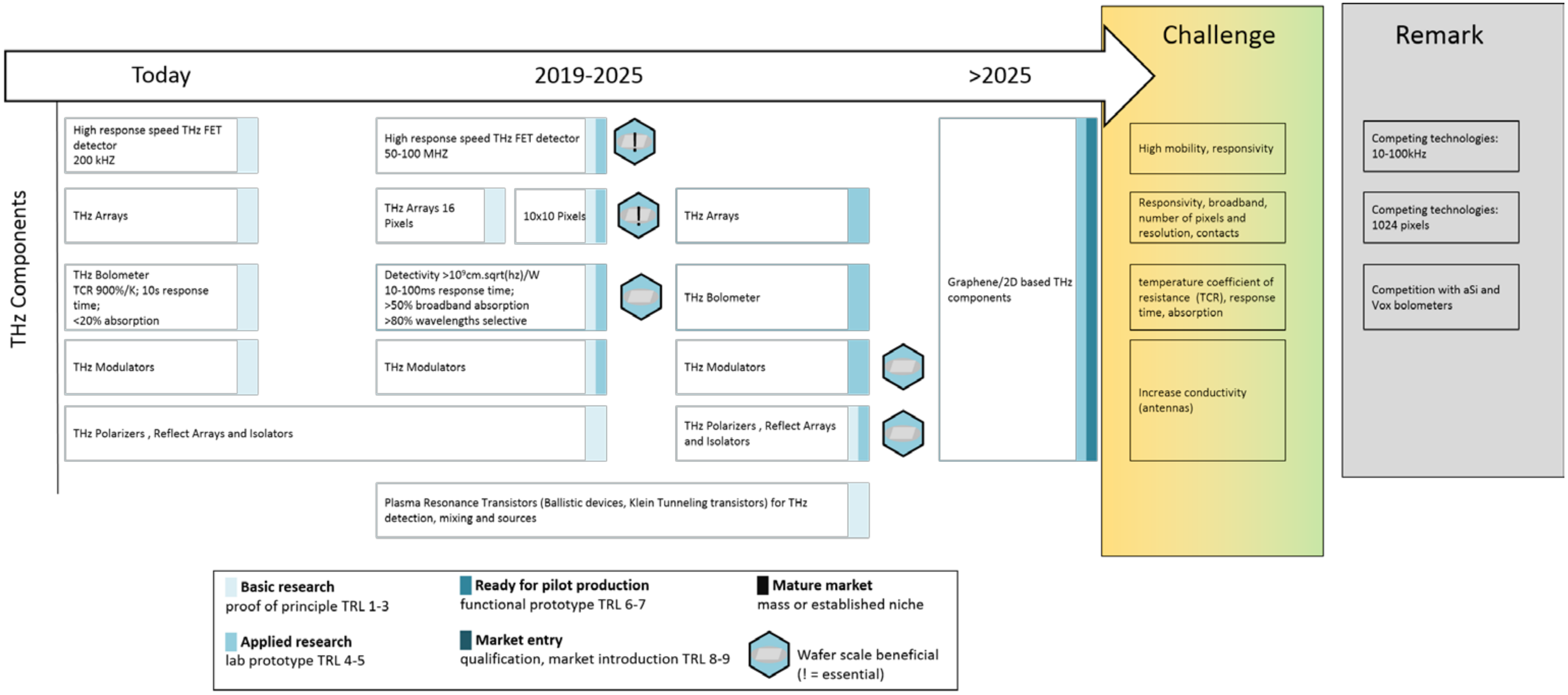


Sources: 5G [451], Ethernet [488], Si Photonics [489, 490]

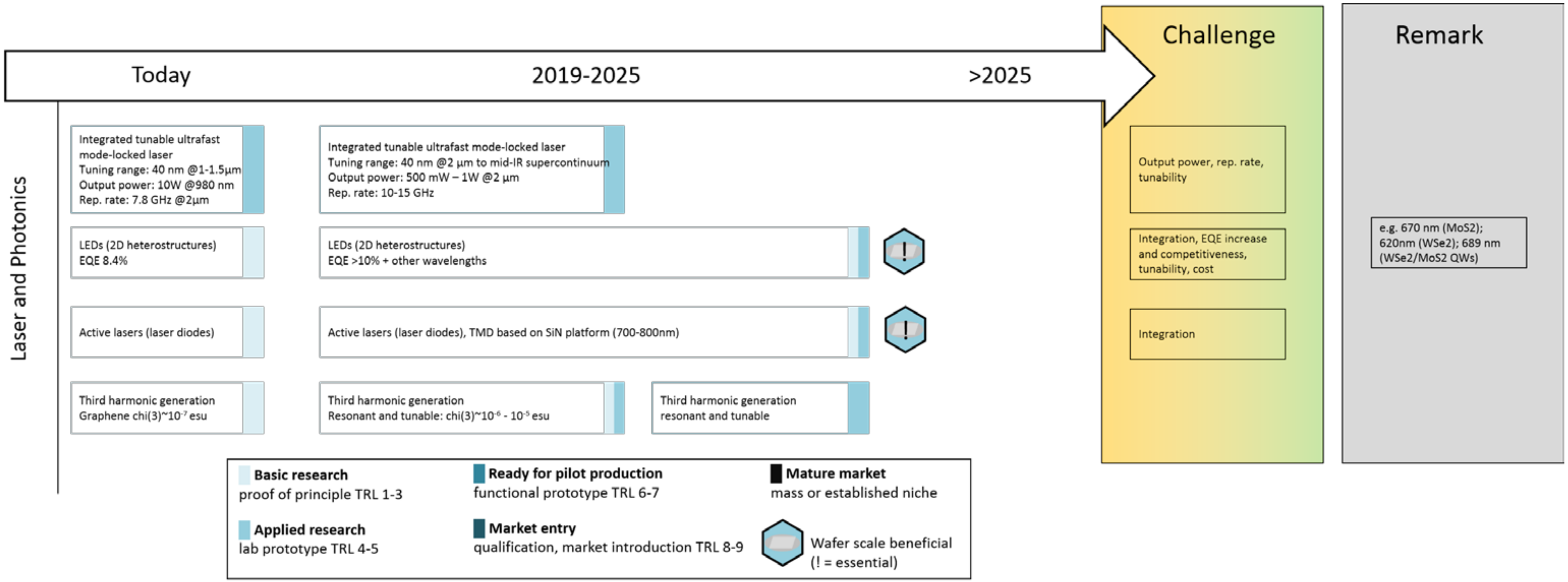


Sources: ITRS [491]


Market
Imaging/Photo-sensors NIR-IR-LWIR
Today
2019-2025
>2025
Challenge
Remark
Food sensing (chemeometrics) needs:
600-2000nm; price below InGaAs with lower sensitivity ok; spatial resolution higher than 256x320 pixels (on cm²)
Photodetectors: early adopters: automotive, industrial (food sensing); later consumer products
Photodetectors for imaging Wavelength <2µm
Photodetectors for imaging 16x16 pixels; 90% yield at wafer level 0.3-2µm wavelength, D* 10¹² Jones
Photodetectors for imaging Wavelength <2µm, resolution >300x300
Photodetectors for imaging Wavelength >2µm
Photodetectors for imaging Wavelength >2µm; D* ~10⁹ ~ MHz speed, tunable
Photodetectors for imaging Wavelength >2µm, resolution >300x300
Photodetectors single to few pixel (without wafer scale), flexible
Photodetectors 300x300 pixel (without proper wafer scale)
Photodetectors 300x300 pixel (without proper wafer scale)
Waveguide integrated photodetectors
Waveguide integrated photodetectors
Ultra-sensitive photodetectors 300-2000 nm D*7x10¹² Jones, 0.5 Hz
Ultra-sensitive photodetectors 1500 nm; 7x10¹² Jones, 100 Hz
Flexibility and Pixel arrays
Ultra-sensitive photodetectors
flexible photodetector (high sensitivity), 40 A/W, 5mA dark current
flexible photodetector (high sensitivity), 1000 A/W, <100nA dark current
flexible photodet. (high sensitivity)
Ultra-sensitive flexible photodetectors
Printed photodetector External photoresponsivity: 23nA/W
Printed photodetector External photoresponsivity: 60µA/W, flexibility up to 3%
Printed photodetector
Broadband responsivity, Integration
Responsivity, speed
Increased sensitivity, preparation
Motion detection, simple sensors Readout and pixels with Si
See also flexible electronics
Basic research proof of principle TRL 1-3
Applied research lab prototype TRL 4-5
Ready for pilot production functional prototype TRL 6-7
Market entry qualification, market introduction TRL 8-9
Mature market mass or established niche
Wafer scale beneficial (! = essential)



Today
2019-2025
>2025
Challenge
Remark
THz Components
High response speed THz FET detector 200 kHZ
High response speed THz FET detector 50-100 MHZ
THz Arrays
THz Arrays 16 Pixels
10x10 Pixels
THz Arrays
THz Bolometer TCR 900%/K; 10s response time; <20% absorption
Detectivity >10⁹cm.sqrt(hz)/W 10-100ms response time; >50% broadband absorption >80% wavelengths selective
THz Bolometer
THz Modulators
THz Modulators
THz Modulators
THz Polarizers , Reflect Arrays and Isolators
THz Polarizers , Reflect Arrays and Isolators
Graphene/2D based THz components
Plasma Resonance Transistors (Ballistic devices, Klein Tunneling transistors) for THz detection, mixing and sources
High mobility, responsivity
Responsivity, broadband, number of pixels and resolution, contacts
temperature coefficient of resistance (TCR), response time, absorption
Increase conductivity (antennas)
Competing technologies: 10-100kHz
Competing technologies: 1024 pixels
Competition with aSi and Vox bolometers
Basic research proof of principle TRL 1-3
Applied research lab prototype TRL 4-5
Ready for pilot production functional prototype TRL 6-7
Market entry qualification, market introduction TRL 8-9
Mature market mass or established niche
Wafer scale beneficial (! = essential)


Today
2019-2025
>2025
Challenge
Remark
Laser and Photonics
Integrated tunable ultrafast mode-locked laser
Tuning range: 40 nm @1-1.5µm
Output power: 10W @980 nm
Rep. rate: 7.8 GHz @2µm
Integrated tunable ultrafast mode-locked laser
Tuning range: 40 nm @2 µm to mid-IR supercontinuum
Output power: 500 mW – 1W @2 µm
Rep. rate: 10-15 GHz
Output power, rep. rate, tunability
LEDs (2D heterostructures)
EQE 8.4%
LEDs (2D heterostructures)
EQE >10% + other wavelengths
Integration, EQE increase and competitiveness, tunability, cost
e.g. 670 nm (MoS2); 620nm (WSe2); 689 nm (WSe2/MoS2 QWs)
Active lasers (laser diodes)
Active lasers (laser diodes), TMD based on SiN platform (700-800nm)
Integration
Third harmonic generation
Graphene chi(3)~10⁻⁷ esu
Third harmonic generation
Resonant and tunable: chi(3)~10⁻⁶ - 10⁻⁵ esu
Third harmonic generation
resonant and tunable
Basic research
proof of principle TRL 1-3
Applied research
lab prototype TRL 4-5
Ready for pilot production
functional prototype TRL 6-7
Market entry
qualification, market introduction TRL 8-9
Mature market
mass or established niche
Wafer scale beneficial
(! = essential)

5.3.5 Conclusion telecommunication, optoelectronics & photonics

With the increase of data traffic (5G and beyond), there is a strong need for new technologies and innovations to reach higher bandwidth and energy efficiencies. The telecommunications equipment market is globalized, and driven by large commercial markets. With Ericsson and Nokia Networks/Alcatel-Lucent, two of the largest telecommunication equipment suppliers are European companies.

Optoelectronic, in particular photodetector applications, also address other larger markets with growth opportunities, e.g. (IR/hyperspectral) imaging, spectrometers and optical sensors in general.

Other potential applications also address reasonable markets or markets with large growth opportunities, e.g. optical or THz imaging, lasers for scientific, communication and machining purposes or radar applications. These also offer niche markets for early adoption (e.g. ultrafast lasers for fundamental science).

Due to the high electron mobility, graphene can play a role in high frequency electronics. The optoelectronic properties of graphene are very promising for optoelectronic applications (optical switches, modulators; optical detectors), ranging from high speed communication applications to hyperspectral imaging (due to its broad optical absorption). In principle, graphene can be also integrated in Si-photonics and integrated photonics. Additionally, graphene can help to reduce form factors or introduce flexibility. The optical properties render it also interesting as wavelength-independent saturable absorbers for lasers.

Although laboratory demonstrators are promising, wafer scale integration is the bottle neck and commercial manufacturing compatible processes are needed. Besides, the demonstrators have to be tested against state-of-the-art and other emerging technologies in systems to show their actual potential. After that, the reliability has to be addressed, as depending on the application, the needed durability can be between 2 years (consumer) and 20 years (network backbone). It is important to also involve the parts of the value chain that actually implement the graphene materials, e.g. the component manufacturers (e.g. of optical transceivers) or chip producers. Implementing a new technology or material in this industry is an effort of the whole (global) ecosystem.

Currently, the not specified performance in devices and the unclear commercially feasible production method impede the uptake in commercial applications. This is not a fundamental problem, as many questions are still open and under investigation, due to the novelty of the 2D material technology.

Table 48: Assessment of market and technological potential of graphene/2D materials use in telecommunication, optoelectronics & photonics on a scale - -, -, 0, +, ++

Application area	Current technological potential (USP)	Market potential (EU perspective)
Photonic networks	++	++
Wireless communication	+	++
RF transistors	0/+	+
Optical switches and modulators	++	+
Photodetectors/Imaging systems/Spectrometers	++	+
Resonators	+	0/+
Antennas (large area, unobtrusive)	-	0/+
THz/sub-mm wave	+	0
Laser/photonics	+	+

5.4 Computing/Logic, beyond CMOS and spintronics

This area deals with digital/logic electronics applications, i.e. high performance computing, the progress of miniaturization of integrated logic circuits ("more Moore"), in contrast to the "more than Moore" path, where improved functionality is key (covered in the other application areas within the electronics and photonics chapter). This area focuses on the use of graphene/2D materials as active semiconductor material and passive channel in or beyond Si electronics/CMOS.

Logic computing can be subdivided in three major areas: high performance computing, low power computing and memory. Beyond CMOS technologies generally address computing with new architectures or principles of computing.

A special focus is attributed to spintronics, an emerging type of beyond-CMOS computing in which information is carried, stored and processed by spin instead of charge. Graphene has some interesting properties for spintronics, which will be further elaborated in this chapter. Graphene based spintronics promise to address some of the major challenges in spintronics technology and can also enable new applications, e.g. in magnetic sensing and microwave generation in nano oscillators.

Device name	acronym	input(s)	control	int. state	output	material	Class
Si MOSFET high perf.	CMOS HP	V	Vg	Q	V	silicon	
Si MOSFET low voltage	CMOS LV	V	Vg	Q	V	InAs	III-V
van der Waals FET	**vdWFET**	**V**	**Vg**	**Q**	**V**	**MoS2**	**TMDs**
Homojunction III-V TFET	HomJTFET	V	Vg	R	V	InAs	III-V
Heterojunction III-V TFET	HetJFET	V	Vg	R	V	GaSb/InAs	III-V
Graphene nanoribbon TFET	**gnrFTET**	**V**	**Vg**	**R**	**V**	**graphene**	**Graphene**
Interlayer tunneling FET	**ITFET**	**V**	**Vg**	**R**	**V**	**graphene**	**Graphene**
Two D Heterojunction Interlayer TFET	**ThinFET**	**V**	**Vg**	**R**	**V**	**WTe2/SnSe2**	**TMDs**
GaN TFET	GaNFET	V	Vg	R	V	GaN	III-V
Transition Metal Dichalchogenide TFET	**TMDTFET**	**V**	**Vg**	**R**	**V**	**WTe2**	**TMDs**
Graphene pn-junction	**GpnJ**	**V**	**Vg**	**R**	**V**	**graphene**	**Graphene**
Ferroelectric FET	FEFET	V	Vg	P	V	PZT	Ferroelectric
Negative capacitance FET	NCFET	V	Vg	P	V	PZT	Ferroelectric
Piezoelectric FET	PiezoFET	V	V	σ	V	AlN	Piezo
Bilayer pseudospin FET	**BisFET**	**V**	**Vg**	**BC**	**V**	**graphene**	**Graphene**
Excitonic FET	**ExFET**	**V**	**Vg**	**BC**	**V**	**MoS2/MoSe2**	**TMDs**
Metal-insulatior transistor	MITFET	V	Vg	Orb	V	NdNiO3	
SpinFET (Sughara-Tanaka)	SpinFET	V	Vg, Vm	Q,M	V	CoFeB	magnetic
All-spin logic	ASL	M	V	M	M	CoPtCrB	magnetic
Charge-spin logic	CSL	I	V	M	I	CoPtCrB	magnetic
Spin torque domain wall	STT/DW	I	V	M	I	CoFeB	magnetic
Spin majority gate	SMG	M	V	M	M	PMN-PT	magnetic
Spin torque oscillator	STO	I	V	M	I	CoPtCrB	magnetic
Spin wave device	SWD	M	I or V	M	M	PMN-PT	magnetic
Nanomagnetic logic	NML	M	B or V	M	M	PMN-PT	magnetic

Figure 87: List of beyond CMOS devices under consideration. B=magnetic field, Vg=gate voltage, Vm=magnetic switching voltage, BC=Bose condensate. The cell color designates the computational variable (from top to bottom): blue=electronic, orange=ferroelectric, yellow=straintronic, purple=orbitronic, red=spintronic devices. Key materials are listed and 2D-materials-based solutions are bold. [492]

5.4.1 Market perspective: graphene/2D materials in computing/logic, beyond CMOS and spintronics

An overview of the overall semiconductor market is presented in chapter 5.2.1 Market perspective: graphene/2D materials in the semiconductor and electronics industry. The logic and memory markets account for the largest share of sales in the semiconductor industry (~50%, ~$168 billion in 2015), see Figure 74.

In logic, Europe has a strength in special applications, e.g. for automotive and low power, and is strong in material, equipment, chip design (fabless activities) and system integration. 20% of the production of equipment and material is currently done in Europe and there is growth potential. [363] Only a very small share of classical PC and mobile phone processors and high performance processors are currently manufactured in Europe, similar to storage media (RAM).

The spintronics market exists nowadays mostly in memory in the form of magnetic hard drives (read heads) facilitating based on the giant magnetoresistance (GMR) and tunnel magnetoresistance (TMR) effect. There are also GMR sensors for magnetic fields and GMR-based signal isolators/couplers/transceivers. Other applications besides that, e.g. MRAM, magnetic junctions, and spin-based logic are still in a nascent stage, but they offer advantages over the traditional electronics such as low power consumption, economic viability, and compactness, high data transfer speed. The spintronics market, especially MRAM is seen as important with strong growth opportunities reaching potentially $50-70 billion in the future [493]. MRAM are expected to contribute with more than $1billion in 2021 (current sales are ~$50 million to few hundred million, depending on the source). [494, 495]

5.4.1.1 Market Opportunities

5.4.1.1.1 Limitations of Si and More Moore: search for new technologies

For digital CMOS/Von Neumann computing, there is little room for improvement after the next nodes in some 5-10 years. FinFETs will probably take CMOS to the 5nm node. As the classical Moore's Law approaches a phase out due to limitations in CMOS technology scaling, and the demands for new chips is diversifying (more and more chips have tailor made functionalities and there is no "one fits all"-solution), the semiconductor industry will also diversify. This can be already seen in the re-booting of ITRS in terms of diversification. [368]

This trend opens up new opportunities for novel architectures, ways of computing (NP-hard problems, non Von Neumann computing, optimization problems like probabilistic computing, machine learning, cellular neural networks etc.) and new materials that add functionality. Moore's Law in that sense can be newly interpreted as doubling the user value every two years. [496]

There is a clear need to especially find new solutions to overcome Si physical limits, such as the transistor density, performance, but most importantly the energy efficiency. The need for reduced power consumption is evident as more and more devices are mobile and remotely powered. Furthermore, as more and more computer power is installed, the need for lower energy consumptions per bit is rising.

In the latest ITRS/IRDS discussions, TMDs, graphene and graphene nanoribbons have still been in the discussion to deliver some solutions, also in the realm of logic transistors.

Furthermore, there are also limitations in the overall system besides the classical transistor, e.g. interconnects (see 5.2 Electronics: Cross-cutting issues) or added functionalities through materials/components that can be integrated in the standard (CMOS) fabrication processes (FEOL, BEOL) achieving better performance and higher energy efficiency, as well as lower cost (see chapters 5.2 Electronics: Cross-cutting issues for wafer scale integration and 5.3

Telecommunication, optoelectronics & photonics, 5.5 Sensors, 5.6 Flexible and/or printed electronics for the respective topics).

Looking at theoretical benchmarking of beyond CMOS devices (Figure 88), it becomes obvious that spin based devices have benefits in energy efficiency (especially in terms of standby and active power), whereas tunnelling devices (including GNR TFET and graphene pn junctions) have advantages in switching speed (lower delay), where spin-based devices are suffering from the low magnetization speeds. [492]

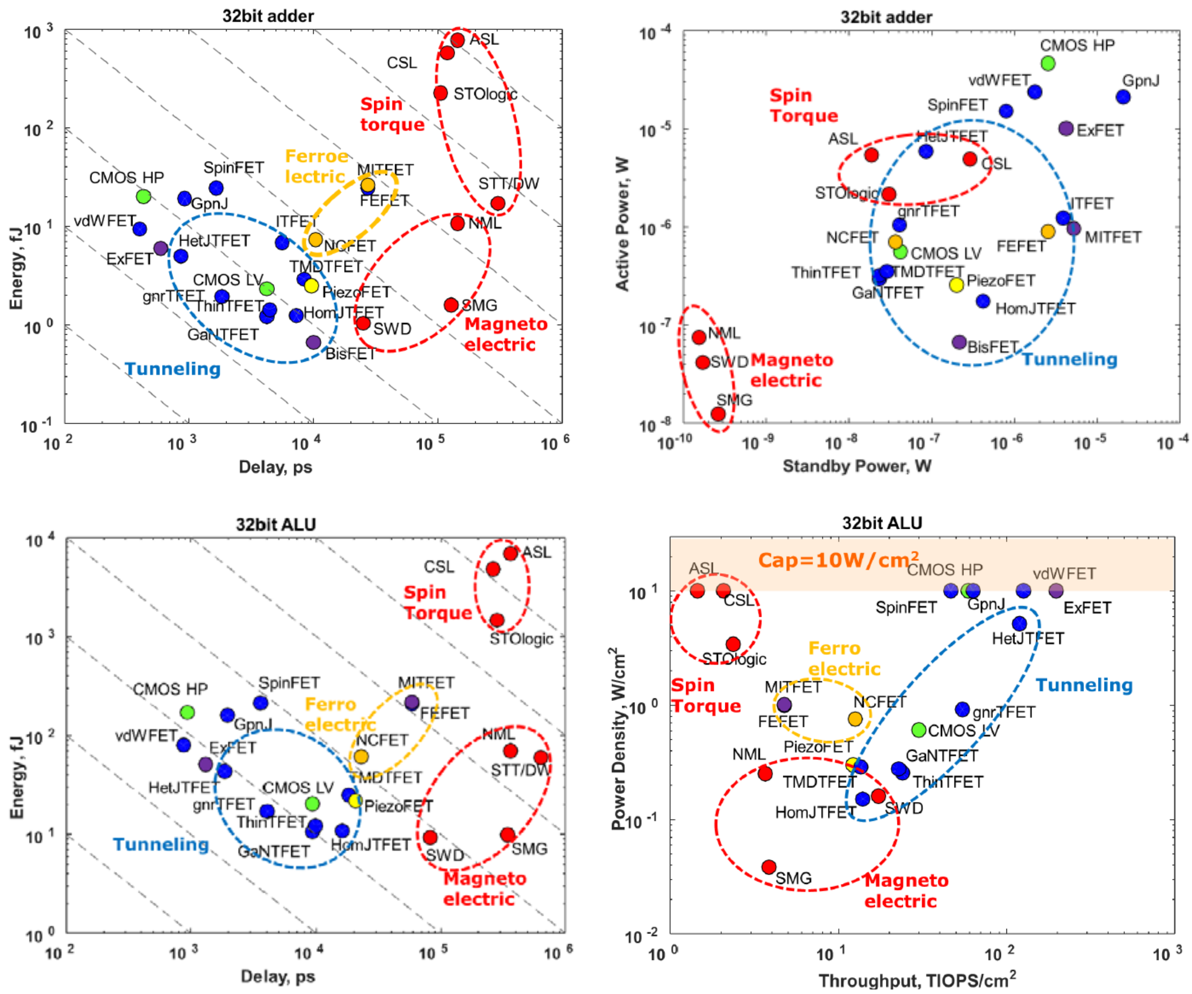


Figure 88: Simulated benchmarking of beyond CMOS devices in a 32 bit adder and ALU. [492]

5.4.1.1.2 Non von Neumann, beyond CMOS

Novel architectures beyond von Neumann are currently investigated for special applications, such as cellular automata, co-located memory-logic (e.g., processor-in-memory, memory-in-logic, computational memory, non-volatile logic), reconfigurable computing, cognitive computing (e.g., neuromorphics, machine learning), statistical and stochastic computing (e.g., statistical inference, approximate computing for pattern recognition), collective-effect computing (e.g., coupled oscillator network), etc. [497]

These new concepts demand new technologies and materials, e.g. for tunnel FETs or spin/magnetic logic or other principles (see Figure 87).

5.4.1.1.3 Thin film low power applications

Within the diversification there are opportunities for transistors which do not perform at highest performance, but consume much less power. This is especially interesting for internet of things, portable and flexible electronics in general and more than Moore applications. For these applications low power consumption is a key demand. They are also employed in displays and other large area applications. For flexible electronics please refer to chapter 5.6 Flexible and/or printed electronics.

5.4.1.1.4 European strength in equipment and materials

Europe plays an important role in material and equipment for cutting edge electronics (20% of the production of equipment and material is currently done in Europe). But besides that, Europe is not strong in cutting edge More Moore technologies, see 5.4.1.3.1.

5.4.1.1.5 Memory: carbon based memory and spintronics in STT-MRAM as potential non-volatile memories with high speed and density

New memory technologies are also investigated by the semiconductor community. Electrically accessible non-volatile memories with high speed and high density are major demands from the industry, as they could initiate a revolution in computer architecture. [498]

MRAMs play an important role in that respect and are heavily researched and already marketed. The disadvantages of classic field switching MRAMs offer an opportunity for spin-torque transfer (STT) MRAMs, which are currently introduced to the market for special applications where high speed and endurance is needed. STT-MRAMS are also seen as the most promising emerging memory device, see Figure 89. STT-MRAMS are spintronics based memories [499], where graphene could play a role in a magnetic tunnel junction (see next subsection).

Ongoing efforts on MRAM involve several non-European companies including Sony, Toshiba, IBM, Samsung, TDK. Everspin recently announced that it is shipping 256Mb spin torque technology (ST-MRAM) chips, now the highest commercial density on the market, aimed at applications requiring persistent memory in storage devices and servers using DDR3 and DDR4 interfaces. The company is expected to deliver further density increases for its MRAM-based storage class memory and plans to sample a 1Gb product based on its proprietary perpendicular magnetic tunnel junction (pMTJ) ST-MRAM by late 2016. [500]

They currently use conventional insulating materials within the tunnel barriers, such as MgO. Unfortunately, further reduction of the cross-sectional area of the junction, as density increases, is expected to lead to prohibitively high junction resistances. The industry already envisions the replacement of the insulating materials, or its complete elimination, using standard giant magnetoresistance structures. The latter, however, leads to a very significant reduction of the magnetoresistance, and therefore a material like graphene can help overcome the future challenges.

STT-MRAM have further issue with cost/bit, as there is currently no strategy how to realize multi-level cell structures or 3D integration. Furthermore, there is limited demonstration of high temperature data storage and retention. [501]

Carbon based memory is investigated for three material systems: nanotubes, graphene and amorphous carbon based resistive memory. Besides resistive memory, many possible mechanisms can be employed for data storage in these material systems (e.g. carbon nanotube based NRAM). [501]

5.4.1.2 Additional market opportunities: spintronics

5.4.1.2.1 Need for new and optimized magnetic tunnel junctions and tunnel barriers for TMR devices

Tunnel barriers are main building blocks of magnetic tunnel junctions (MTJs), which are part of for instance read heads of hard drives, sensors, MRAMs etc. For many of these applications, it is crucial to achieve sufficiently high tunnel magnetoresistance (TMR) signals with optimal junction resistances. This demands for controlling the thickness of metal oxide tunnel barriers with atomic level precession, a challenge for the production of these MTJs. [502] Graphene and other 2D Materials,such as BN and TMDs, can play a role in these MTJs addressing this challenge.

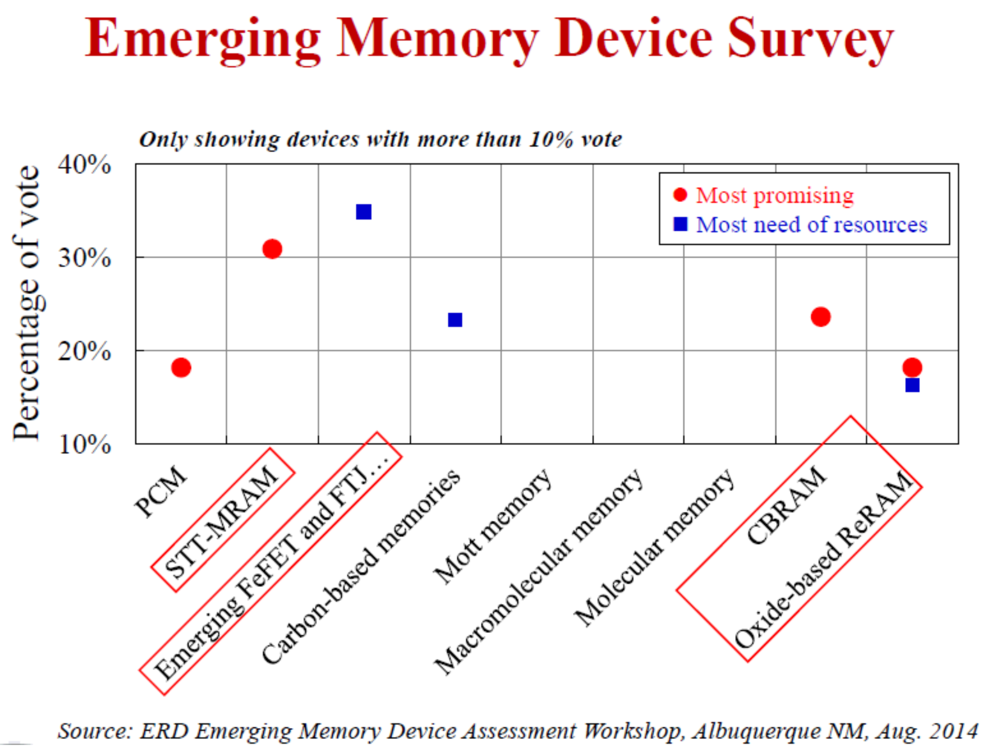


Figure 89: Emerging memory device survey for most promising devices and devices in most need of resources. Graphene can play a role in carbon-based memories, as well as in STT-MRAM and ReRAM. [497]

5.4.1.2.2 Magnetic sensors and nano oscillators as a market opportunity for TMR devices

Graphene-based magnetic tunnel junctions (MTJs), where graphene is used as a tunnel barrier, can be used in magnetic sensors, e.g. in fast and accurate position and motion sensing and automotive sensors, refer to 5.5.1.2 Additional market opportunities: Magnetic sensors. Furthermore, the spin torque nano-oscillators can be used as a source for microwave signals for telecommunication, refer to 5.3.1.5 Additional market opportunities: HF/microwave/THz generation, detection and processing for further opportunities in telecommunication and 5.3.1 Market perspective: graphene/2D materials in telecommunication, optoelectronics & photonics for further market insights.

5.4.1.2.3 Beyond CMOS: All-spin logic devices (ASLD) and spin-based interconnects

All-spin logic devices (ASLD) have attracted increasing interests as one of the promising candidates for post-CMOS technology thanks to their low power consumption, non-volatility and logic-in-memory structure. ALSDs are also amongst the promising candidates to overcome the power dissipation issues, particularly relevant for high density computational circuits and one of the main road block for future downsizing of CMOS technology. ASLD with perpendicular magnetic anisotropy nanomagnets is anticipated to reduce the critical current, while spin transport efficiency can be enhanced by optimizing the device structure, dimension, contact resistance as well as the material parameters. Some benchmarking models [503] of ASLD opens up new prospects for design and implementation of future spintronics applications, which can be based on graphene and 2D materials [504]. Unlike the all-magnetic logic, which require magnetic fields, the ASLD uses spin currents, which may lead to a significant increase in both scalability and versatility.

The expected key feature of the ASLD are its compactness, completeness and simplicity because no CMOS transistor is needed for logic operations and all the logic functions can be constructed with a minimal set of Boolean logic gates [505].

Power dissipation is an additional factor that should be taken into account One of the most critical challenges for ASLD is to find a suited material for the spin-coherent channels. Metals, semiconductors and graphene are the main candidates for fabricating these channels, exhibiting long spin diffusion lengths. The main disadvantage of using semiconductors is the very low efficiency in the spin injection due to the mismatch in the conductivities of a ferromagnetic metal and a semiconductor (so called “conductivity mismatch” problem). Graphene exhibits the longest spin diffusion length reported to date.

5.4.1.3 Market Threats

5.4.1.3.1 Highly competitive and conservative market and major players not in Europe

The logic devices and memory market is a highly competitive market. The major IDM and foundry players are in the USA and East Asia. There is no major cutting edge high performance logic chip producer or memory producer headquartered in Europe at the moment (despite fabless ones). Intel operates a fab in Ireland with 14nm technology and Globalfoundries operates a state-of-the-art fab in Dresden. Therefore, in contrast to more than Moore technology, it is unlikely that an existing European company would integrate high performance logic or memory advancements realised with graphene or 2D materials. In cutting edge semiconductor “more Moore” technologies Europe still plays an important role in the machinery and equipment, as well as material area. Thus, the benefit would be only indirect for the European downstream economy and the equipment and material suppliers could benefit upstream. But the integration for high performance logic itself would probably not be done by a European company. This of course does not exclude the initiation of spin-offs for niche markets or fabs in Europe from international companies that build on the European IP and research infrastructure.

Major logic graphene activities have been at Samsung, IBM (most patents now moved to Globalfroundries) and Sandisk (now Western Digital).

Furthermore, the four major players in the semiconductor industry remain to date very conservative with new materials.

5.4.1.3.2 New types of logic and memory: graphene/2Ds one out of many

It is in principle anticipated that FinFET or Nanowire technology will be capable to go to 5nm with materials already used in fabs (classical semiconductors, e.g. Ge, III-V,…) continuing the von-Neumann architecture. SWCNTs are also still in the race due to better intrinsic properties for digital electronics compared to graphene (e.g. intrinsic bandgap, compatibility with Nanowire FET structures). Recent advances in that area have proven that one major challenges related to use CNTs is controllable, namely the scalable contacting [506]. But other challenges such as the separation of semiconducting and metallic CNTs as well as reliable, non-lithographic ways to place billions of nanotubes exactly where they are needed on a chip remain open. [507]

There is a common perception by many semiconductor producers that the GFET has no chance for broad uses in high performance logic and will not replace the CMOS FET in the conventional charge based transistor. This is further supported by the notion that the majority of high performance chip producers do not touch graphene at the moment beyond research level (only on research level for new device architectures, e.g. spintronics).

Other 2D materials (TMDs) on the other hand have a better perception and are still considered as viable options.

In terms on carbon base memory, CNT is more studied. With Nantero, there is already a US based company commercializing CNT based NRAM.

5.4.1.3.3 Window of opportunity: 5 years from now, the decisions will be made

No matter where graphene or 2D materials will be used in high performance logic and more Moore (beyond CMOS/non van Neumann or further scaling of CMOS), the window of opportunity lies in the next 10-15 years. To be recognized in time, important breakthroughs are needed within the next 5 years, because 5-10 years are needed for scale up and decisions will be made then. If these breakthroughs are not achieved by then, other technologies will be most probable more promising and it might be too late to be still recognized as a valid alternative.

5.4.1.4 Additional market threats: spintronics

5.4.1.4.1 Competing materials, technologies and worldwide competition

Graphene competes in spintronics with established materials like silicon and metals. It has benefits towards these materials (see 5.4.2.2 Additional strengths: spintronics). Current STT-MRAMs work without graphene and 2D materials and it remains to be tested to which extent graphene and 2D materials can add value or enable the technology.

Spintronic based on MRAM technologies is a quite mature branch of ICT, although they so far only address niche markets due to limited storage density and competitiveness with standard volatile RAM technolgy. There is strong effort of implementation/production of non-volatile very large scale integration (VLSI) of spintronics, notably in Japan with a strong academic/industrial bond. Industrial companies such as Toshiba, Samsung, Qualcomm and Intel are involved in spintronics. Hence graphene spintronics co-integration will strongly rely on graphene's ability to be integrated. Integration of graphene has been demonstrated on lab scale in CMOS-technology through existing graphene-interconnects [508].

Furthermore, some applications can also be realized with the more mature GMR effect. And in terms of sensors and microwave sources, it competes with other well established concepts, e.g. hall sensors or GMR sensors for magnetic sensing (see 5.5.1.7 Additional market threats: Magnetic sensors).

It is noted that a coordinated effort is undergoing in Europe, America, whereas Spintronics activities in Japan and Korea are also identified. Further progress will require convincing operational demonstrators and further demonstration of wafer-scale graphene device integration (see 5.2 Electronics: Cross-cutting issues). This issue not only derails spintronics but all electronic and optoelectronic applications, which require fast processing of high-quality graphene over large areas.

5.4.1.4.2 Limitations of ASLDs

ASLD provides the stage for majority logic operations since the output magnet state can be controlled by the sum of the spin-currents from all input magnets. As a trade-off, by increasing the number of input devices in a majority gate, the uncorrelated thermal noise of these devices adds up and impacts the transient magnetization output. This phenomenon sets a practical limit on the number of input devices to a majority gate.

5.4.1.4.3 Connectivity of ASLD to CMOS, design tools and library needed

Whatever the logic macro, at some point one has to interact. outside the chip, between units (where the spin diffusion length is exceeded) or within a System-on-Chip (SoC). Circuits are needed to generate (on/off) currents at the inputs of some logics macros and others, for readout and conversion of the magnetic data in electrical signals (currents, voltages) to drive a copper line or a chip I/O. The magnetoresistance is not infinite and requires a well-designed amplifier, applied currents (drivers) might need regulation, to avoid overdrive of the macro for instance. Up to now, standard CMOS is the best choice for those developments, but CMOS technology has some drawbacks in term of leakage, scalability, power and the use standard interconnects. To maximize the efficiency, it is mandatory to have as few as possible interfaces, meaning that all-graphene ASLD need to perform a "quite complex" calculation (inversion is not good enough for instance). Part of the challenge is therefore to define the minimal subset of functions/macros (or the minimal size, complexity) allowing the description of standards digitals with a minimum number for electrical/magnetic interfaces.

Digital designers use HDL (Hardware Description Language) to describe digital functions and a synthesis tool generates the circuit thanks to a library of CMOS "standard cells" (inverter, nand, nor…). At the macro level (all-graphene ASLD), it is mandatory to define a library of magnetic "standard cells" and find a way to connect the HDL description to the ASLD generation through an update of the synthesis tool. At the chip or system level, one needs to combine the standard CMOS approach (interfaces management…) and the all-graphene ASLD blocks in order to generate an efficient and usable digital product. The generation of complex digital functions using this technology plus the CMOS interaction will require a specific software development in term of design automation going from pure Electronic Design Automation (EDA) to (Spintronic (+Electronic) Design Automation).

5.4.1.4.4 Weak European industrial base and engagement

In Europe, the graphene flagship spintronics WP is exploring how graphene and other 2D materials can be harnessed for spintronics applications in both vertical and lateral geometry and trying to solve several challenges. The C-SPIN consortium in USA is a world-leading center that brings together top researchers from across the nation to develop technologies for spin-based computing and memory systems. Sponsors of the network activities include organizations and companies such as DARPA, GLOBALFOUNDRIES, IBM, Intel Corporation, Micron Technology, Raytheon, Texas Instruments, United Technologies. Specifically, Intel Corporation is exploring the use of graphene and other 2D materials having high spin-orbit coupling for developing spintronics beyond-CMOS technology. There is also a strong commitment in Japan with Tohoku University (own a 300mm line) working on spintronics VLSI and several industrial companies such as Toshiba or Canon-Anelva. Therefore, the international competition is high and especially non-European companies and bigger players address the field and generate IP (see also 5.4.1.3.1 Highly competitive and conservative market and major players not in Europe)

5.4.2 Graphene/2D materials perspective: current strengths, weaknesses and challenges for the use in computing/logic

5.4.2.1 Current strengths for graphene/2D materials use in computing/logic

5.4.2.1.1 Combination of graphene and other 2D materials are still in the race for beyond CMOS

Graphene and other 2D materials are still considered as a valid candidate for beyond CMOS technologies in the ITRS discussions, see Figure 90. TMDs are (theoretically) more promising due to the intrinsic bandgap. Also GNRs are still considered. The role of graphene FETs and graphene as a channel material in standard CMOS is no option anymore (conventional charge based transistors), as CNT and other technologies are more promising and advanced. But GNRs can potentially be uses as nano ribbon in tunnel-FET (conventional charge based). Furthermore, 2D materials can play a role in charge-based as well as non-charge based novel structures, such as the 2D transistors or in spintronic devices (see below). For instance, there is a potential in combining and stacking TMDs to 2D transistors, a novel type of a charge based transistor.

Figure 91 shows a result of an ITRS workshop from August 2014. Here, TFET, nanowire FET and CNT FET were assessed as the most promising devices for beyond CMOS. 2D channel FET was one of the topics assessed to be in most need of resources. This topic addresses 2D materials as germanene, MoS_2, WSe_2 as a 2D channel. Open questions are related to scaling: it is still unclear whether dielectric thickness/gate control or body thickness is more relevant for scaling. In case the dielectric is the issue, it would call for a nanowire or fin structure solution, which is probably not so well suitable for 2D materials. [509]

Overall, the strengths of 2D materials for high performance logic transistors are reduced short channel effects and reasonably good I_{On}/I_{Off} performances. Strengths of low power transistors (tunnel FETs) are the lower power supply (<0.5V) and the good control of the gate over the tunnel barrier combined with a subthreshold swing of $\ll$60mV/dec and large I_{On} currents of >10^3µA/µm. 2D materials provide a fully terminated surface, free of dangling bonds. [510]. Very recently, new experiments clearly demonstrate the potential of MoS_2 for ultimately scaled devices. [384, 385, 511]

Independent of the high performance solutions, 2D materials have also chances in TFT (lower constraints, less scaling) in the medium term, as well as in flexible solutions. [386, 512] For the latter please also refer to chapter 5.6 Flexible and/or printed electronics.

In summary, for high performance logic transistors, 2D materials will most probably only play a role beyond CMOS after the end of the ITRS 2013, as also outlined in the scenario presented in reference [386], see Figure 92.

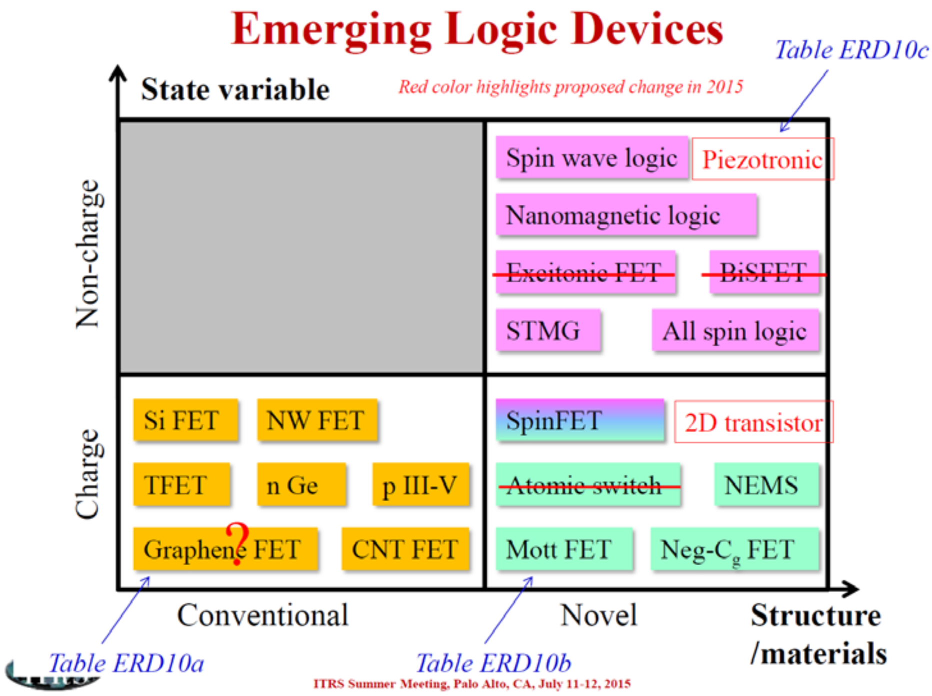


Figure 90: New concepts for beyond CMOS. STMG: Spin Torque majority gate. From [497].

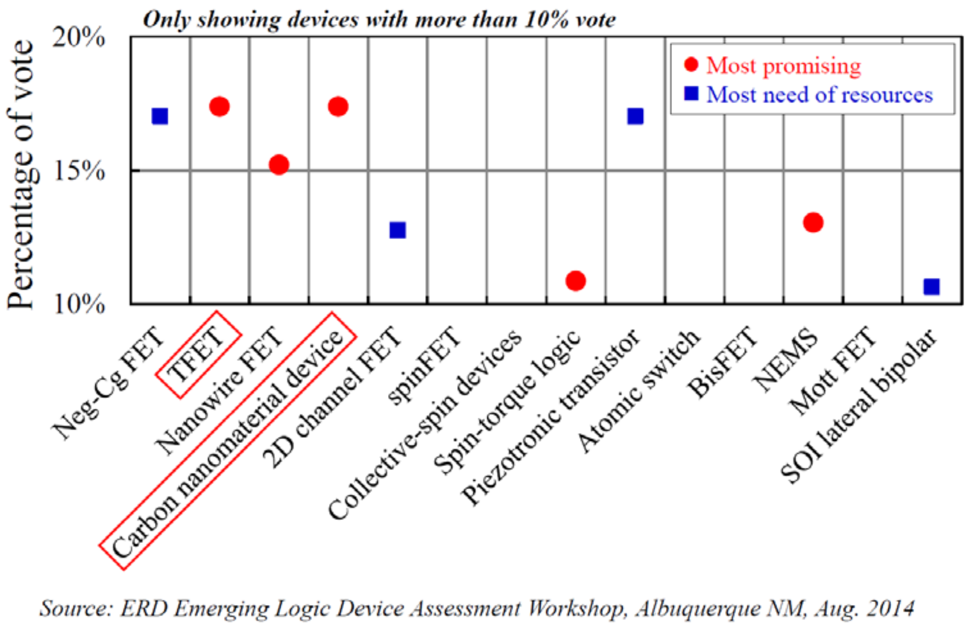


Figure 91: Results of an ITRS ERD Emerging Logic Device Assessment Workshop, Albuquerque NM, Aug. 2014. Carbon nanomaterials device relates to CNT or GNR. Taken from [497]

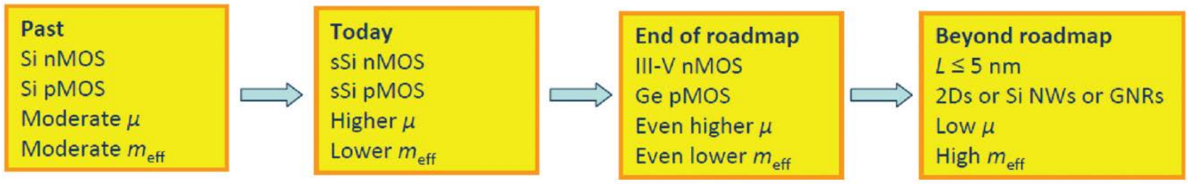


Figure 92: Selection of the channel materials for logic MOSFETs, a scenario from [386]. sSi means strained Si, μ is the carrier mobility, m_{eff} is the carrier effective mass, and 2Ds means semiconducting 2D materials. Roadmap refers to the ITRS 2013 roadmap.

5.4.2.1.2 Promising results for TMDs

Recent experiments show that MoS2 can be use in FinFETs contributing to very short gate lengths. These breakthroughs push TMDs at the forefront of logic developments and scaling for low power, high performance technologies. [384, 385, 511]

5.4.2.1.3 New and unconventional logic as potential application area

In terms of high performance logic, 2D materials are not only a candidate as a gate/FET channel material, but there are also potentials in post-Si spintronics or unconventional switching. Several realisations of beyond CMOS transistor types under consideration are based on graphene or 2D materials, see Figure 87. In case there is a new concept, e.g. a new type of logic or device, which is not realizable with other materials, it might actually create an important uniqueness for 2D materials. However these solutions need to outperform other solutions targeting the same functionality.

It might also become interesting once wafer scale integration becomes economically feasible and competitive, which could be driven by the more than Moore path. As soon as this is possible, the barrier to also look at logic or spintronics applications of graphene and 2D materials becomes lower and an entry scenario could be via cost reduction (e.g. compared to compound semiconductors), for instance when a complex device is made simpler with graphene.

5.4.2.2 Additional strengths: spintronics

5.4.2.2.1 Spin filtering properties

Advantages of graphene/2D materials for magnetic tunnel junctions-based memory and nano-oscillator applications are its spin filtering properties, passivation properties for new process development such as ALD, its relatively low barrier resistance, a low enough density of defects and the capability of sustaining large applied currents.

Graphene (including multilayers and graphite), h-BN and their heterostructures, have a strong potential for vertical geometry spintronic devices and MTJs to increase tunnel spin polarisation. It has been demonstrated that graphene/ferromagnet and graphene/h-BN/ferromagnet interfaces can efficiently filter spin channels. [513] [514, 515]

Other 2D materials beyond graphene are also investigated for magnetic tunnel junctions, especially those that can be directly grown by CVD on ferromagnets. [516] This could improve interfacial spin polarization giving rise to high tunnel magnetoresistance values, similarly to the case or better than epitaxial MgO.

Graphene can also alter the magnetic properties at ferromagnet|graphene interfaces, e.g. by increasing the perpendicular magnetocrystalline anisotropy, an important direction to pursue for the downscaling of spintronic devices to improve energy efficiency [517].

5.4.2.2.2 Long spin diffusion length

Graphene is a promising material candidate for spin communication and transport due to its weak spin-orbit coupling. The measured spin lifetime of graphene at room temperatures is about 10 ns and the spin diffusion lengths is up to 30 µm, the longest of any metal or semiconductors.

The long spin lifetime and high electron velocity make graphene a suitable candidate for future emerging and proposed spintronics transistors (Datta-Das device), magnetologic gates and spin coherent interconnects for ASLD. Furthermore graphene could be used in new spin-based data communication devices (see 5.3.2.1.5 New types of spin-based data communication)

5.4.2.2.3 Direct CMOS compatible growth (without transfer) on Nickel

Vertical 2D MTJ technology requires in-situ growth of ferromagnetic materials and large area CVD graphene/h-BN heterostructures with clean interfaces without air exposure. Within the Graphene Flagship, experimental demonstration of this effect has been obtained using CMOS-compatible processes (<450°C large scale CVD processes developed by Spintronics WP in collaboration with Materials WP) for the direct integration of graphene in devices [518]. For this process, no transfer was needed as the graphene was directly grown on Nickel (which is the ferromagnetic material used). Already these novel electrodes have been proven to be oxidation-resistant and allowed to unlock low-cost processes for the fabrication of Magnetic Tunnel Junctions (MTJ) such as ALD. [519]

5.4.2.2.4 Graphene magnetologic gates and spin-coherent channels/interconnects for ASLD

One possible building block of graphene spin logic is a magnetologic gate (MLG) consisting of a graphene sheet contacted by five ferromagnetic electrodes [520]. By integrating memory and logic within the MLG device, i.e. all-spin logic device, spintronic circuits could produce substantial gains in data-intensive applications by alleviating the von Neumann bottleneck, i.e. the computational overhead involved in transferring data between memory and CPU. A proof of concept has been recently reported by the US consortium C-SPIN [521], see “XOR Operation in Graphene Magnetologic Gates at Room Temperature” [522].

Functionalization of graphene by proximity of materials with large spin orbit interaction or ferromagnetism can enlarge and diversify the opportunities for all-graphene ASLD.

With the features of high electronic mobility, weak spin-orbit and hyperfine interactions and long spin diffusion length, while reducing dynamical crosstalk between wires, RC bottlenecks, and electromigration. graphene has also attracted considerable interest as channel material and spin-based interconnects. Metallic channels (e.g. copper) outperform graphene in terms of energy dissipation but seriously suffer from a low breakdown current limit - the breakdown current density of graphene is at least two orders magnitude larger than that of copper [520].

Spin-based interconnects cannot replace “long” chip interconnects but they can be used as local interconnects within specifics blocks. A trade-off needs to be found between function and speed requirement. The advantages of spin-based interconnects are low power transmission but also the ability to remain within the magnetic domain and at substrate level. The classical approach requires to use an extra metal layer adding cost and resistance. Spin-based local interconnects offer a higher density and potentially lower cost (no extra layers of metal, contact, via on substrate level), low power and more scalable solution (layers spacing, resistance, IR drop).

5.4.2.2.5 Promising advancements for graphene in spintronics

After one decade of intense research efforts to achieve long spin lifetimes in graphene [504, 523], the potential of graphene and two-dimensional (2D) materials for spintronic applications is now attracting the attention of large companies as well as small and medium enterprises, including EU-companies such as NanOsc AB and eVaderis, offering non-volatile solutions for the data-processing, wearable computing and Internet of Things (IoT) markets. Indeed, the first practical applications harnessing the unique properties of graphene, such as nano-oscillators based on spin transfer torque (STT) seem within reach.

Besides, graphene and h-BN materials have proven useful to unlock low-cost processes such as Atomic Layer Deposition (ALD) for the fabrication of spintronic devices and could play a role in novel memory concepts and realizations. Interestingly first proofs of principle of graphene-based spin logics has been reported (XOR logic functions), paving the way towards all spin-based information processing circuits.

5.4.2.3 Current weaknesses and challenges for graphene/2D materials use in computing/logic

5.4.2.3.1 Missing bandgap in graphene

The missing bandgap in graphene calls for additional tuning, making the preparation processes more complex. It is obvious nowadays that the GFET has no chance in logic applications/computing. Figure 75 summarizes values of mobility and bandgap of 2D materials. A major challenge for 2D transistors is thus to maximize the I_{on}/I_{off} ratio, whilst maintaining the speed.

5.4.2.3.2 Low maturity of 2D materials for logic make actual benefit assessment difficult

For conventional logic, other materials than graphene are more promising and needed (e.g. Germanene, TMD such as MoS_2, etc.). The maturity of these 2D materials is still very low, only on fundamental research level. Often concepts are not yet demonstrated, only simulated (especially for TMDs). However, recent results show very promising devices based on TMDs. [384, 385, 511] But there is still a gap in fundamental understanding and feasibility, e.g. in terms of fundamental understanding of 2D materials impact on a device, influence of defect density, grain boundaries, etc. Additionally, complete device architecture needs to be better understood.

For realistic broad "beyond Si" implementation in next 10 years, i.e. when the need will be largest, groundbreaking ideas/lab demos are needed already today and recent developments of MoS2 field effect transistors show promising results. There are rather low expectations on graphene, but after recent development, the opinion of 2D materials increased for logic and memory applications to be ready and competitive in 10 years from now.

5.4.2.3.3 Graphene is out, TMDs are in

Currently, the overall experimentally realized performance of graphene demonstrators fabricated with mass production compatible processes is not good enough to be competitive with other emerging solutions.

Also some new 2D/graphene-based logic devices have certain disadvantages. For instance, the graphene barristor suffers from a lot of parasitic capacitance. The 2D tunnelling FET also has a huge parasitic capacitance as the gate overlaps with source and drain. Such a high parasitic capacitance is a strong disadvantage for a beyond silicon technology. However, hot electron graphene base transistors could also be interesting for logic, as they make use of gapless graphene, although their true potential for the future is still not fully understood. [386] Spintronics can be a similarly interesting field where the bandgap is irrelevant. For most solutions, two-dimensional hBN is needed additionally, which is still at the exfoliation stage.

Another important issue is that there is some scepticism in industry towards comparisons/improvements in scientific publications: the comparisons are often not fair and helpful because they compare to a wrong competitor and not the SOTA ("50x improvement towards best graphene based FET", instead of "towards CMOS Si based FET").

However, the most recent developments with TMDs are very promising and might be a way forward towards further scaling. [384, 385, 511]

For RF, flexible RF an flexibled logic applications, TMDs and graphene are still both valid options and interesting candidates.

5.4.2.3.4 Implementation challenges: contact resistance and integration schemes

A critical issue for 2D materials is the contacting and related contact resistance which additionally limits device performance. This needs to be under control for further exploitation.

Besides that, the major challenge is the integration scheme and how 2D materials can be produced and integrated into electronic systems on large scale with necessary quality and adequate cost (see also 5.2 Electronics: Cross-cutting issues for wafer scale integration assessment and roadmap).

Also for spintronics, integration and CMOS compatible processes are essential.

5.4.2.4 Additional current weaknesses and challenges: spintronics

5.4.2.4.1 Spin relaxation

Spin relaxation is an important issue that needs to be solved for graphene. The origin of the spin relaxation mechanism is complex and and multiple theoretical advances have been accomplished by the EU Flagship consortium in recent years partly solving past controversies and false expectations and related to the variety of device fabrication techniques and lack of fundamentals on spin dynamics in supported graphene samples. [524]

5.4.2.4.2 Non-collinear spintronic phenomena such as spin transfer torque not yet explored

So far the use of graphene in spin transfer torque devices has not been investigated. An important next step is to explore the behaviour of non-collinear spintronic phenomena such as spin transfer torque, important for development of STT-MRAM and spin-torque nano-oscillators (STNO) [525, 526]. Magnetization dynamics properties play a key role for these devices and also need to be explored. Magnetic properties of ferromagnet|graphene and h-BN interfaces such as perpendicular magnetocrystalline anisotropy are also an important direction to pursue for downscaling of spintronic devices. In graphene based magnetic tunnel junctions, the contact resistance can be tailored to desired regimes by introducing heterostructures with h-BN tunnel barriers without compromising spin polarization, which would be useful for high-density MRAM [514]. It is also important to explore STT-related phenomena for lateral and more complex geometries. The use of such 2D materials heterostructures in magnetic tunnel junctions can also provide flexible spintronic devices.

5.4.2.4.3 Energy dissipation and long latency in spin-based interconnects (for ASLD)

Metallic channels (e.g. copper) outperform graphene in terms of energy but suffer from a low breakdown current limit. The energy performance of a graphene channel ASLD is partly restricted by its large contact resistance. Notwithstanding, it is possible to find new tunnel materials with lower contact resistance as well as high spin-injection efficiency.

Another intrinsic issue is to understand, and improve the energy efficiency, i.e. the mechanism of spin transfer torque from the graphene channel to the magnetic layer. A Japanese team has demonstrated the spin torque switching in a lateral spin valve network (similar to the ASLD geometry) via spin currents at room temperature using Cu as channel material [527]. However, this technology is still in its infancy and many issues - such as reliability, cascading and operation speed - have to be carefully addressed.

Another main disadvantage is the latency of a few nanoseconds.

5.4.2.4.4 Challenges and maturity of graphene ASLD

The concept of ASLD shows a potential advantage for future implementation. However, at this stage a number of technological challenges must be overcome before they can be adopted in applications, in particular the graphene-based all-spin logic gate with perpendicular magnetic anisotropy. The input write current must be further reduced to enable multi-gigabit memories, representing one of the most critical issues. Furthermore, increasing magnetoresistance to over 300% is necessary for large memories and fast reading. Other matters that need to be addressed include: new fabrication recipes need to be developed for deposition of magnetic materials; etching methods to give lower spread in resistance from bit to bit have to be improved; the stacking composition of the magnetic tunnel junction (or spin valve) needs to be simplified.

Graphene is an attractive material for non-volatile spin logic applications because of the long spin coherence at room temperature and gate-tunability. However, there are several challenges at this stage: (i) production of large area high quality graphene and h-BN heterostructures (ii) Reproducible fabrication of ferromagnetic tunnel junctions on graphene with reliable spin source-drain performance. (iii) Achieving the high speed switching of ferromagnets in graphene spin valve devices. (iv) Finding low energy schemes based on spin transfer torque for reading and writing. (v) Demonstration of a complete magnetologic gate operation at room temperature.

5.4.3 KPIs for computing/logic, beyond CMOS and spintronics

5.4.3.1 Logic/computing

Table 49: Desirable properties of ideal FET channel materials for logic. Hp: high performance, L: gate length. From [386]

Property	Desireable
Bandgap	≥0.4 eV
Carrier effective mass	For gate length L > 5 nm: light, $m_{eff} < 0.1\ m_e$ For gate length L ≤ 5 nm, heavy $m_{eff} \geq 0.5\ m_e$
Mobility	high, > 500 $cm^2\ V^{-1}\ s^{-1}$
Peak/saturation velocity	high, >10^7 cm s^{-1}
Heat transport	Thermal conductivity: High Thermal boundary resistance: Low
Contact resistance	Low ≤0.08 Ω mm
Scale length, channel thickness	Small

Typical quantities are on/off ratios of 10^4-10^6 for digital electronics and sub-threshold swing of 60mV/dec. The reduction of V_{DD} (<1V) would be favourable to reduce power consumption. For low power devices a subthreshold swing of <60mV/dec is desired.

For high performance transistors the saturation velocity of carriers and effective mass are relevant (for short channels, mobility is irrelevant), as well as the electron distribution and density of energy states [512].

Table 50: High performance and low power FET properties in the ITRS 2013 (PIDS Tables). [399]

High performance logic FET	**2014**	**2016**	**2019**	**2025**	**2028**
Physical Gate Length for HP Logic (nm)	18	15.2	11.6	6.7	5.1
V_{DD} Power supply voltage (V)	0.85	0.81	0.77	0.68	0.64
I_{off} (nA/µm)	100	100	100	100	100
I_{on} MG (multi gate, NMOS drive current, µA/µm)	1680	1660	1600	1100	900
I_{on}/I_{off} (/10^3)	16.8	16.6	16	11	9
Dynamic Power Indicator (fJ/µm)	0.77	0.69	0.58	0.33	0.24
τ (MOSFET Intrinsic Delay, ps)	0.541	0.512	0.474	0.446	0.423

Low power FET	**2014**	**2016**	**2019**	**2025**	**2028**
Physical Gate Length for LP Logic (nm)	21	18	13.3	7.7	5.9
V_{DD} Power supply voltage (V)	0.85	0.81	0.77	0.68	0.64
I_{off} (pA/µm)	10	10	10	30	50
I_{on} (multi gate, NMOS drive current, µA/µm)	610	589	550	396	295
I_{on}/I_{off} (/10^5)	610	589	550	132	59
Dynamic Power Indicator (fJ/µm)	0.86	0.78	0.65	0.38	0.28
τ (MOSFET Intrinsic Delay, ps)	1.661	1.64	1.525	1.422	1.492

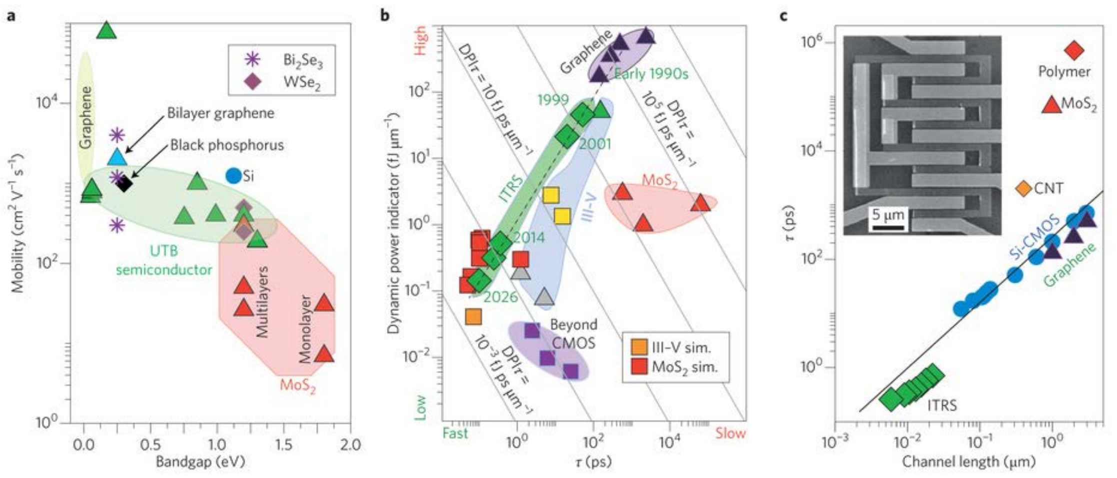


Figure 93: Comparison of 2D materials and bulk semiconductors figures of merit for high performance transistors. [510]

For TFTs, a digital transistor switch is needed without the extreme performance requirements of computational devices. The mobility of μ> 100 cm^2 V^{-1} s^{-1} is sufficient for the longer channels. [512] Typicaly materials in used today are InGaZnO (IGZO), which replaced amorphous silicon due to the higher electron mobility.

5.4.3.2 Memory

Table 51: KPIs for STT MRAM from ITRS 2013, Table PIDS 7b. [399]

Year of Production	2016	2019	2025	2028
MRAM technology node F(nm)	65	45	22	16
MRAM cell size area factor a in multiples of F^2	20	14	8	8
MRAN typical cell size (μm^2)	0.08	0.028	0.004	0.002
MRAM materials technology: In-plane (IMA) or Perpendicular Magnetic Anisotropy (PMA)	IMA	PMA	PMA	PMA
MRAM switching current (μA)	175	100	35	25
MRAM write energy (pJ/bit)	2.5	1	0.18	0.15
MRAM active area per cell (μm^2)	0.008	0.005	0.0011	0.0006
MRAM resistance-area product (Ohm-μm^2)	11	10	9	6
MRAM magnetoresistance ratio (%)	120	150	180	200
MRAM nonvolatile data retention (years)	>10	>10	>10	>10
MRAM write endurance (read/write cycles)	>1E12	>1E12	>1E15	>1E15

MRAM endurance-tunnel junction reliability (years at bias)	>10	>10	>10	>10

Table 52: Field switching MTJ MRAM KPIs from ITRS 2013, Table PIDS 7b. [399]

Year of Production	**2014**	**2015-2017**
MRAM technology node F (nm)	90	65
MRAM cell size area factor a in multiples of F2	51	52
MRAM typical cell size (µm2)	0.41	0.22
MRAM switching field (Oe) [12]	67	82
MRAM write energy (pJ/bit) [13]	120	110
MRAM active area per cell (µm2) [14]	0.124	0.066
MRAM resistance-area product (Kohm-µm2) [15]	1.2	0.6
MRAM magnetoresistance ratio (%) [16]	65	90
MRAM nonvolatile data retention (years)	>10	>10
MRAM write endurance (read/write cycles)	>3E16	>3E16
MRAM endurance-tunnel junction reliability (years at bias) [17]	>10	>10

For STT-MRAM, the R&D focus has shifted from in-plane to perpendicular magnetization.

The following characteristics were demonstrated for perpendicular MTJ STT MRAMs [501]:

- Potentially near "infinite" endurance for switching voltage below 650mV
- Sub-5ns read and write operation in a 8Mb test chip between -25°C and 125°C
- Thermal stability after 400°C 90min annealing, ready for BEOL CMOS process
- Switching V/I reduced to <450mV/60µA at error rate below 10^{-7} for 37nm MTJs
- Scalability down to 15nm demonstrated

Carbon-based memories are more mature based on CNT (e.g. Nantero).

5.4.3.3 Spintronics

Spintronics has to compete with the KPIs of the addressed application, i.e. the KPIs for memory, logic, sensing or sources. Besides these KPIs, typical performance indicators for spintronics are:

- Spin diffusion length at RT (as long as possible)
- Spin relaxation time (as long as possible)
- Spin injection and spin polarisation
- Tunnel magnetoresistance (high difference between polarisations, low resistance in “on” state)

5.4.4 Roadmap for computing/logic, beyond CMOS and spintronics

5.4.4.1 Current maturity: ‘Too early to assess actual potential’

In summary, for logic and beyond CMOS transistors, graphene has some benefits but many open questions and challenges. Therefore it is essentially out of the race for logic applications, besides spintronics. On the other hand, MoS_2 and TMDs have recently shown very promising results opening up great opportunities. It remains to be seen to which extent the processes can be implemented economically feasible, but the lab results are very promising. Still, the race is open and nothing is decided yet.

Spintronics is mostly in the proof of principle stage. Interesting theoretically described behaviours and benefits have to a certain extent been verified experimentally, but the readiness at the moment is still on a fundamental research stage.

5.4.4.2 Barriers/challenges (summarized)

Essentially, the same challenges apply as for wafer scale integration and other cross-cutting electronics issues (see chapter 5.2.4.2). Additionally, the following challenges are specifically relevant:

General

- Manufacturing and integration schemes of higher quality graphene, TMDs and other 2Ds, graphene nanoribbons and bilayer graphene
- Material quality
- Demonstration of theoretical predictions and benchmarking with competing technologies to allow a better and realistic assessment of the actual potential
- Current realized results are not promising enough for industry to justify investment to solve manufacturing
- Exploration of new device architectures
- Timing: for beyond CMOS, focusing will happen soon and in probably 5 years the decision will be made, so that demonstrators with strong advantages are needed very soon. The new developments for TMDs are suggesting that they will be in the race.
- Bandgap vs. mobility

- From European perspective: How shall the European economy benefit from advancements in logic transistors though 2D materials? Will the technology be implemented in Europe and how can it lead to a competitive advantage? How can equipment and material supplier benefit (who are already strong)?

High performance [510]

- Fabrication of ultrashort channel devices (channel length smaller than 10 nm), and large amounts of transistors per area
- Fabrication of devices based on new principles to reduce V_{DD} and subthreshold swing
- Good ohmic contacts with low source–drain parasitic resistance

Low power [510]

- Fabrication of doped tunnel junctions
- Low interface states to reduce subthreshold swing
- Design of new device architectures

Spintronics

- Wafer scale integration (especially with hBN and other heterostructures, also with magnetic materials
- Reproducible fabrication of ferromagnetic tunnel junctions on graphene with reliable spin source-drain performance
- Achieving the high speed switching of ferromagnets in graphene spin valve devices
- Missing fundamental understanding of spin relaxation and how to improve it
- Spin-transfer torque not yet investigated
- Finding low energy schemes based on spin transfer torque for reading and writing
- Missing investigation on magnetization dynamics
- Perpendicular magnetization unclear
- Need for new tunnel materials with lower contact resistance as well as high spin-injection efficiency to overcome energy problem
- understand, and improve the energy efficiency (mechanism of spin transfer torque from the graphene channel to the magnetic layer)
- Missing knowledge on reliability, cascading and operation speed
- graphene-based all-spin logic gate with perpendicular magnetic anisotropy not yet good enough (reduce write current, increase magnetoresistance, simplified stacking structure, lower spread resistance)
- No demonstration of a complete magnetologic gate operation at room temperature available
- Interface to CMOS logic not available
- Complex calculation schemes and minimal subset of functions needed to describe standard digital functions with a minimum number of electrical/magnetic interfaces
- Library of magnetic “standard cells” to be used in a spintronics+electronic design automation tool

5.4.4.3 Potential actions

If the area of graphene/2D in logic or spintronics is seen as promising for Europe and the topic is further pushed, the following potential actions, derived from the challenges, are suggested:

Also here, the major potential actions for wafer scale integration and cross-cutting issues apply (see chapter 5.2.4.3).

These additional conclusions are derived from the assessment:

Ecosystem

- Elaborate the cross-fertilisation with the other electronics areas
- Elaborate how the European economy can benefit from 2D material developments in logic (developed in Europe)

Materials and devices

- Investigate preparation methods to get rid of the material quality issues that currently dominate the device performance
- Focus on new device architectures that are capable of outperforming competing technologies
- Show actual potential with demonstrators that can be compared to existing devices in terms of functionality
- Compare results with competing technologies (e.g. III-V, Si CMOS) and not with the best “2D material based device” to allow serious potential assessment
- Further investigate integration schemes and processes to increase the maturity and reduce the manufacturing risk for companies (but at some point companies need to take over, which will only happen if demonstrators are promising enough)

Spintronics:

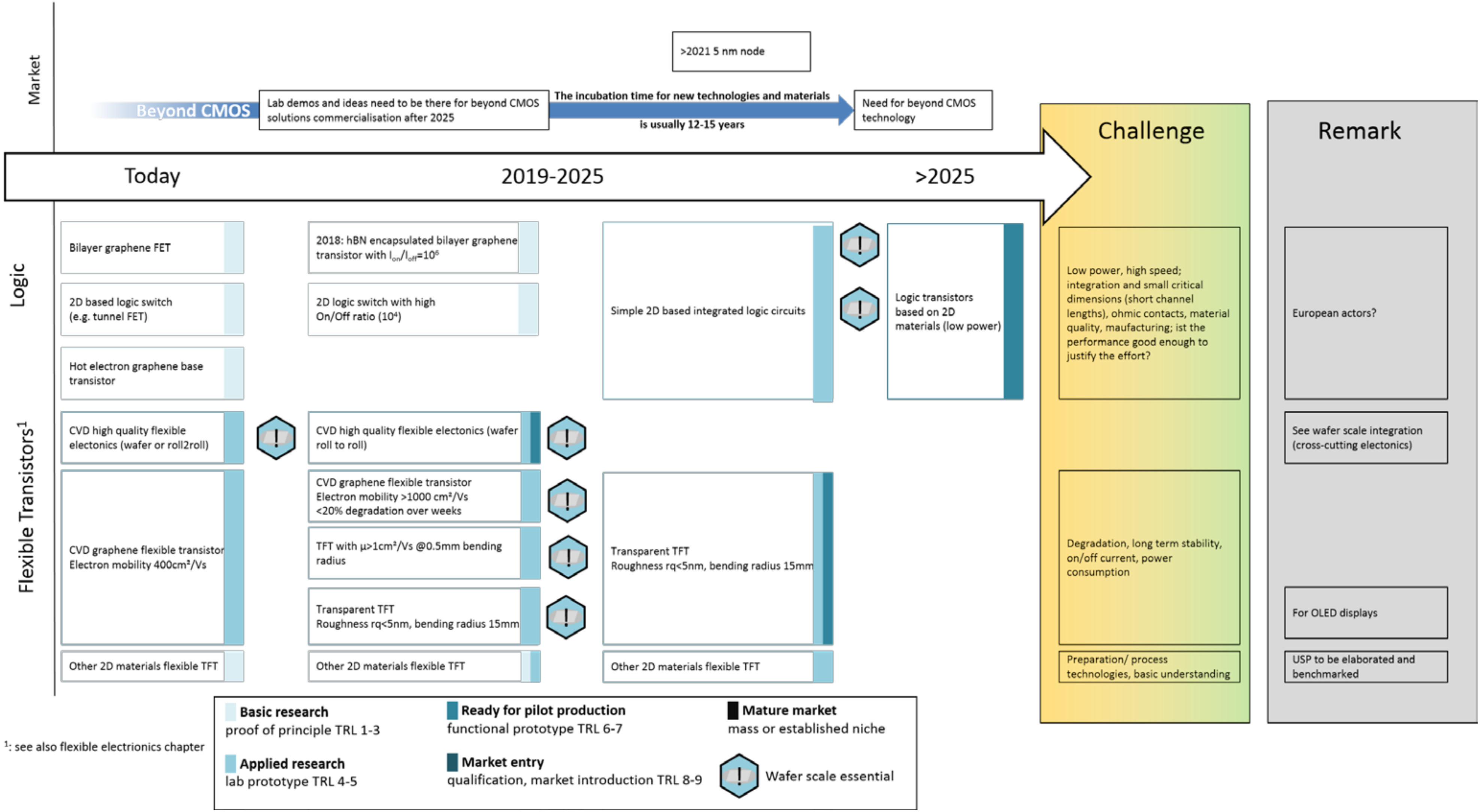
- Due to the low maturity of spintronics, more fundamental research would be needed to elaborate foundational building blocks and first competitive realizations of spin devices and architectures, either for new memory technologies or non-charge based information processing protocols
- An important next step would be to explore the behaviour of non-collinear spintronic phenomena such as spin transfer torque, important for development of spin transfer torque magnetic random access memories (STT-MRAM) and spin torque nano-oscillators (STNO), potentially interesting for for next generation high speed communications. Both are currently intensely explored within research labs, but are still waiting to be introduced to the market.
- Vertical 2D MTJ technology requires in-situ growth of ferromagnetic materials and large area CVD graphene/h-BN heterostructures with clean interfaces without air exposure.
- Explore graphene/2D heterojunctions for all-2D ASLD.
- Demonstrate the theoretical ideas in lab demonstrators that resemble the realistic device as much as possible and benchmark it to competing technologies/devices addressing the same function (no comparison with other graphene-based devices)
- Address challenges as described in the section above

In general, each new technologies in terms of devices or architectures should address the following questions: adapted from [528]

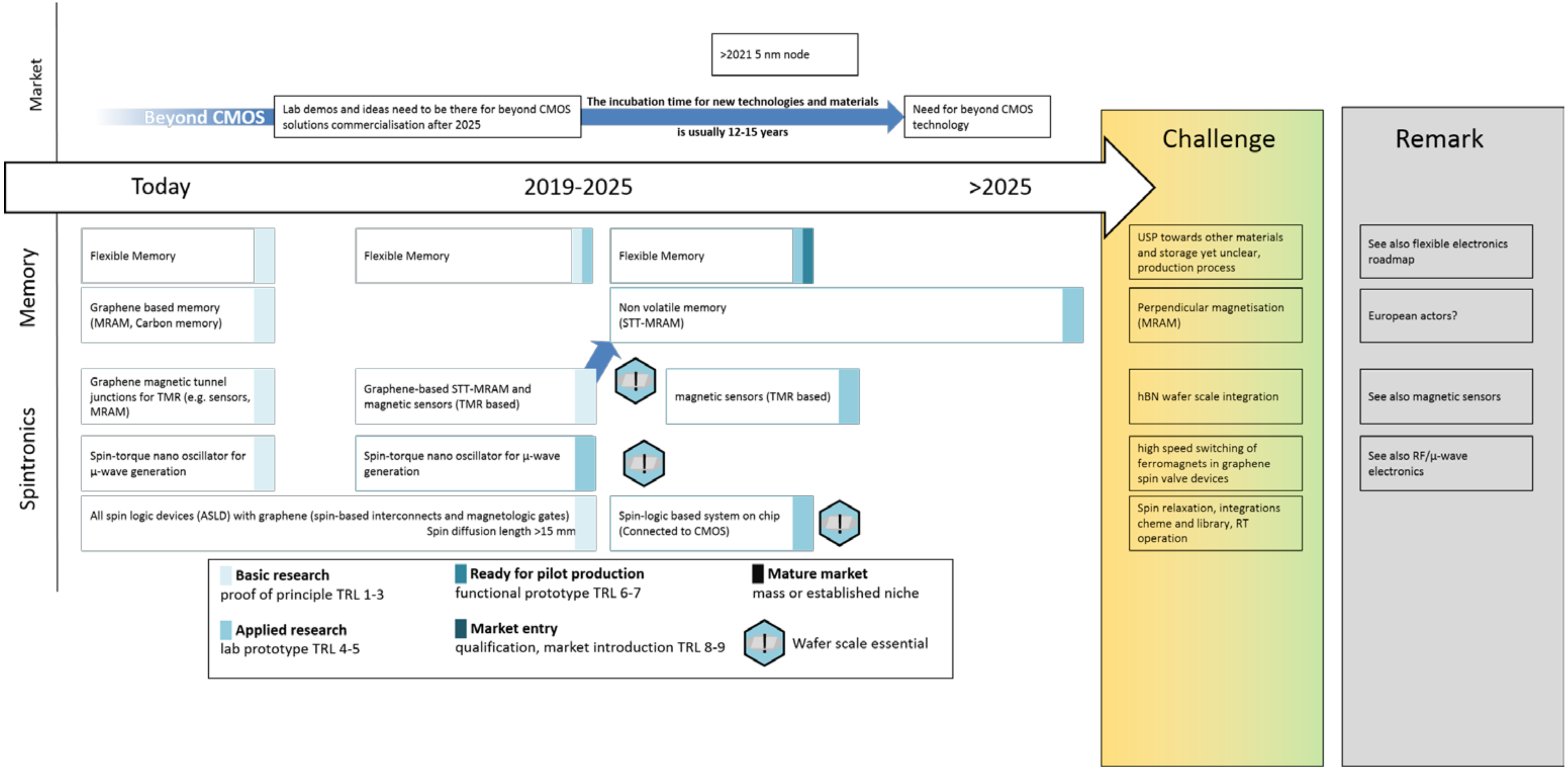
1. What are the key advantages of the device or architecture?
2. What are the main challenges of the device or architecture?
3. What are the most suitable applications for the device or architecture?
4. What are the figures of merit for assessment?
5. How does the architecture fit into the overall scheme of computing?
6. What range of problems can the architecture solve? (von Neumann? Learning?)

7. Do you have a programming model – or another way of controlling the system?
8. How does the architecture tie to SWAP, runtime, etc. in an implemented system?
9. Can this tie be quantified? (vs. CMOS? Is improvement path exponential?)
10. For a stored program model approach, please present a programming model.
11. Will you be better than the end of the roadmap CMOS?
12. Is exemplary application representative of a general class of applications?
13. What device characteristics are desired to implement the proposed architecture?
14. What are current device choices and future options?
15. How essential are emerging devices for your architecture?
16. How might emerging devices improve your overall system?

5.4.4.4 Roadmap



[1]: see also flexible electrionics chapter


Market
Beyond CMOS
Lab demos and ideas need to be there for beyond CMOS solutions commercialisation after 2025
The incubation time for new technologies and materials is usually 12-15 years
>2021 5 nm node
Need for beyond CMOS technology
Today
2019-2025
>2025
Challenge
Remark
Memory
Flexible Memory
Graphene based memory (MRAM, Carbon memory)
Flexible Memory
Flexible Memory
Non volatile memory (STT-MRAM)
Spintronics
Graphene magnetic tunnel junctions for TMR (e.g. sensors, MRAM)
Graphene-based STT-MRAM and magnetic sensors (TMR based)
magnetic sensors (TMR based)
Spin-torque nano oscillator for µ-wave generation
Spin-torque nano oscillator for µ-wave generation
All spin logic devices (ASLD) with graphene (spin-based interconnects and magnetologic gates)
Spin diffusion length >15 mm
Spin-logic based system on chip (Connected to CMOS)
USP towards other materials and storage yet unclear, production process
Perpendicular magnetisation (MRAM)
hBN wafer scale integration
high speed switching of ferromagnets in graphene spin valve devices
Spin relaxation, integrations cheme and library, RT operation
See also flexible electronics roadmap
European actors?
See also magnetic sensors
See also RF/µ-wave electronics
Basic research
proof of principle TRL 1-3
Applied research
lab prototype TRL 4-5
Ready for pilot production
functional prototype TRL 6-7
Market entry
qualification, market introduction TRL 8-9
Mature market
mass or established niche
Wafer scale essential

5.4.5 Conclusion computing/logic, beyond CMOS and spintronics

In computing/logic, the further miniaturization and performance improvement of computer chips is addressed ("more Moore"). Europe has a particular strength in the material and equipment industry for that purpose, whereas the later parts of the value chain are mostly focusing on the more than Moore path.

There is indeed a need for novel approaches, as the Silicon era reaches miniaturization levels where the physical limits are reached in the next 10-15 years. This in turn means that the window of opportunity is on that time scale and for a large scale introduction important breakthroughs have to be reached in the next 5 years.

In search for new materials and concepts, graphene and 2D materials are also investigated. Graphene has a high electron mobility, but the intrinsic problem of a missing band gap. Graphene is essentially out of the race for FETs. Other 2D materials have a bandgap, but so far the mobilities were too low. Recent developments suggest that MoS2 is a hot candidate for further scaling of FETs. For completely new concepts, such as spintronics, graphene or 2D materials might have an opportunity.

The question remains, however, which European industrial basis integrates this technology in a fab for high performance logic (or whether this can be licensed or facilitated by new companies). An opportunity is rather seen for low power computing and "more than Moore" spintronics. USA and Asia are much stronger in the field of logic and memory.

Table 53: Assessment of market and technological potential of graphene/2D materials use in computing/logic on a scale - -, -, 0, +, ++

Computing/logic	Current technological potential (USP)	Market potential (EU perspective)
Equipment (wafer scale)	0	+
GFET	-	-
2D channel FET (MoS2)	+	-
New transistors (novel charge-based transistors, TFET, GBT)	0	0/+(low power)
Spintronics	+	-/0

5.5 Sensors

Sensors are transducer devices which detect events or changes in their environment and convert them into interpretable signals, their output often being electrical or optical signals.

This chapter covers all applications of integrated sensing, except photodetection, i.e. pure light sensing, which is covered under 0

Telecommunication, optoelectronics & photonics. Note that some of the integrated sensors can be based on optical principles, but with a focus on e.g. sensing of gases or other stimuli. Furthermore, the field of nanogenerators/micro-energy harvesters is also covered, where external energy sources are turned into electrical energy. The addressed areas are (see also Table 54):

- pressure sensors/microphones/NEMS, where graphene/2D materials are used as membrane to sense pressure changes, also possibly as mass sensor
- magnetic sensors, such as hall sensors
- mechanical force/stress/strain sensors
- nanogenerators/micro-energy harvesters to harvest mechanical/vibrational/thermal waste energy as micro-power supply
- gas/chemical sensors, e.g. for inline sensing, air pollution sensing.
- biosensors (according to UPAC 1996 a self-contained integrated device that is capable of providing specific quantitative or semi-quantitative analytical information using a biological recognition element that is in direct spatial contact with a transduction element)

Biosensors are a special case where graphene/2D materials can be used as transducer and biomaterials as biological recognition element. Biologically important biospecies such as enzymes, proteins, nucleic acids and derivatives and antibodies can be used as biological elements of recognition (bioelements) for biosensors. Due to the substrate specificity of the bioelement, biosensors are especially suited for the analysis of biomolecules and/or in complex mixtures (e.g. body fluids). Detection of the binding event between analyte and bioelement can be done e.g. electrochemically, piezoelectrically, optically.

Sensors cover broad markets from highly specialized applications to broad mass markets. Some of the markets will be highlighted in the following section.

Table 54: Sensor applications of graphene/2D materials

Sensor	Graphene/2D use	Recent review
Magnetic	In hall sensors, magnetic tunnel junctions	[529–531]
Pressure/Microphone	as (piezoresistive) membrane in NEMS pressure sensors and microphones, also as nano-resonator for mass sensing	[532–534]
Mechanical force/stress/strain sensors	As flexible strain gauges in wearables, electronic skin, strain sensor in composites, included functionality in composites (technology covered in 5.6 Flexible and/or printed electronics)	[535–537]
Nanogenerator	As micro-energy harvester	[538]
Gas/chemical	As electrochemical, optical or GFET sensor for health monitoring, domestic and building applications (“domotics”), automotive, consumer, food packaging (e.g. ethylene); also possible as electrochemical biosensor if recognition element is a bio-molecule	[199, 410, 539–543]
Biosensor	As transducer for lab on chip applications, point of care diagnostics, label free analysis, e.g. blood analysis, sweat analysis; electrochemical gas and chemical sensing (with bio recognition element)	[199, 544–547]

5.5.1 Market perspective: graphene/2D in sensors

Sensors are becoming more and more important as the interface between the virtual and real world. Smart phones have witnessed a strong increase of sensors installed per phone. The same is true for automotive, where more and more sensors are integrated towards the autonomous car. This led to an unforeseen CAGR growth of sensor devices of over 200% between 2007 and 2012. [548]

In 2015, the global sensors market revenue was above $106 billion and is projected to grow at a CAGR of 11.6% to more than $162 billion in 2019. The market for pressure, temperature, flow and level sensors is expected to grow at a CAGR of 6.6% from $23.3 billion. The market for viscosity, tilt, vibration, torque, strain gauge, knock, speed, motion, acceleration, image, gas, humidity, dew-point, rain, moisture, LiDAR, and other application based sensors is expected to grow at a CAGR of 11.1% from $73.7 billion. Newly emerging sensors are expected to grow at a CAGR of 19.0% until 2019 from $9.9 billion in 2015. The market share of different sensor types relevant for graphene/2D materials is summarized in Table 55. Almost all end-user markets employ sensors, see Table 56. The increasing use of (combined) sensors in various applications along with the digitalisation, replacement and upgrading of mechanical technologies drives the sensor market growth. New sensor technologies are heavily researched to improve sensor products, sensing precision, energy consumption and communication protocols. Key trends are towards non-contact technologies, remote connectivity for IoT solutions and 3D vision sensing. Sensors are key enablers for IoT and increasing automation of industrial production processes (e.g. "Industry4.0"), autonomous driving robotics, etc. Further drivers and trends comprise sensor applications for the optimization of resource and energy consumption, smarter sensing systems and mobile/wearable applications, e.g. in consumer electronics. [425] Semiconductor based sensors accounted for global sales of $9 billion in 2015 (+3.7%). Sensors and MEMS are among the fastest growing semiconductor technologies. [361] The (MEMS) microphones market is expected to grow at a CAGR of 11% (2015-2019). The market is projected to reach with $1.3 billion revenue generated by 5.8 billion units. [549]

Table 55: Global market size by sensor type for relevant sensors. High growth markets are highlighted in the right column (CAGR 2015-2019) with a growth trend: ↑ = increasing growth; ↔ = stagnating growth; ↓ = low growth. *: see also 0

Telecommunication, optoelectronics & photonics. Source: [425]

Sensor Type	Market share 2015	Market size (billion US$)	High/low growth markets and trend
Biosensors	11.91%	12.7	CAGR 13.5% ↑
Image Sensors*	9.91%	10.6	
Emerging Sensors[21]	8.61%	9.20	CAGR 19.0% ↑
Pressure Sensors	6.81%	7.28	
Optical Sensors*	4.91%	5.25	
Temperature Sensors	4.53%	4.84	
Gas Sensors/ Detectors/ Analyzers	2.89%	3.09	
Touch/Haptic/Tactile Sensors	2.36%	2.52	CAGR 15.3% ↔

21 According to the source, emerging sensors include a large number of new and different sensors for diverse applications addressing a large number of vertical markets, among others tide gauge sensors, pyranometer, nitrogen oxide sensors, tilt sensors, contact image sensors, free fall sensors, boost gauge, zinc oxide nanorod sensors, leaf sensors, contact image sensors, colorimeter, flame detector, photodetector, photodiode, photoelectric sensors, photoionization detector, photoresistor, hydrometer, viscometer, bolometer, microbolometer, heat flux sensor, water sensors (water in fuel sensors) etc.

Sensor Type	Market share 2015	Market size (billion US$)	High/low growth markets and trend
Load Cells	1.94%	2.07	
Hall Effect Sensors (Magnetic Field)	1.69%	1.81	
Strain Gauge Sensors	1.53%	1.63	
LiDAR sensors*	0.84%	0.898	CAGR 15.2% ↑
Humidity Sensors	0.75%	0.801	
Moisture	0.42%	0.449	
Optoelectronic Color Sensors*	0.39%	0.417	CAGR 15.9% ↑
AMR Sensors (Magnetic Field)	0.32%	0.342	
Combined Sensors	0.26%	0.278	CAGR 15.3% ↑
Energy scavenging sensors	0.26%	0.278	CAGR 15.2% ↑
Distance Sensors	0.24%	0.256	CAGR 22.8% ↔
pH Sensors	0.22%	0.235	CAGR 12.8% ↑
(Micro-) Energy Harvesters	0.07%	0.0748	
GMR Sensors (Magnetic Field)	0.06%	0.0641	

Table 56: End-user markets for sensors 2015. Data taken from [425]

Application	Share of sensor market 2015	Market Size in billion US$
Automotive	11.52%	12.3
Chemicals & Petrochemicals	11.47%	12.3
Life Sciences	10.61%	11.3
Process Control	7.95%	8.50
Oil & Gas	6.13%	6.55
Aerospace & Defense	5.46%	5.83
Water & Wastewater	4.35%	4.65
Food & Beverages	4.30%	4.59

Application	Share of sensor market 2015	Market Size in billion US$
Military	3.75%	4.01
Power Generation	2.95%	3.15
Security	2.85%	3.05
Infrastructure	2.78%	2.97
Plastic Injection Molding	2.70%	2.89
Building Automation	2.30%	2.46
Agriculture	1.98%	2.12
Semiconductors	1.96%	2.09
Environment	1.90%	2.03
Test & Measurement	1.80%	1.92
Others	1.75%	1.87
Mining & Metals	1.45%	1.55
Paper & Pulp	1.45%	1.55
Research & Development	1.45%	1.55
Avionics	1.44%	1.54
Pharma	1.42%	1.52
Oceanography & Marine	1.20%	1.28
Consumer Electronics	1.17%	1.25
Metrology & Meteorology	0.99%	1.06
Shipping	0.47%	0.502
Smart Grid	0.45%	0.481

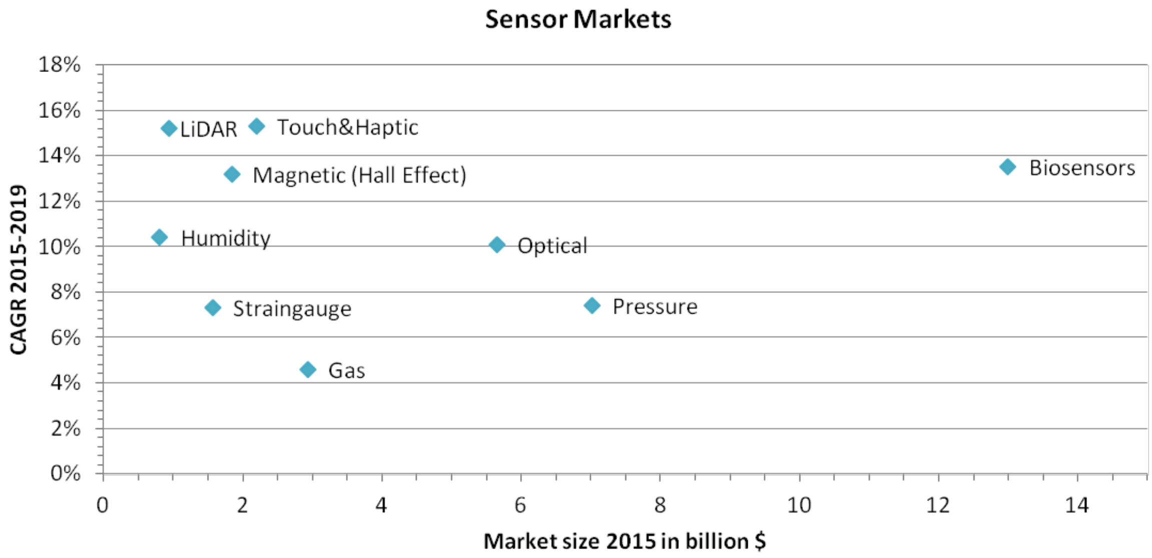


Figure 94: Different expectations of sensor markets in terms of market size 2015 and CAGR between 2015 and 2019. Data taken from [425]. Values also agree with other sources ~±10% deviation.

Actor landscape and patent activity

With respect to companies, the global sensor market is to a great extent highly fragmented: the top 10 key sensor companies have market shares of 20%, and there are numerable SMEs which develop and produce special sensors (about 385 companies worldwide and growing). More than 50% of sensor sales are done by distributors, followed by direct sales (30%) and sales by system integrators (10%). There is an increasing trend away from distributors to direct sales. [425]

The European semiconductor industry has a strong position worldwide and with Bosch Sensortec and STMicroelectronics, the two largest MEMS manufacturers are headquartered in the EU, see Figure 95. 4 Europe-based companies are within the top 30, generating revenues with MEMS of $2.5 billion in 2015 (28% of all top 30). Most revenues are generated by US-based companies (45%).

Looking at transnational patents on sensors in general (Figure 96), it becomes obvious that Europe has the strongest position in transnational patent activity pointing towards a strong and innovative industry. Also with respect to graphene related sensor patenting activities, Europe is strong and the efforts increased heavily in the last 4 years. Still, the USA is leading in terms of patent count. In terms of relative graphene/2D activity with respect to all sensor patents, South Korea is leading, showing that they specialise in graphene technologies.

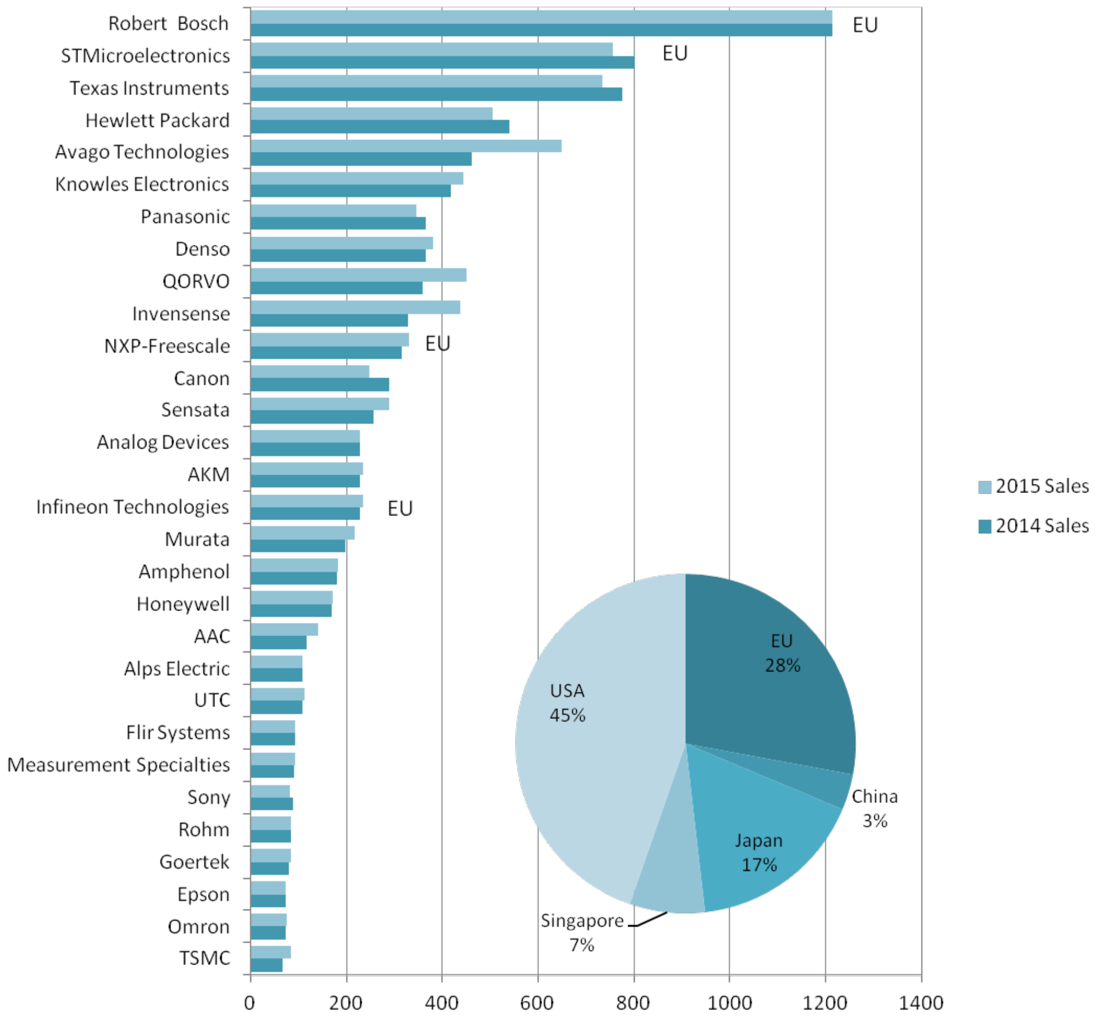


Figure 95: Major MEMS manufacturers (top 30) in 2015. The inset shows the regional distribution of revenue by headquarters. MEMS are mostly employed for sensor applications. [550]

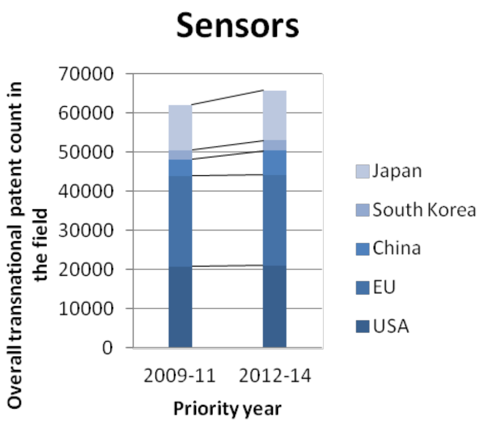
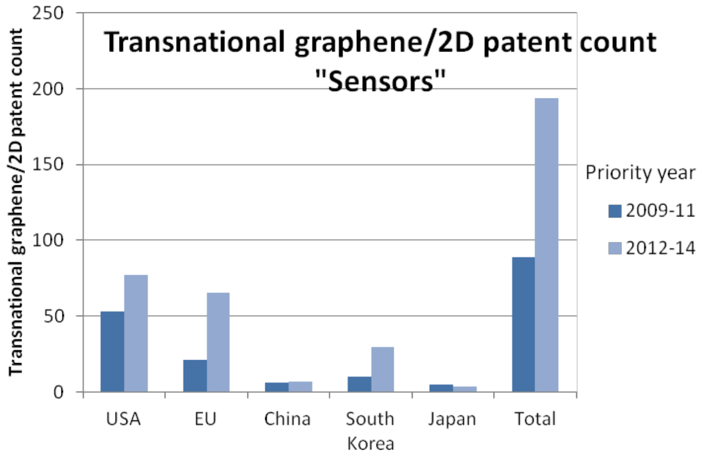


Figure 96: Overall transnational patent count in sensors. 2012-2014 values are projected. [137]



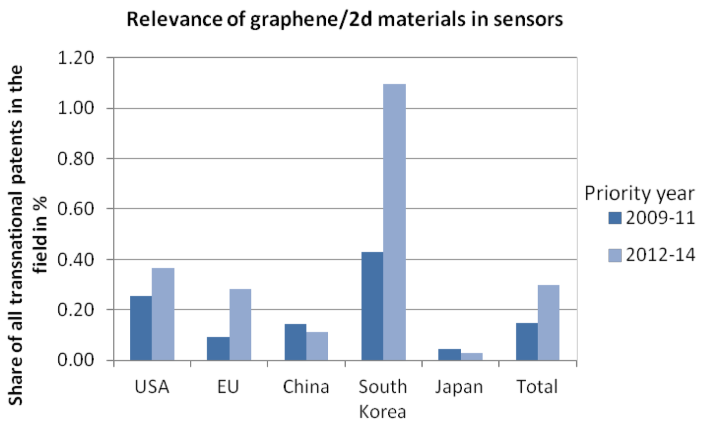


Figure 97: Patent analysis of graphene/2D materials in sensors (without optical sensors). Top graph: Number of graphene related transnational patents in 2009-2011 and 2012-2014. Bottom graph: Patent share of graphene/2D related materials with respect to all transnational patents in sensors (without optical sensors). 2012-2014 values are projected. [137]

Sensors in infrastructure and smart buildings

One key market of sensors is the infrastructure and smart buildings market, which was estimated at $4.2 billion in 2014 and expected to grow above average at a CAGR of 14.3% to reach $10.6 billion in 2021. The average price unit per sensor was $183.3 in 2014 with a clear downward trend. Infrastructure accounted for about 1/5 of the market, whereas 4/5 of the market was sensors for smart buildings. 66 companies were active in 2014 and 44.8% of the revenue was generated by the top 10 companies (60% by top 19). The 5 EU headquartered companies (Vaisala Inc, FI; Thermokon, DE; EnOcean, DE; HBM, DE; Sauter, CH) among the top 19 generated revenues of $480 million (11% market share). Of the 43 other market participants, 5 were headquartered in Europe. The market is dominated by US companies, which serve more than 43% of the market (11 among the top 19 and 31 among the other 43 companies). [551] Thus, the market is dominated by the US, but there are considerable market participants in Europe.

Sensors in IoT

Another strongly growing key market for sensors is the internet of industrial things market. It had a size of about $3.8 billion in 2014 and is expected to grow at a CAGR of 16.8% to $11.23 billion in 2021. Major market shares of this market are held by industrial control applications (38.6%) followed by applications in smart cities (15.8%), eHealth (7.3%), safety & security (6.7%), smart meter (5.9%), and smart environment (5.6%). Industrial control is further expected to dominate the market in future (CAGR of 15.8%) with over 20 different sensor types used. The largest growth opportunities arise from the logistics market segment with an expected CAGR of 18.6%. The sensors with the highest revenue contribution in 2014 were temperature ($318.7 million), pressure ($264.6 million), flow ($245.2 million), image ($242.6 million), gas ($196.6 million) and accelerometers ($188.5 million). These sensors wills also dominate the market in 2021 with a revenue share of 30.7%. New and combined sensors are a particularly dynamic growing field. [552] More than 40 companies are active in sensors for IoIT. Of the top 16 companies, which create a revenue of >40% in the topic, 3 are headquartered in Europe, incl. Switzerland (Siemens AG, Germany; ARM Ltd., UK; ABB, CH) creating a revenue of $334 million (in 2014, 8.8% of the world market). Other major companies are from the USA (12 companies) and Canada (one company), top companies being Texas Instruments, Qualcomm, Intel and Honeywell (together holding a share of 15% of the market). 40 other companies with market shares below 1% are from the USA, 12 from Europe including Switzerland, another 4 from Korea and Japan, one from Israel and one from Canada, clearly demonstrating the leading role of the USA. [552]

(Micro-) energy harvesting

Micro energy harvesting and nanogenerators currently represent a nascent market with revenues of $1.2 billion in 2015. The projection for 2030 is $12.5 billion representing a CAGR of 16.4%. By 2026, revenue growth is expected to slow down. Figure 98 shows the market development by type of energy harvesting from 2015 to 2030. Figure 99 shows the most important markets for energy harvesting technologies. Europe is among the fastest growing regions. The average price per unit is 8.13$. [553] Other sources looking at off-grid power ranges of µW to MW foresee a market development from $1.4 billion in 2015 to above $6 billion in 2026 (CAGR ~15%). 5 out of 19 (micro-) energy harvesting manufacturers investigated in the F&S study are headquartered in the EU (inc. CH), being Perpetuum (UK), EnOcean (DE), Pavegen (UK), Ferrotec (DE) and GreenTEG (CH). 11 are from the US and Canada, three from China and Japan. For system integrators, 5 out of 13 are headquartered in the EU (incl. CH), ABB (CH), Schneider Electric (FR), Alphanetrix (GR), Lufft (DE) and Eaton Industries (DE/IR). [554]

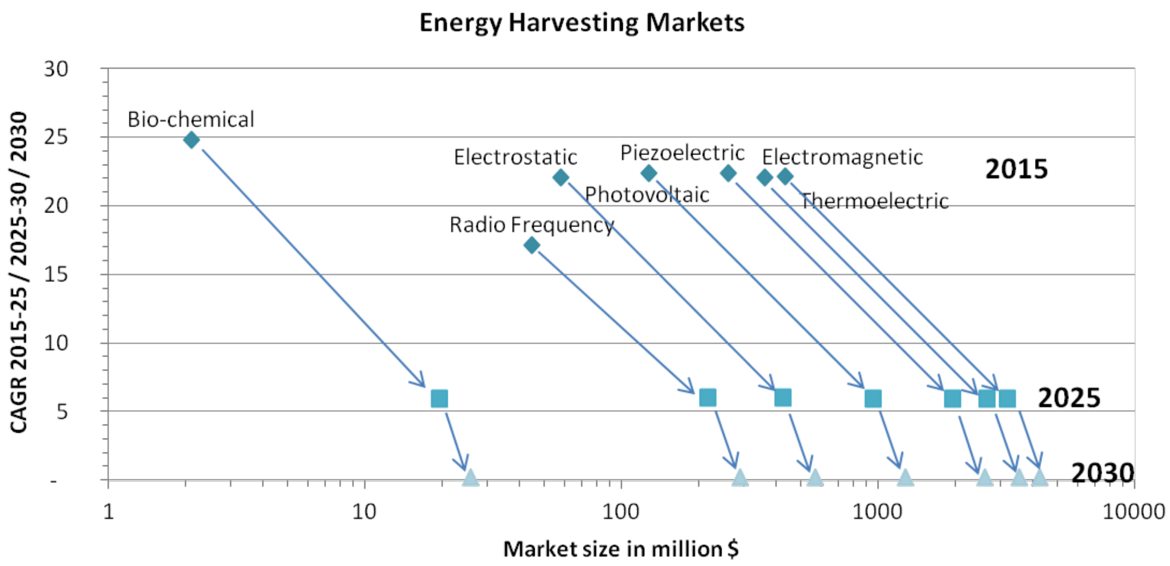


Figure 98: Energy harvesting markets. Data taken from [553]. Please not that the estimates vary for the different types. Especially piezo- and thermoelectric energy harvesters are estimated to have lower market shares in other sources. [554]

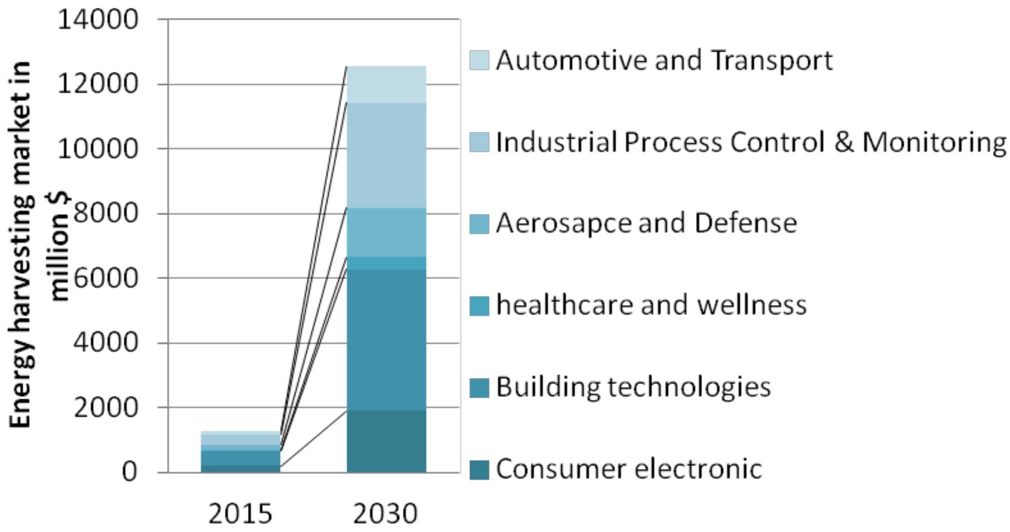


Figure 99: Energy harvesting market by application [553]

Gas sensors

Looking at gas sensors, detectors and analyzers, the global market was $2.8 billion in 2014. Estimates project it to reach $3.8 billion by 2021 (CAGR of 4.5%). The market share of the top 3 competitors (Honeywell, US; MSA, US; Dräger, DE) was 42.2% in 2014. Of other key companies, 9 were headquartered in Europe, 8 in the US and one in Japan. Gas detectors had the largest share in 2014 with a market value of $1.9 billion. Gas sensors contributed with $490 million to the market, whereas gas analyzers created a revenue of $391 million. [555] Figure 100 shows the market share of gas sensors, detectors and analyzers for different target gases.

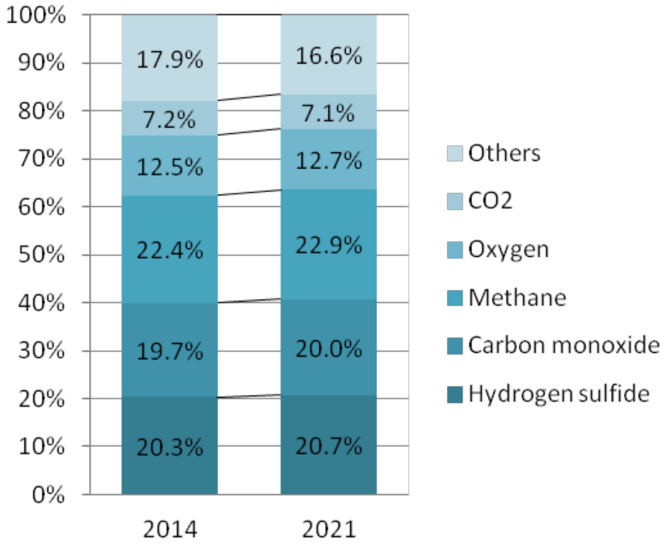


Figure 100: Market share of target gases for gas sensors. Others comprises of toxic and combustible gases, such as volatile organic compounds (VOCs), hydrocarbons, sulfur-dioxide, nitrous oxide, nitrogen-dioxide, ammonia, chlorine, and chlorine-dioxide. [555]

Looking at only the gas sensor market ($490 million in 2014), a steady market growth of 5% per year could be observed in the past. It is expected to grow to $713 million in 2021 at a CAGR (2014-2021) of 5.5%. Oil and gas companies are major customers of gas sensors. Declining oil prices will decrease the demand in this market and slow down the demand for gas sensors. The gas sensor market can be subdivided into toxic gas sensors and combustible gas sensors. The main technologies for toxic gas detection are electrochemical, photoionization and semiconductor sensors. Combustible gas sensors mostly use catalytic and infrared sensors. Gas sensors are integrated in gas detectors and analyzers. Those can be wireless or wired. All top 3 gas sensor companies addressed by the F&S study are headquartered in Europe and have a market share of roughly 1/3 of the gas sensor market (~$160 million). They are City Technology Ltd. (UK), Alphasense (UK), and SenseAir AB (SE). Of other key market participants, 8 are in the EU (incl. CH), 5 in the USA, 3 in Japan and one in New Zealand. [555] Europe therefore has a strong base in gas sensors.

Biosensors

The analysis of biological parameter, primarily in a medical context, attracts a considerable number of patent activities. Thus it is a large, competitive market where the US and the EU dominate (Figure 101). The share of graphene-based bioanalysis is still very modest, but growing. In particular the activities of the EU show a clear take-up (Figure 102).

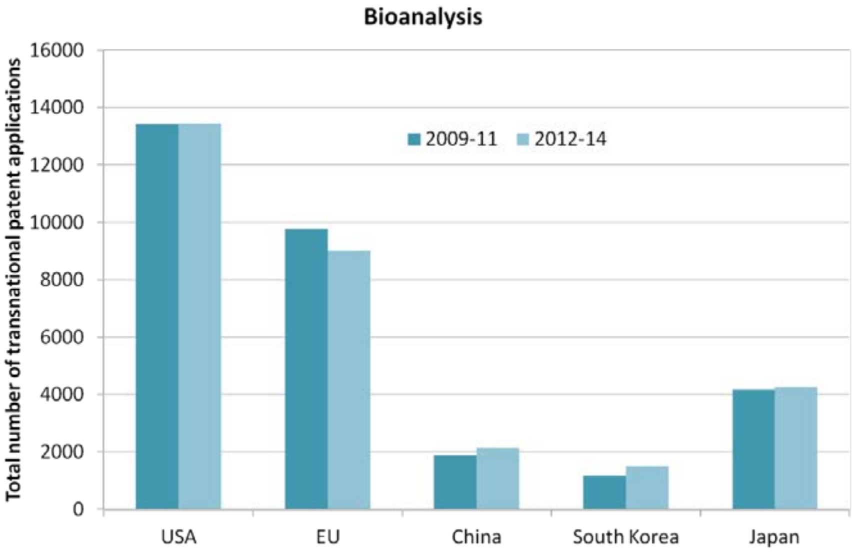


Figure 101: Transnational Patents in Bioanalysis. [137]

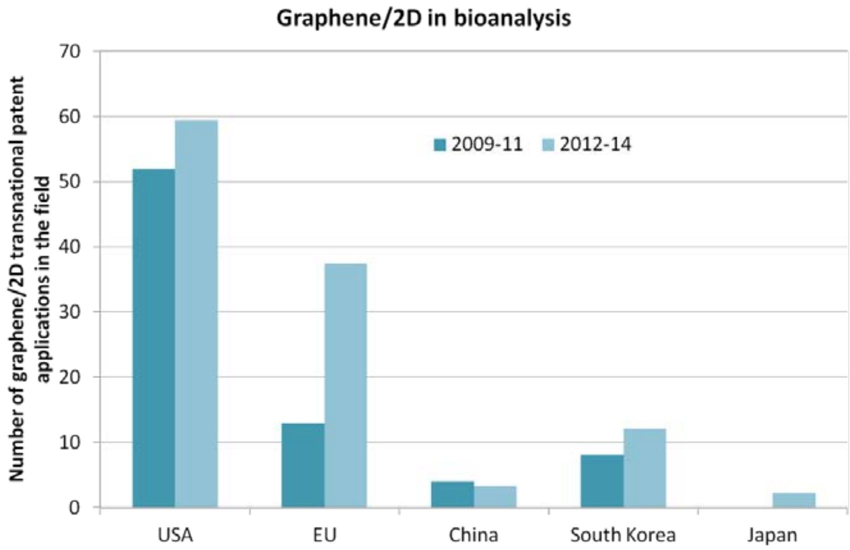


Figure 102: Transnational Patents in graphene-based Bioanalysis by Priority Years. [137]

With $11-14 billion in 2014, the volume of the biosensor market is highly relevant. It is expected to be worth more than $20 billion by 2020 (CAGR of 10-14%) [556, 557]. Diabetes/glucose sensors had the largest market share with almost 1/3 of the revenue in 2014. However biosensors are very versatile and used for more than 40 different pathogens and enzymes (Table 57). The market attractiveness for biosensors is high and they can be used in many different applications, see Figure 103 for the market shares of different end user markets. They are also getting into new markets, such as into mobile platforms (smartphones and other mobile devices) and into automotives. Established markets are research labs, fermentation and bioproduction industry (e.g. biopharmaceuticals, food, biobased chemicals), medical care, defense and safety. Biosensors are used in these areas for analysis, process and product control, quality control, environmental/pollutant/toxic substances monitoring, medical diagnosis or health monitoring (clinical, point of care, home care). A trend is observable towards portable and wearable biosensors and biosensors are more and more used in microfluidic devices (e.g. Lab-on-a-chip), point-of-care diagnostics, or medical implants. [557] However, this market comprises a broad variety of technologies and apparatus, so that the specific contribution of graphene-based approaches is difficult to assess.

Table 57: List of key pathogens and enzymes tests by biosensor devices. [557]

No.	Type of test	No.	Type of test	No.	Type of test
1	Glucose	15	E.coli/Coliform	29	Tetryl
2	A1C	16	Crypto	30	DNT
3	Cholesterol	17	Girdia	31	RDX
4	Infectious diseases	18	Micro cystins	32	Nitroglycerin
5	Coagulation PT	19	West Nile virus	33	PETN
6	Coagulation ACT	20	Anthrax	34	Drug discovery
7	Drugs of abuse	21	SARS	35	Virus detection
8	Lactic acid sensors	22	BSE	36	Cronobacter sakazakii
9	Peptide sensors	23	Cocaine	37	Campylobacter jejuni
10	E.coli 0157:H7	24	Methamphetamines	38	Listeria
11	E.coli O55	25	Ecstasy	39	Listeria monocytogenes II
12	Salmonella	26	Opiates	40	Pseudomonas aeruginosa
13	Salmonella enteritidis	27	THC (cannabis)	41	Staphylococcus aureus
14	Toxicity	28	TNT explosives	42	Clostridium perfringens

32 companies generate 2/3 of the total biosensors market. Within this top companies, there are 10 companies headquartered in Europe (including Switzerland) generating a revenue of 23.2% ($2.7 billion in 2014). Roche Diagnostics (CH, 10% market share) and Bayer (DE, 6.6% market share) are the largest Europe based companies in this statistics. Dominating country is the USA, with 35% market share of US based firms. Among the further companies beyond the top 30, European companies have a share of 13 out of 29, of which 10 are based in Germany. 11 companies out of 29 are based in the US. Looking at key biosensor manufacturers 17 out of 57 are headquartered in Europe and 37 are based in the US. [557] This shows that Europe plays a leading role in biosensors, but that the USA has more and stronger companies in that area.

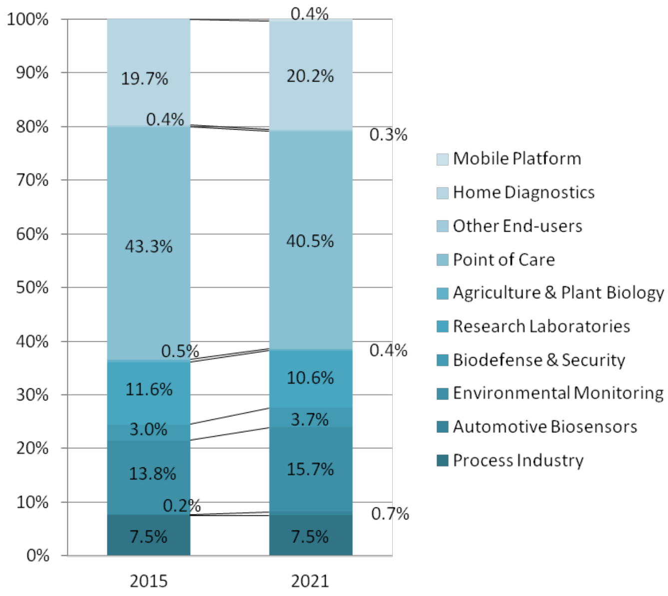


Figure 103: Biosensors markets by end users. Other end-users include: Mobile Platform (2015), Sericulture, Marine, Pharmaceuticals and Drug Research. [425, 557]

The major market of biosensor is the point of care testing (POCT) market, which accounted for $5 billion in biosensor revenues in 2014. The overall POCT market was $2.9 billion in 2015 in Western Europe with a projected CAGR of 5.8% until 2020 to reach $3.9 billion. [558] Figure 104 summarizes the different segments of the POCT market in Western Europe. Highest growth potentials are seen in Cardiac, infectious disease and blood gas and electrolyte POCT. Opportunities due to low competition, high growth and high average prices can be seen in Infectious disease, Cardiac and Cholesterol POCT in Europe. [558]

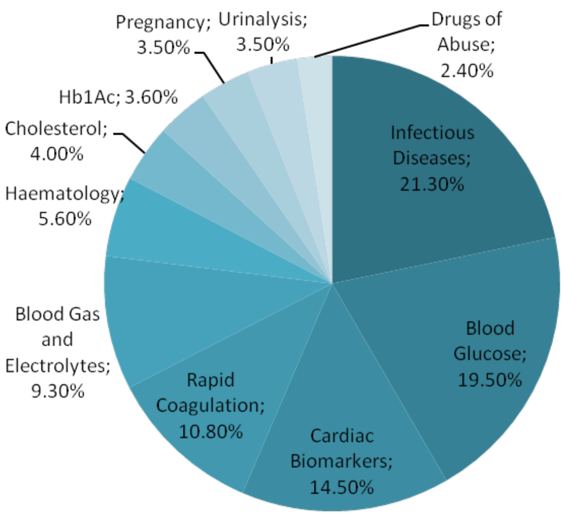


Figure 104: Western Europe POCT market by segment 2015. [558]

The European POCT market is dominated by non European companies (besides Roche, CH). Almost 60% of the revenue is generated by non-European companies (however, they also produce in Europe). Another 20% of revenue is generated by Roche. The majority of the remaining 20% are split between 6 EU based companies, 4 USA and 1 Japan based companies. [558]

5.5.1.1 Market Opportunities

5.5.1.1.1 Diverse growing markets with many niche applications and drivers

As presented in section 5.5.1 Market perspective: graphene/2D in sensors, the sensor market is a very fast and strongly growing market. It covers everything from low value high volume markets to high value markets with lower volume, where added sensitivity is paid for (as early adopters, e.g. in biosensing). Many niche markets available with potential early adopters.

Several areas are expecting extraordinary high growth rates, such as wireless sensors and sensor networks, cloud connectivity, remote monitoring – especially in the realm of IoT and industry 4.0. It is expected that the sensor demand from IoT will pick up pace in 5-10 years. Another strongly growing area is mobile sensors for smartphones and consumers, also in the realm of wearables and e-Health. In this respect also printed sensors for low cost applications will be required (see 5.6 Flexible and/or printed electronics for further assessments). The automotive market is also demanding sensors already and the demand will increase, the more the automobile is pushed towards (semi-) autonomous driving and intelligent vehicles. Further interesting areas are related to robotics and artificial intelligence. [425]

Regulatory frameworks can also increase the demand for sensor solutions, e.g. in terms of air quality regulation the demand for gas sensors/analysers in increased, or in terms of safety and security the compulsory use of smoke detectors in residential housing increased the demand for smoke detectors heavily.

5.5.1.1.2 Market requirements: accuracy, selectivity, response time, cost, lifetime, integrated sensing and multi-sensing

High level of accuracy, instant response time, and assured lifetime performance are main demands and selection criteria for sensor customers. Additional needs are cost reduction and miniaturization towards small footprints. The latter is demanded through chip-level integration as well as sensor integration on device, component and system level. The integration into complex systems and along with that increased smartness and intelligence are important aspects. [425] This is for example addressed by complex (wireless) sensor networks providing in-situ, real-time and continuous measurements. These integrated sensing capabilities of previously inactive components can be seen as an opportunity e.g. for added functionality in composites (force sensors, strain gauge).

Higher sensitivity sensors can create or address new markets that previously were not possible to address due to high performance demands. Furthermore, there is a strong trend and wish towards for multi-sensor capabilities and combined sensors, i.e. one integrated sensor measuring different parameters.

Selectivity and reversibility of sensors is also important in particular for gas/chemical sensors.

5.5.1.1.3 Additional market needs: disposable, flexible, etc.

Some of the trends particularly demand flexible/conformable sensors, which can be easily confined to a certain host (e.g. wearables, IoT for small parts). Further interesting opportunities are existing for biodegradable/combustible sensors, e.g. for disposable/one-use applications. Depending on the addressed market and sensor type, flexibility, conformability or biodegradability can be important USPs.

In many sensors rare materials (rare earth materials, high value metals) are used. Graphene, an abundant and more sustainable material, can have an opportunity to address those sensors as an alternative material.

5.5.1.1.4 European strength and industrial basis in sensors

Europe is a strong player in sensors. This is obvious in transnational patent activities (see 5.5.1 Market perspective: graphene/2D in sensors and Figure 96). There is an innovative and strong basis in Europe that could take up graphene inventions and innovations. Also in the semiconductor field, Europe is strong in sensors and MEMS devices, with the two world leading MEMS companies being headquartered in Europe (see Figure 95).

5.5.1.2 Additional market opportunities: Magnetic sensors

5.5.1.2.1 Broad applications of magnetic field sensors

Magnetic sensors are used in a variety of applications from smartphones (e.g. compass function, position sensor) to cars (tire “pressure” sensors, ABS, ESP, seat belt alarm). Magnetic sensors can essentially be used for fast and accurate position and motion sensing among others in mechanical engineering, computer games, robotics and in minimally invasive surgery. With a CAGR of 8-13% until 2019, the magnetic field sensor market is expected to in-crease to $2.7-3 billion by 2019. [425, 559]

5.5.1.2.2 Performance of Si based sensors not very high

Silicon-based hall sensors have a rather low sensitivity but can be fabricated very cheaply. There is a demand for higher sensitivity, lower cost sensors. Higher performance sensors at similar or lower prices, footprint and energy consumption provide a good opportunity for new materials in magnetic sensing. Higher sensitivities can even justify slightly higher prices, especially in particular industries, e.g. automotive.

5.5.1.2.3 Interest from European key players

European key players are investigating graphene-based Hall effects. [531] The application focus lies especially possible in consumer and automotive areas, but both need manufacturability and rather low cost. There is a moderate competition on the market and some of the market leaders are European (Infineon, Germany; Melexis Microelectronic Systems, Belgium; AMS, Austria). The overall market of hall sensors, however, is dominated by Asahi Kasei Microdevices (Japan) and Allegro Microsystems (USA). [425] Honeywell (USA), MEMSIC Inc. (USA), Micronas (Switzerland) and NXP Semiconductors (Netherlands), NVE Corporation (USA) and Hitachi (Japan) play also a role in the magnetic sensor market in terms of AMR and GMR. [559] In the market for smartphones and semiconductor based hall sensors Yamaha (Japan), Bosch (Germany), STMicroelectronics (France), ALPS (Japan), Diodes (USA) also play important roles. [560]

5.5.1.3 Additional market opportunities: nanogenerators

5.5.1.3.1 Nanogenerators for micro energy harvesting for autonomous integrated systems

Upcoming autonomous systems and sensor solutions, such as in IoT or smart buildings, drive the demand for autonomous energy solutions. The obvious idea besides storage soluteons like batteries is to harvest energy from the environment of the device, e.g. movement, vibration, heat or radiation. Maintenance free solutions for building automation and industrial process control, self-powered sensors for smart energy and transport networks and more broadly IoT will drive the demand for such solutions. [553]

The window of opportunity is still there, as IoT will pick up pace in the next 5 years. The demand for such energy harvesting solutions is thus expected to increase strongly in the near future (CAGR >15%, see 5.5.1 Market perspective: graphene/2D in sensors).

5.5.1.3.2 Competing technologies not yet broadly marketed

Major solutions today are electromagnetic/-dynamic and photovoltaic energy harvesters, thermoelectric and piezoelectric energy harvesters are also present. However, these solutions are mostly not yet sufficiently powerful or cheap. The challenges for a broad market roll out (especially for mass markets like IoT or smart buildings) are still there. Thermoelectric energy harvesters have poor efficiency and most versions are toxic. Piezoelectric solutions are brittle, some are also toxic and they have poor power density. Emerging triboelectric harvesters have poor power density and unproven efficiency. [554]

Thus, the technologies and the market is still quite immature, due to either low power density or high cost/low maturity and graphene/2D material bases innovations can still contribute (e.g. in tribological nanogenerators). Especially the Si-based MEMS devices for energy harvesting are suffering from a too power density. The existing technologies are therefore not yet feasible for many applications and full market introduction has not yet happened. This can be either triggered by better energy harvesters (higher power, lower price) or by lower energy consumption of the devices driven by the harvesters, so that the low existing power density harvesters are sufficient. The market itself currently only has moderate competition, but is highly fragmented.

5.5.1.3.3 European companies in energy harvesting and system integration

There are several European companies active in the area of (micro-) energy harvesting, although the US dominates this emerging market. Especially for system integration, there is an equal number of key companies from the US and the EU, see 5.5.1 Market perspective: graphene/2D in sensors, energy harvesting).

5.5.1.4 Additional market opportunities: chemical/gas sensors

5.5.1.4.1 Promising and diverse market expectations

Several market drivers affect the need for chemical gas sensors/detectors, such as the increased need for air quality control in megacities or increased awareness of climate change, health and safety among end users. In the industrial space rising concerns about personnel and plant safety is a key market driver. Regulation also drives the market though rising enforcement of occupational health and safety regulations by government bodies. Furthermore, the increasing industrial standards for safety and monitoring drive the need for gas sensors. Some of the internationally accepted standards are IEC, NFPA, EN (ATEX), and ANSI/ISA [555]

There are several possible markets from high price to low price and niche to mass markets, e.g. from research/biomedical applications to food packaging or from very special devices to consumer markets. The market allows first market entry via higher valued niche products, but major markets with higher volumes will be rather moderate or low cost. Gas sensors provide a good opportunity for quick commercialisation of integrated systems.

One can distinguish 3 types of sensor/detectors:

1. extremely high quality measurement, but permanent installation
2. high quality measurement (20 ppb), portable;
3. ppm-range measurement, low cost, broad distribution (mass market)

All can be equipped with wireless functionality.

Gas sensors can in principle be seen as a platform technology, especially if selectivity can be changed through different functionalization.

5.5.1.4.2 High demand for innovation: competing technologies have deficiencies, e.g. are expensive and/or have a large footprint

Selectivity is the most important prerequisite for a gas sensor, as it is otherwise useless. There is a high demand for innovation in gas sensors to develop smaller products that are more robust, durable, and cost-competitive. A longer lifespan and maintenance-free products are requested from the end users. [555] Common systems are often too bulky and have high maintenance cost. An added value for customer can lie in longer periods of good performance of graphene-based sensors, as compared to conventional sensors, and thus lower costs per sensor life-time. Furthermore, the response time is also an important factor, that together with the other parameters mentioned above can create a unique selling proposition.

Competition in the market is mostly moderate but increasingly intense, especially in terms of new applications (e.g. for smart cities). Compact and cheap sensors addressing environmentally harmful compounds or compounds harmful to health, e.g. ions, heavy metals or volatile compounds, provide interesting opportunities for applications in safety monitoring.

5.5.1.4.3 Selective multi gas/chemical sensing

Developing selective multi gas sensors and several sensors integrated in one small footprint device is a major opportunity and one of the most important goals for gas sensors, as these devices are heavily sought for.

5.5.1.4.4 Opportunities for lower performing low cost sensors

Battery-powered wireless detectors and very-low power detectors open up more opportunities for gas detectors. [555] However, only very few sensors can satisfy the demanding specification for phones (usually < 5 mW, < 3.0 V, 2 year lifetime, <€2 price per sensor, small footprint of a few mm^3).

Although there is a need for higher sensitivity sensors on the one hand, on the other hand cheaper applications tolerate lower sensitivity. There is an opportunity in addressing these cheaper but less sensitive sensors. Often, the available gas sensors cannot meet these cost targets and have an overshooting sensitivity. Some potential products are not yet broadly available on the market (e.g. gas sensors in food packaging), mostly due to cost constraints.

Printed sensors, sensors based on organic electronics or on low cost Silicon platforms could address this, probably enabled by graphene/2D materials. Also sensors that are only used a few times (e.g. in packaging) could have their applications, as long as the cost is low enough.

A very important competing technology is metal-oxide gas sensors in CMOS packages. These are hitting the market and can achieve small form factors, high enough sensitivity, low enough energy consumption whilst being in an adequate cost range. [561]

5.5.1.4.5 European actors are strong

There are various European actors in the gas sensing area, especially when it comes to the gas sensors themselves. (see 5.5.1 Market perspective: graphene/2D in sensors, gas sensors).

5.5.1.5 Additional market opportunities: biosensors

5.5.1.5.1 Platform character of biosensor technologies

Biosensors are very diverse and can be seen as a universal platform with a large diversity of end products (= sensors, actuators, devices). Biosensors can be also used as gas/chemical sensors, so the market opportunities in 5.5.1.4 Additional market opportunities: chemical/gas sensors also apply.

Similar to gas sensors, it is also an opportunity to address functional hybrids, i.e. the combination of different target analytes in one sensor. Biosensors are usually used due to their high sensitivity, accuracy and specificity and because they are easy to use. [557]

5.5.1.5.2 Need for direct and fast testing (IVD, point of care testing)

The largest and classical markets for biosensors are in-vitro diagnostics and point of care testing, as well as direct-to-consumers testing markets (Home care and wellbeing).

In these markets, high specificity and fast diagnosis are important requirements. Opportunities lie in label free testing and high speed for POCT, because this eliminates the time needed to wait for incubation or labelling. These properties combined with high sensitivity – i.e. real-time detection of target analyte reaction and conversion into a usable electrical signal – are the most important performance indicators in these markets. POCT and lab on chip can complement complicated lab analysis (e.g. mass spectroscopy). However, so far POCT currently only is a smaller part of the in-vitro diagnostics (IVD) market, mostly in areas where time-to-testing-result is therapy-modifying, i.e. often in rescue vans, emergency rooms and hospitals. The POCT market in Europe is about 1/4 the size of the IVD market, i.e. $2.9 billion [558] POCT vs. ~$12 billion overall IVD market. [562].

A trend in POCT is the quantitative detection with electrical readout, allowing testing at home and sending/storing/analyzing health data online (e.g. in the cloud) or remote to a medical doctor. This area is for instance interesting for medicine dosing feedback, risk marker control.

A key opportunity for biosensors in point of care testing is to address multi-target detection of multiple biomarkers. Furthermore, not only purely medical diagnostics can be addressed, bit also wellbeing and home diagnostics are interesting and probably less demanding in terms of regulation. [557]

5.5.1.5.3 Trends driving biosensor demand

Demand for biosensors in increasing due to several trends in the market. For instance increasing interest in personal health and wellness, as well as monitoring of harmful pathogens can stimulates the use of biosensors. This is further supported by a shift towards rapid detection devices. From the regulatory point of view, implementation of strict food safety regulations further increases the demand.

In summary, the opportunities to expand into different and new applications is increasing, e.g. in the automotive sector, as more and more areas demand highly sensitive siosensor devices. [557]

5.5.1.5.4 Diverse markets from low cost to high value

Biosensors address many different markets with differing expectations in terms of sensitivity and cost. This means that market entry is possible via high value niches but also via cost advantages. In general, the medical diagnostics market, although under price pressure from health systems, is not as price sensitive as some other consumer markets. Good margins can usually be obtained for products delivering clear benefits towards existing technologies addressing the same functionality. Therefore, biosensors can possibly be early adopters for graphene/2D technologies. Biosensors are also used in less regulated markets (e.g. automotive, consumer/wellbeing, gas sensing, process monitoring and control), which opens up further opportunities. There is a chance that biosensors become more and more mainstream due to their versatility and ease of use.

Three kinds of market entry scenarios are conceivable:

1. Novel test analyzers/sensors not yet available with new functionality usually have a low cost sensitivity, so cost is not the major barrier (“first of a kind”), e.g. flexible biosensors in e.g. functional medical implants for instance for the eye or brain.

2. for lab analyzers/lab on chip/IVD: moderate to high valued systems using biosensors for measurement techniques that usually use even more expensive equipment (e.g. ICP mass spectrometers), medium cost sensitivity
3. for POCT or home testing/home care, automotive, consumer, domotics: very/rather price sensitive markets, e.g. glucose sensing, where lower cost and more adequate sensitivity are combined with disposability.

5.5.1.5.5 Competition is open

The competition between new technologies is open and there is always space for a new material or technology. If graphene/2D-based function/performance gain comes at a similar cost there will be a market opportunity. For some existing technologies, sensitivity sometimes is an issue as well as readout times; lack of long-term stability, size/miniaturization, cost and mass production compatibility and sufficient ruggedness. By addressing one or several of these issues, graphene/2D can find USPs towards existing solutions in this interesting market. The market itself has a moderate competition and is quite fragmented. The top 3 companies have a market share of less than 30% and the top 10 of ~50%.[557]

5.5.1.5.6 European industrial basis

Although the USA leads the biosensors market, European companies are in the business and there is an industrial basis for this large market. In terms of the POCT market, the European market is dominated by non-European companies.

5.5.1.6 Market Threats

5.5.1.6.1 Price is key for consumer markets and better performance only secondary

Consumer markets are large markets, but if they are to be addressed, low cost is a very decisive factor for success. These markets, e.g. as a sensor in mobile phones, typically demand cost of less than 1$ per detector and a volume of multi-million pieces. Only a small range of products are of interest for those markets. Usual prerequisites are to achieve better performance at the same price or even cheaper. Especially in this area the 10x better performance or 10x lower cost rules apply. In some areas, an increased performance/sensitivity is even not needed and price reduction is more important (e.g. in gas sensors or IR).

It appears that key players in these consumer markets are deeply cynical about timeframes of graphene/2D material development and the prospects for a medium term success are not very good according to their opinion and assessment.

5.5.1.6.2 Mobile phone market in very high competition

Especially the mobile phone sensors market is under very high competition. Diminishing returns are expected over the next 4-5 years and lower cost is ever more important. Hard competition fights are expected in this market. [560]

5.5.1.6.3 Expectations on reliability, durability and operating conditions are high

Reliability, durability (shelf life and in operation performance over lifetime), repeatability and flexible operating conditions are important assets of sensors and detectors. Lifetime and reliability expectations differ depending on the addressed markets, from, e.g. automotive (15 years) to consumer (2 years). First products entering the market need to have a good reliability to generate trust in the product and technology and to not spoil the technology in further uses.

5.5.1.6.4 Fragmented market, existing systems, interoperability and data analytics

The rather fragmented sensor market is on the one hand a big opportunity as new players can enter the market. On the other hand it also poses a threat and restraint. For example, different standards are pursued by different providers and interoperability is often difficult to achieve. This poses a problem for new technologies and broader use as a platform technology. [425]

For networked sensors, the IEEE 1451 family of standards is important. Connectivity and data analytics are becoming more and more important for networked and smart sensors and need to be regarded for a sensor system from the early design of prototypes. [425]

Another restraint in the sensor markets arises from the installed base of legacy systems with significant economic, technical and non-technical barriers to replace existing systems and to switch to novel, innovative sensor systems (even if they come with interesting improvements). [425]

5.5.1.6.5 Health applications have additional constraints

Health applications underlie further regulation (CE, FDA, reimbursement of health test), which are important for a success. For further information please see 6.2 Excursus: The specific structures of the health market.

5.5.1.6.6 Sensors in IoT and smart building markets are dominated by US companies

Although Europe is strong in sensors and sensor development, the emerging markets of sensors in IoT and smart buildings are dominated by US companies (see 5.5.1 Market perspective: graphene/2D in sensors, page 394). But there are also considerable efforts in Europe-based companies, so that there is an industrial basis for take-up of new technologies in Europe.

5.5.1.7 Additional market threats: Magnetic sensors

5.5.1.7.1 Mature market and competing technologies

Magnetic sensing addresses a very mature market with many established technologies. There are different technologies for different applications on the market, from magneto-resistive sensors (GMR sensors, AMR sensors, TMR) to hall sensors and MEMS-based Lorentz force sensors. [563] Hall Effect sensors dominate the market currently, with more than 70% of the market share [559]. Cheap and mass produced hall sensors are based on silicon (e.g. for mobile phones, automotive). Higher sensitivity hall sensors are based on InSb, which is currently not integratable and thus rather expensive. Higher sensitivity for smaller or similar prices has its demand, but there are also other technologies addressing this area (e.g. GMR sensors).

5.5.1.7.2 Low cost products

Mass produced magnetic sensors are produced in the billions (almost 6 billion units in 2014 [559]). For consumer/mass market products the prices are below 20-50ct per piece. For some automotive applications a higher quality and higher cost i possible, but also only in the few Euro range.

5.5.1.8 Additional market threats: pressure sensors/microphones/NEMS

5.5.1.8.1 Competing technologies are more mature and perform better in mass sensing

In terms of nano-resonators for mass sensing, better and more mature concepts are available than graphene based sensors. Graphene is pretty lossy, has a low Q-factor and silicon-based resonators are so cheap and good that it is tough/impossible to compete.

5.5.1.8.2 Competing MEMS microphones sensors are well established and cheap

Pressure sensors/microphones based on Si CMOS MEMS are already very cheap and quite good. It is an open question whether higher sensitivity or a broader spectral range is actually needed. To address consumer markets one has to have a cheap product and large volume or nothing. The market is not willing to pay more for more functionality, but rather expects more functionality for less or similar cost.

5.5.1.9 Additional market threats: nanogenerators

5.5.1.9.1 Nanogenerators only successful if stringent market requirements are met

It is yet not clear whether nanogenerators/energy harvesters in general can satisfy market needs, e.g. for IoT, i.e. small size, very low cost <1$, sufficient output power, maybe even disposable.

On the other hand, competing candidates/materials and principles of energy harvesting are more mature, established and closer to the market, although the above raised question still remains. Careful benchmarking with competing technologies is needed to address this barrier. Alternatives such as cabling or batteries and low power consumption are mature and well used.

5.5.1.10 Additional market threats: chemical/gas sensors

5.5.1.10.1 Unawareness of end users regarding improved gas sensing opportunities

Especially when it comes to innovative and wireless sensor solutions and networks, end users are not yet aware and convinced of the benefits and technical possibilities. The maturity of gas sensors and wireless detectors is currently rather underestimated. End users are often unaware of recent technological improvements. [555]

5.5.1.10.2 Price pressure increasing

The market becomes more and more price sensitive. A trend towards decreasing prices was observed in the last years and is expected to continue. Manufacturers increase the prices pressure by lowering product prices of marketed and established products to keep the market share and expand the market base. [555] This poses a threat for new and possibly more expensive technologies, but on the other hand, opens opportunities for cheaper/simpler technologies. For instance, new sensor technologies, such as low-power IR, CMOS MOx and wireless gas detectors, increase price pressure on traditional detectors. [555]

5.5.1.10.3 MOx sensors and other nanotechnologies as competitors

CMOS-integrated MOx sensors are a main competitor in terms of sensitivity and price towards graphene/2D based sensors, especially for compact and integrated sensors. [561]

Other nanotechnology based sensors are also heavily researched and propose interesting opportunities as competing materials to graphene/2D materials (e.g. CNT, nanowires) [540]

5.5.1.10.4 Patent thicket

The patent thicket in the sensor area is a major threat for new graphene-based sensors, especially for small companies and start ups.

5.5.1.10.5 Proof of benefit not necessarily straight forward

Often, the value for customer lies in longer periods of good performance of graphene-based sensors, as compared to conventional sensors, and thus lower costs per sensor life-time. This particular issue will be difficult to prove to customers, as the initial expenditures might be higher for a graphene based sensor. The critical factor in that case is not the overall sensitivity, but a good, continuous and reliable performance over long time periods (> 2yrs).

5.5.1.11 Additional market threats: biosensors

5.5.1.11.1 Diversity of biosensor applications and requirements pose a problem for focusing and creating a critical mass

The diversity of biosensors is both a blessing and a curse. It allows niches and early adopters on the one hand, but on the other hand, the market needs for so many sensors are so different making it hard to decide what to go for and to focus on in the first place. The variety and unsure potential and way of functionalization demand focussing on particular use cases, which then need to be tailored to the application area.

5.5.1.11.2 Usually long development time of biological recognition element and functionalization optimization

Additionally, the protracted time usually needed for technology transfer from laboratory to commercial applications (for biosensors in general) limits and hinders adoption. Furthermore, novel biosensors usually suffer from rather long development cycles, due to e.g. the development and optimization of the functionalization (biological recognition element). [557]

5.5.1.11.3 Medical/health applications: Regulation and cultural threats

For POCT and other medical applications conformity with EU/FDA medical device regulatory requirements is mandatory and it is important to meet the stringent and specific requirements of the medical device industry. Furthermore, medical applications depend on reimbursement by health insurances, which may be currently critical/difficult to obtain (see also 6.2 Excursus: The specific structures of the health market). Additionally, a lack of technology awareness among users and practitioners poses a barrier for further adoption. [557]

POCT (with or without graphene) competes with established laboratory testing but comes in most cases at a higher price (higher cost per test, no economy of scales as in laboratories). For POCT to become more custom, a paradigm shift towards prevention rather than post event testing is needed, requiring structural and organisational changes in the user institution (e.g. clinic, doctor).

Typical requirements for lab on chip systems are:

1. CE or FDA approval
2. Coefficients of Variation: 1-5%
3. Sensitivity, specificity, system control
4. 5-6 minutes TTR
5. < 1 USD per piece price at high volumes
6. Room temperature stability min 1 year

5.5.1.11.4 Large existing markets are well established and technologies are mature and cheap

Today's major market for biosensor-based glucose (e.g. for diabetes) analysis works already fine and is reasonably cheap. There is no strong need for a completely new material like graphene and the market dominating technology will defend its share. The barrier to enter this market as a new technology is rather high and therefore it is not advisable to address this big existing market in the first place.

The market of bioanalysis is highly competitive, thus graphene-based approaches have a chance, only if the analyses can detect unique parameters or can achieve a much higher precision than other methods. Graphene/2D materials additionally compete with other emerging and partially more mature technologies, which have been studied for a longer time and where more demonstrators are available, such as nanostructure devices, e.g. CNTs and semiconductor nanowires.

Furthermore, the laboratory analyzer solutions in the market are also advancing (e.g. large laboratory equipment such as ICP spectrometers). The advancements in medical devices challenge biosensor manufacturers to keep pace [557]. But for instance with POC, other opportunities exist that cannot be addressed with laboratory equipment. But there are also many other technologies addressing POC.

5.5.1.11.5 Sterilization, reproducibility and durability in different environments

Reproducibility and only small variations between measurements are essential for biosensors. Furthermore, depending on the use case, the possibility to sterilize the sensor might be a prerequisite. In harsh environments, the limited resilience of biomolecules restricts the durability, rather than graphene. [557]

5.5.1.11.6 Not only graphene determines cost

The costs of a biosensor can heavily depend on the biomolecules used, its availability and production. Thus, this can possibly not be influence by graphene research but needs to be addressed when looking at different analytes and biological recognition elements.

5.5.2 Graphene/2D materials perspective: current strengths, weaknesses and challenges for the use in sensors

5.5.2.1 Current strengths for graphene/2D materials use in sensors

5.5.2.1.1 Added value through added functionality and conformability

2D materials and especially graphene offers a large variety of sensor applications employed as an electrode (e.g. in electrochemical sensors), electrical conductor and electrically active material and transducer (e.g. in hall sensors, strain gauges, pressure sensor, nanogenerator, as GFET biosensor) and optoelectronic element (optical sensors). Adding new functions to sensors can enable sensors to address new markets.

In these applications graphene/2D materials can in principle deliver added values:

- It can act as a versatile platform, that can be also functionalized and used in different sensor application looking at different stimuli.
- The two-dimensionality and high specific surface area together with the interesting electrical and optical properties and the sensitivity of those properties to the direct environment make 2D materials highly sensitive transducers with several possible read-out options (electrochemical, transistor, optical)
- Mechanical flexibility: Flexibility and conformability can be important USP depending on the targeted market (see also 5.6 Flexible and/or printed electronics)
- Potential biodegradability/combustibility, which is interesting for end-of-life considerations and disposable sensors
- Transparency. Single layers or double layers of graphene are almost transparent and could be used in unobtrusive sensors.
- Multi-functionality: further interesting intrinsic properties such as the barrier properties and thermal conductivity can be beneficial for applications involving heat and protective layers. Graphene can therefore act as a barrier material an conductor
- Essentially, the substrate can be freely chosen (although this can influence the performance)
- High quality (encapsulated) graphene offers new realizations of quantum technology devices for multi-functional sensing
- Embedded or integrated sensor functionality in composites (e.g. strain gauge), for instance composites made conductive with graphene can change the conductivity depending on strain

- Graphene can be also used as a membrane to filter analytes (e.g. size selective filtering of nanoparticles) during detection (see also 3.5 Special application: Filtering, desalination/deionization and membrane applications)

5.5.2.1.2 Sensor applications also possible based on flakes

Sensors can be realised with high quality graphene as electrodes and in GFETs. Besides this high quality approach, it is also possible to realize sensors based on bulk graphene flakes. For some applications such as electrochemical sensors, some biosensors or strain gauges, the quality of graphene does not need to be as high as for transistors, so that also GO and LPE graphene can be used. These sensors are then usually also printable (see also 5.6 Flexible and/or printed electronics).

This also opens up applications that do not rely on the success of wafer scale integration and where higher readiness levels can be easier achieved and commercialisation is closer. For instance, there are screen printed electrochemical sensor electrodes based on graphene flakes already commercially available (e.g. from DropSens, Spain [94]).

5.5.2.1.3 Overall potential in sensing seen as promising

Sensor applications are seen as one of the most promising key applications for graphene/GO materials by many experts. Due to the variety of potential applications and benefits, as well as the market structure, sensor applications of graphene/2D materials seem feasible and in reach. Furthermore, the technological benefits are promising and USPs are quite evident in many sensor applications.

5.5.2.2 Additional strengths: Magnetic sensors

5.5.2.2.1 Orders of magnitude higher sensitivity proven on lab scale

Graphene/hBN based hall sensors have a 100x higher proven sensitivity on lab scale than Si-based hall sensors, which is similar to other ultra high sensitivity sensors (InSb). [530, 531] The graphene-based hall sensors have a high technological potential but the highest performances are currently based on manually exfoliated graphene and hBN and as such not scalable. Wafer scale integration of graphene and hBN is needed to achieve these performances in a mass manufacturing compatible way.

InSb has similar sensitivity but is very expensive. Graphene based sensors have a better potential in terms of manufacturability, although many questions are still open. The future cost reduction (if integration works) towards InSb can become eventually an advantage. On the other hand, hall sensors also have to compete with other magnetic sensors, such as magnetoresistance-based sensors (GMR, AMR, TMR) or Lorentz-force sensors.

Furthermore, high quality graphene-based (without hBN) flexible hall sensors were proven to have a comparable sensitivity compared to rigid Si-based hall sensors [529].

5.5.2.2.2 Spintronics based magnetic tunnel junctions

Graphene has interesting properties for spintronics and can be used in magnetic tunnel junctions for TMR sensors. This application still needs to be proven for magnetic sensing but could provide another opportunity for magnetic sensing. See also 0

Computing/Logic, beyond CMOS and spintronics for further considerations on spintronics.

5.5.2.3 Additional strengths: pressure sensors/microphones/NEMS

5.5.2.3.1 Ultimate membrane characteristics render it interesting for pressure sensing/microphones

2D materials are the ultimately thin membranes with unreachable mass, thinness and high strength and elasticity (1.1TPa Young's modulus of graphene vs. ~130GPa for Si MEMS). Use of these membranes in NEMS as pressure sensors or microphones is possible in form of suspended piezoresistive membranes or membranes with electrostatic readout and it has been shown that they can be very sensitive and robust. [564] The former work because strain, e.g. induced through pressure, changes the density of states and induces a bandgap in graphene leading to changes in mobility and resistance.

The proof of concept has been shown and some parameters are better than standard MEMS microphones. [565] But the improvement does not justify a change to this type of microphone. Further implementations show a broad wavelengths range (ultra sonic). [566]

These results are promising to achieve smaller sensor (outstanding scalability), higher sensitivity and broad wavelength ranges, with potentially simpler readout. However, the improvements are not yet tested in terms of thermal stability and other important parameters for microphones. If the mechanical properties on macro scale are as theoretically expected and can be realized experimentally, the potential is quite high to outperform state of the art technologies, mostly because the elongation of membrane is large, which can compensate for the low k factor.

A completely different implementation are printed pressure and strain sensors, which are flexible but more coarse in terms of sensitivity. The implementation is quite easy but the technological advantage in terms of sensitivity is not extraordinary high. On the other hand, flexibility and the end-of-life characteristics (combustibility, disposability) and environmental properties also during manufacturing, can be very interesting (see also 5.6 Flexible and/or printed electronics).

5.5.2.4 Additional strengths: Nanogenerators

5.5.2.4.1 Rather simple realization if wafer scale integration is feasible

Graphene is especially tested as (flexible) triboelectric energy harvester [538]. It is also examined in piezoelectric nanogenerators, e.g. as substrate for piezoelectric materials [567], and in thermoelectric nanogenerators, e.g. as additive for thermoelectric composites [568]. Also other means of energy harvesting are investigated, such as acoustic wave harvesting [567] and for other new means of energy harvesting (e.g. from moisture [569]). Other 2D materials are also investigated, e.g. for piezoelectric energy harvesting. [538]

The application is in most cases rather simple (lower quality constraint on CVD, maybe even LPE possible) and a nanogenerator should be easily processable with wafer scale integration. Graphene-based tribological nanogenerators have been realized in the lab.

A major benefit is the flexibility and potential transparency. So far the lab results are interesting and expectations are good, but the proven performances and manufacturing is not yet sufficient for an actual uptake from industry.

5.5.2.5 Additional strengths: chemical/gas sensors

5.5.2.5.1 Sensitivity proof of concept promising

The high specific surface area and the sensitivity of electronic properties of 2D materials to the direct environment are important prerequisites for highly sensitive gas sensors. Graphene gas sensors have been demonstrated and the concepts have been proven with very promising sensitivity, response times and working at room temperature. The performance in terms of sensitivity realized in labs today is already as good as competing non-graphene sensors and there is still potential for further improvements of the performance. The sensors are potentially robust, as graphene is neither brittle nor prone to a high chemical reactivity. The sensitivity is expected to be similar or better to competing technologies, but due to the higher robustness with a significantly prolonged life-time and potentially shorter response time. Current major problem is the selectivity.

Several target gases and chemicals have already been addressed, ranging from humidity, nitrogen oxides and hydrides, carbon oxides, hydrogen to form- or nonanaldehyde.

5.5.2.5.2 Enabling new sensing capabilities

Graphene based sensors could enable completely new functionalities, e.g. multi-gas sensing through simply implemented and compact multiple sensor arrays for air quality or breath analysis. Sensitivity and robustness are already shown, but the selectivity and capability for multiple sensor arrays needs to be proven. 2D materials promise to have the potential to become cheaper, smaller and more sensitive and selective.

Graphene plays an important, but not unique role in gas sensing. Other nanostructured materials are competing with comparable results (e.g. metals, metal oxides, organic semiconductors) and higher maturity. However graphene/2D materials have the potential to provide a) the same level of performance, but over longer time periods or b) more sensitive (and probably selective) sensing.

As printed sensors, the uniqueness for low cost and flexible solutions might be higher.

5.5.2.5.3 Implementation with and without wafer scale

Gas sensors can be based both on high quality films and flakes. The implementation is in principle easier than for many other emerging competing technologies, such as CNT. Sensors based on rGO flakes are simpler to produce and no wafer scale integration is needed. But the reproducibility of LPE graphene and rGO is not good enough at the moment to prepare reliable sensors.

For electrochemical and GFET-based gas sensors, wafer scale integration is beneficial (for the latter a prerequisite). If wafer scale integration succeeds on a broad scale, cost reduction compared to existing technologies could become a major USP, as current technologies are usually quite costly (although there are now first low-cost CMOS based MOx sensors addressing the mobile market [561]).

5.5.2.6 Additional strengths: biosensors

5.5.2.6.1 Intrinsic properties are good for biosensors

Graphene can be used in several ways as biosensor. The two major kinds of implementation are as electrode for electrochemical sensing (measuring for instance impedance, amperometry or potentiometry for instance from a screen-printed electrode), and as GFET, where the analyte changes the transistor response by modifying the graphene channel. Further implementations are sensors based on surface plasmon resonance, fluorescence quenching (both optical measurements), as electrode to measure electrical/neural activity and as membrane with nanopores and sensing capabilities, e.g. for DNA analysis. For almost all sensors types GO, rGO, graphene and other 2D materials can be employed, depending on the need for sensitivity, loading, selectivity and response time. Graphene-based biosensors have been developed for various inorganic and organic analytes, e.g. glucose, proteins, DNA, NADH, biomarkers, antigens, pathogens, heavy metals, H_2O_2, NO.

Graphene materials offer good properties for biosensing, especially due to the following benefits:

- high **chemical stability** (for instance better than silicon nanowires)
- large **specific surface area**
- **capability of high bioelement loading for high sensitivity**: for instance, GO can be well used as a matrix for binding the bioelement due to many functional groups and a high surface area, thus allowing to create functional hybrids with an increased sensitivity due to high bioelement loading. There is also a potentially large range of surface chemistry available to modify/functionalize the surface.
- **Direct quantitative recording of analyte**: analyte can be directly and quantitatively recorded as electrical changes and output as data (the binding interactions themselves are electronically measuredand not via piezoelectrical or optical signals). The direct electron transfer between the bioelement and the electrode surface does not need a mediator. This can **reduce process complexity**, **response time** and **hardware costs** and **increase sensitivity**, **portability and ease of use**
- **rather simple device structure**
- high sensitivity, low noise, fast response time; potentially high specificity (depends on bioelement)
- **label free** detection possible, even of separate bases in DNA, which is unique.
- due to high sensitivity: **low sample volumes needed**
- mechanical flexibility for **flexible substrates** and sensors, allowing addressing new markets
- Biocompatibility
- Some realisations can be made **transparent**
- Hydrophilicity and hydrophobicity possible
- Potential for low power consumption

The combination of all the strengths makes graphene/2D materials rather unique for biosensors with a strong enabling character. There are of course also other options, e.g. CNT or other nanotechnologies, but there are only a few competing technologies which could be competitive from the technological point of view.

The available scientific analyses show that graphene-based biosensors can detect specific biomolecules with high precision. This may be a competitive advantage compared to other biosensing approaches. It will be decisive to establish graphene-based approaches in relevant segments of the biomedical market, e.g. in the context of cancer.

5.5.2.6.2 Multifunctionality: several functionalities in one material/layer

The combination of different sensing capabilities and functionalities seems possible with graphene materials. For instance in a process cell for IVD, graphene can be used for temperature control and as catalytic surface cell for enhancing reactions and sensing.

It is also possible to combine electrical and electrochemical measurements with optical measurements (high freq/optical plasmonic detection possible).

Graphene can also be applied in Lab-on-Chip devices, as multiuse sensing element that is possible to functionalize repeatedly. As a charge sensitive element, the only requirement for the analyte is a change in the charge distribution with bio-recognition. In this respect it competes with nanowires, but it is not yet clear which material is more stable.

For electrodes and neural sening, both sensing and actuation are possible (e.g. brain/heart electrode as sensor and to deliver electrical stimulus).

5.5.2.6.3 GO electrochemical biosensors for less demanding applications

With GO and rGO screen-printed electrodes, electrochemical electrodes and even GFETs can be prepared. GO has many functional groups and can thus be well functionalized and loaded. Functional hybrid materials can thus be obtained. However, the electrical properties are not as good as for high quality films, especially in GFETs. Thus, the sensitivity might be lower/different. On the other hand, even graphene/GO inks may be sufficient for less demanding applications, e.g. monitoring (food, environment).

5.5.2.6.4 GFET biosensors for more demanding applications

The functionalized bilayer-graphene based FET sensor benefitting from the above mentioned unique properties has the potential to challenge all biosensors (as a platform). The overall technological performance and advantages already realized in labs and proven by academia is often better than competing options such as carbon nanotubes or semiconductor nanowires. The sensor has the potential to overcome disadvantages of Si-based FETs, e.g. the high electric noise, integration with flexible substrates or stability under physiological conditions. The performance of the GFET based sensors are expected to be better than the state of the art in the future. Also, simpler to produce functionalized GFETs (e.g. based on rGO) are promising to provide quantitative electronic readout in biodetection with a simple device structure and low-cost fabrication as even on flexible substrates. The higher quality GFETs have a cost reduction potential towards common lab analyzers, but probably not towards other upcoming technologies (nanowires, CNT) at the moment. For the high performing GFETs based on high quality single or bilayer graphene to become cost competitive, a low-cost direct graphene layer generation and functionalization of graphene surface for specificity is required. With a larger scale and economically feasible wafer integration scheme this might be realisable.

There are already companies working on the use of graphene FET as biosensors and first implementations of commercial graphene-based FET biosensors are expected on the market in 2016/17.

5.5.2.6.5 Build on CNT experiences

CNT have been investigated for biosensing for a longer time and a lot of experience is in this field. This experience can in part be used for graphene-based biosensors, especially with respect to e.g. similar behaviour, surface chemistry or the use in electrochemical applications.

5.5.2.7 Current weaknesses and challenges for graphene/2D materials use in sensors

5.5.2.7.1 Current maturity too low for comprehensive feasibility assessment

Although many sensors show promising technological parameters, the available data and the means of manufacturing is still too immature to allow a comprehensive feasibility assessment for industry.

Especially issues that are besides the technological performance very important for a broader roll-out, such as reliability, power consumption, repeatability or cycle times need to be tested/proven. Furthermore, economically feasible and as simple as possible means of production are necessary, providing a high yield and good reproducibility. These factors are still too elusive for most sensor applications avoiding to go beyond the R&D stage or the “manually” manufactured low volume, high price niche sensors. Especially the sensors based on high quality films (such as GFET sensors, NEMS/pressure sensors, hall sensors) need wafer scale integration to become commercially viable (see SWOT analysis in 5.2 Electronics: Cross-cutting issues).

For sensors where the production is rather simple and possible, on the other hand, such as printed sensors, the technological USP is probably not high enough.

For almost all sensors, the design and fabrication are manually done at lab-scale and commercial scale-compatible design and fabrication is rarely done. Furthermore, also the technological assessments are mainly based on laboratory experiments and measurements in controlled laboratory environment. “Real world applications” in real samples and relevant environments are rarely done. For instance, very often improvements are only shown for one performance parameter (which is better than anything else), neglecting others, e.g. temperature stability, power consumption, etc.

5.5.2.7.2 Challenge to create adequately performing low-cost G-sensor

The requirements for particular sensors on the manufacturing, in terms of needed quality of 2D material, size of sheets, parameters such as mobility, etc. are often unclear and need to be systematically investigated to provide insights on the preferred production methods. This further calls for material standards to allow exchange between manufacturing and applications. The major idea needs to be that the quality should be high enough to provide the performance needed and low enough to allow simple and cost effective production methods.

5.5.2.7.3 Besides the material also data analysis and readout are important

For sensors, not only the sensor itself and the sensing element is important, but also data analysis and read-out is crucial to show the actual functionality. The full package of sensor, readout and even software is needed to show the actual potential of graphene in demonstrators and create awareness of the potential. This is particularly important for multiple sensor arrays, where the implementation, software and algorithms to reach the required performance are crucial to show the actual performance.

5.5.2.7.4 Autonomous sensing, IoT, mobile applications: Energy consumption

Especially for internet of things, autonomous and mobile applications, energy consumption is key and needs to be addressed. A sensor can be very sensitive, selective, small and cheap, but if the energy consumption is too high, which will lead to higher system cost as larger batteries or other power supply strategies are needed, it is out of the game. For these remote applications, power supply should be below few milliwatt, the smaller the better.

5.5.2.8 Additional current weaknesses and challenges: Magnetic sensors

5.5.2.8.1 Economically feasible manufacturability unclear

The best performing hall sensors reaching a one to two orders of magnitude better sensitivity than Si-based hall sensors require perfect graphene sheets encapsulated in two-dimensional hBN. Also magnetic tunnel junctions make use of hBN. Thus, manufacturability is the biggest issue for those sensors to become commercially viable. Beside the graphene production, especially the production and integration with hBN is a large challenge, as 2D hBN is still at the exfoliation stage and can yet not be produced industry-compatible in sufficient quality. But also the mass production-compatible quality of graphene is currently not good enough to reach the needed performance level. Further critical issues are graphene contacting, delamination of the stacks and reproducibility. Therefore, integration and manufacturability with CMOS compatible processes is a must to reach relevant markets (see 5.2 Electronics: Cross-cutting issues for further information on wafer scale integration).

Similar issues apply for flexible hall sensors, however, here the performance requirements are essentially lower and similar performance as Si-based sensors could be sufficient. On the other hand, the cost constraints are equally high and therefore a mass production method is needed.

5.5.2.8.2 Maturity: only lab scale experimental level at the moment

The realized impressive performance of graphene-based hall sensors has only been achieved on experimental laboratory level with manual preparation at the moment.

5.5.2.9 Additional current weaknesses and challenges: pressure sensors/microphones/NEMS

5.5.2.9.1 Manufacturability challenging and some intrinsic properties not convincing

The piezoresistive gauge factor k of graphene is only 2-4, which is not disruptive and rather low. But the elongation per force much is higher than for other materials, such as silicon, which can eventually lead to a better sensitivity per unit area.

Prototypes are currently made manually, but integration is needed for a commercialisation. As a free-standing graphene/multilayer graphene membrane on wafer, wafer scale integration is a must, in best case using standard MEMS equipment. Reliability and reproducibility investigations are additionally needed to clearly address the benchmark with existing solutions.

For some pressure sensors in form of touch sensors, especially printed ones, wafer scale integration is not a must but could be beneficial.

5.5.2.9.2 Mechanical/thermal stability unclear

The performance improvement has not been shown for all relevant parameters (e.g. thermal stability, reliability). So for a fair and complete benchmark, the actually realized mechanical/thermal stability of the membrane needs to be proven.

5.5.2.10 Additional current weaknesses and challenges: Nanogenerators

5.5.2.10.1 Maturity and unclear cost

The maturity of graphene-based nanogenerators is low compared to other materials under investigation. Cost/performance advantage towards other materials are not yet clear. In order to get a better assessment, the devices need to be further developed and tested and benchmarked with competing technologies.

5.5.2.11 Additional current weaknesses and challenges: chemical/gas sensors

5.5.2.11.1 Proof in relevant environments needed: Unclear long term performance/lifetime/stability

Laboratory prototypes are promising, but the functionality and working in different real systems needs to be proven. Besides sensitivity, the value for customer lies in longer periods of good performance of graphene-based sensors, as compared to conventional sensors, and thus lower costs per sensor life-time. This is especially the case if graphene-based sensors are more costly in the beginning. Thus it is very important to address KPIs such as stability and life cycle, by proving longer periods (this has not been done yet). For currently investigated graphene-based sensors, the critical factor therefore is not sensitivity, but good performance over long time periods (> 2yrs). Some even doubt, whether graphene can hold up to the promises of better stability and longer life cycle, as problems of aging/degradation have not been addressed or solved yet. The promises of longer lasting sensors will only be believed, if they are experimentally proven under realistic conditions, which is still unclear at the moment. An important aspect in this respect is that the sensors last longer without maintenance. This leads to a needed general prove of the quality and variability. If a proof succeeds, it can easily be turned into a strength for graphene-based gas sensors.

It is very important to address the full set of gas sensor KPIs, because performance is not only defined by sensitivity, but by the full set of KPIs. This also allows a fair and realistic benchmarking with other technologies, an important prerequisite for companies to consider a new technology.

5.5.2.11.2 Selectivity is a key challenge and needs to be solved: functionalization and surface chemistry

Selectivity to the target analyte is a key property of gas sensors. Depending on the analyte, there is a lack of recognition in graphene based sensor, which calls for functionalization. However functionalization also influences the graphene electrode or FET itself and can as such have an effect on the sensitivity. There is a trade off and optimal balance between loading of the recognition element and sensitivity (similar issues are true for biosensors). The functionalization can be key, although the potential selectivity through functionalization in some cases is not enough. It is therefore of crucial importance to further investigate different functionalization. This includes following challenges:

- Surface chemistry: the surface chemistry needs to be effective, simple and not too aggressive to affect the 2D material performance too much
- Functionalization needs to be stable to allow stability and long lifecycles, this is today still a huge challenge

- The functionalization needs to be compatible with resetting of sensors, the latter being an important issue. Also resistance to contamination should be possible to a certain extent, which depends on the application.

If specificity/functionality to one gas is solved regarding the above mentioned issues, the knowledge can be transferred to other gases and the material gets closer to being a gas sensing platform technology. Please also refer to the assessments of biosensors in this chapter, as bio recognition elements can also be used to functionalize for gas sensing. [570]

5.5.2.11.3 Manufacturability to a certain extent unclear (wafer scale, LPE/rGO reproducibility)

Wafer scale integration is necessary for higher performing sensors (see 5.2 Electronics: Cross-cutting issues for further assessments of wafer scale integration). If this integration scheme works economically feasible, cost competition could become possible. If not, rather high production costs can only be justified if the performance (sensitivity, selectivity, life cycle, stability, size) is significantly improved over competing sensors.

For the simpler preparation of lower performing sensors with LPE and rGO, reproducibility is a major obstacle for the sensors.

5.5.2.11.4 Unclear environment, health and safety barrier for some applications

As for all other nanotechnology-based sensors, the environmental, health and safety of the nano-sized layer is a matter of concern, in particular for applications in the food or medical sector. These concerns need to be actively addressed if such an application is pursued and it should be clear that this pushes the time frame or can be a killer argument against the use in these areas.

5.5.2.12 Additional current weaknesses and challenges: biosensors

5.5.2.12.1 Address the full set of KPIs

The full set of relevant performance parameters, such as sensitivity, selectivity, cost, stability, reliability, cycle time, waste management, etc., all are important aspects for a biosensor to be competitive in a certain application area. For a realistic comparison with competing technologies, the full set of relevant KPIs for an application needs to be addressed in relevant environments. Similar arguments as for gas sensors in 5.5.2.11.1 Proof in relevant environments needed: Unclear long term performance/lifetime/stability apply.

5.5.2.12.2 Challenge of device stability and contacting

Besides the optimisation of the sensitivity, e.g. through contact optimisation, device stability and cycle times are still key challenges for biosensors based on 2D materials. Furthermore, contamination in operation and how to dealt with it need to be addressed. The latter depends of course on the targeted application.

5.5.2.12.3 Challenge of reliable and economically feasible functionalization by surface chemistry

Label-free biosensing with graphene or other 2D materials heavily depends on the functionalization, in case of biosensors with a bio recognition element. Challenges are essentially comparable to the field of overall gas sensors, see 5.5.2.11.2 Selectivity is a key challenge and needs to be solved.

For biosensors, especially the optimisation of selectivity for different analytes is required, e.g. by selection/optimisation of the biocomponent as well as targeted and controlled coupling of the biocomponent to the graphene/GO surface by surface chemistry.

Most importantly, the trade off between covalent functionalization (right binding site, loading) and the properties of graphene (conductivity etc.) needs to be investigated and understood. The graphene/2D materials' properties are influenced by the binding sites and biocomponent. For optimal selectivity and sensitivity, a balance/optimal point between the number of binding sites, i.e. the loading, and the properties of graphene (e.g. in a GFET) needs to be found.

Furthermore, there is a large variety of recognition elements possible [570], and it needs to be investigated which ones are feasible for use with graphene or whether there are even recognition elements that are of particular enabling character for graphene or vice versa.

Further challenges are related to the surface chemistry, which is often quite aggressive using for instance plasma, electrochemical oxidation, hydroxylation, silanization. Different types of binding need to be investigated, such as covalen/non-covalent, also looking at the orientation of the recognition element. For antibodies, this orientation is important. And a blocking chemistry is needed to avoid becoming unselective. Often, many steps are needed for functionalization and it should be a major goal to make it as efficient and simple as possible.

5.5.2.12.4 Adequate and tailored graphene quality

The needed graphene quality differs from application to application. It is most important to be able to provide the same quality in a reliable and continuous way. Defects or dangling bonds need to be controlled, as they can provide binding sites for recognition elements. Especially for GFET based high sensitivity (flexible) solutions, high quality SLG or FLG is needed and the quality is critical (need wafer scale integration, high quality transfer). For rGO or graphene flake based sensors it is also important to have an adequate, continuous and homogeneous quality from batch to batch.

Further specific production processes are required to apply the surface chemistry and functionalization with the bio recognitions elements.

5.5.2.12.5 Targeted developments according to best business case needed

The field of biosensors is very broad and many opportunities exist. However, to date it is unclear for which analytes/biosensors the specific features of graphene-based biosensors really provide an advantage over competing products. After broader screening of possibilities, a very careful choice of analytes and application scenarios is required to focus on the areas with highest relevance and added value.

5.5.3 KPIs for sensors

5.5.3.1 General KPIs relevant for all sensors

Mobile applications: <€2, < 5 mW, < 3.0 V, 2 year life, package in the lower mm range.

Table 58: Typical prices per unit for different sensor types. [551, 552]

Sensor Type	Price per unit	Trends
Pressure sensors	$49 to $195	▼
Temperature sensors	$59 to $350	▼
Humidity sensors	$25 to $250	▼
CO/VOC sensors	$240 to $310	•
Flow sensors	$15 to $300	▼
Strain gauge Sensors	$25 to $450	•
Vibration Sensors	$20 to $390	▼
Corrosion Sensors	$30 to $340	•
Image sensors	$17 to $230	•
Combined Sensors	$45 and Up	▲

Acoustic sensors	$3.6 to $4.5	
RFID reader and tags	$1 to $50	
Motion sensors	$4 to $35	
Obstacle sensors	$1.5 to $9	
Particle sensors	$28 to $35	
HVAC	$25 to $100	
Air quality sensors	$10 to $175	
Proximity sensors	$1.5 to $8	
Energy meters	$20 to $40	

5.5.3.2 Hall sensors for magnetic field sensing

Table 59: Comparison of KPIs of competing technologies and hall sensors based on graphene, adapted from [530] and supplemented with other sources and research

	S_I (V/AT)	S_V (V/VT)	B_{min} w ($pT/\sqrt{Hz} \cdot mm$)	Freq. (kHz)	Remarks
Si	100-200	0.1	1500	3	2W for Sensitivity 10mV/mT, 20-50ct per piece; temperature range: -40 ... 110°C (typical)
GaAs	1100	NA	8000	3	
InAsSb	2750	NA	50	1	(few $ per piece)
InSb	1250	3.8			~4$, values roughly estimated from data sheet; temperature range: -40 ... 110°C (typical) [571]
NiFe Thin film AMR		20			10mT saturation field [572]

GMR		200	<10 (not normalized to contact) @1Hz	~1-10	[573], operating temperature typical: -25 ... 85°C; price ~5-50$
Graphene	2093	0.35	5000	3	in air
Gr-hBN	4100	2.6	150	3	in vacuum (1 sample)
Gr-hBN	4000-6000	~3	NA	NA	in air (2 samples)

5.5.3.3 Pressure sensors/microphone and NEMS

Microphones: high Signal-to-noise ratio (SNR), high sensitivity

Table 60: ST Microelectronics MEMS microphone KPIs. [574]

Parameter	MP45DT02	MP34DB01	MP34DT01	MP33 AB01	MP33 AB01 H
Sensitivity	-26 dBFS			-38 dBV	
Directivity	Omnidirectional				
SNR /dB	61	62.5	63	63	66
AOP /dB	120	120	120	125	125
EIN /dB	33	31.5	31	31	28
THD+N	<5% @115dB			<5% @120dB	
PSR	-70 dBFS			-75 dBV	
Maximum current consumption /µA	650	600	600	250	250
Package dimensions /mm	4.72x3.76x1.25	3x4x1	3x4x1	3.76x2.95x1	
Port location	Top	Bottom	Top	Bottom	Bottom
Operating temperature	-40°C<T<+85°C	-30°C<T<85°C	-30°C<T<70°C	-30°C<T<100°C	
Price range	~<1$				

Pressure sensors

ST MEMS: Current consumption: 0.5-1µA (for 260-1260hPa), 25µA for high precision (1Pa RMS), price ~2-3$.

Bosch BMP180 MEMS piezoresistive pressure sensor, incl. readout IC and package, size: 3.6 x 3.8 x 0.93 mm3, time/pt: 5 ms, RMS noise: 2 Pa.

Table 61: ITRS 2013 goals for 2017 MEMS microphones. [399]

Signal-to-noise ratio @1 kHz	70 dB(A)
Frequency response	0.02-20 kHz
Current consumption (1.5-3.6V)	100 µA
Package size (L*W*H)	2 x 3 x 1 mm^3

5.5.3.4 Nanogenerators

Micro energy harvester (thermoelectrical, vibrational, etc.); very low cost needed for IoT and mobile applications ~1$ with reasonable output power and efficiency

The average price per unit currently is 8.13$ and falling [553]

5.5.3.5 Gas/chemical sensors

Table 62: KPIs for chemical/gas sensors [539, 575] supplemented with additional information.

Specification	Description
Sensitivity S	Change in the measurement signal per concentration unit of the analyte, i.e. the slope of a calibration graph, e.g. nA/ppb or µV/ppm.
Detection Limit (LOD)	The lowest concentration value which can be detected by the sensor in question, under definite conditions. Whether or not the analyte can be quantified at the detection limit is not determined. Procedures for evaluation of the detection limit depend on the kind of sensor considered. It can for instance be the concentration of target gas that gives a signal greater than three times the standard deviation of the noise level. Detection limits are depending on application usually in the ppb to ppm area. For instance for CO_2 100-1000ppm are often sufficicient, other analytes demand 100 ppb or less.

Specification	Description
Dynamic range	The concentration range between the detection limit and the upper limiting concentration.
Selectivity	An expression of whether a sensor responds selectively to a group of analytes or even specifically to a single analyte. Quantitative expressions of selectivity exist for different types of sensors. It can for instance be the ratio of response to the target gas (Sc) and response to the disturbed gas (Si). D=Sc/Si
Linearity	The relative deviation of an experimentally determined calibration graph from an ideal straight line. Usually values for linearity are specified for a definite concentration range
Resolution	The lowest concentration difference which can be distinguished when the composition is varied continuously. This parameter is important chiefly for detectors in flowing streams.
Response time T_{res}	The time for a sensor to respond from zero concentration to a step change in concentration. Usually specified as the time to rise to a definite ratio of the final value. Thus, e.g. the value of T_{99} represents the time necessary to reach 99 percent of the full-scale output. The time which has elapsed until 63 percent of the final value is reached is called the time constant.
Recovery time T_{rec}	If the sensor is resettable, which is usually desired, it is the time it takes for the sensor signal to return to its initial value after a step concentration change from a certain value to zero.
Hysteresis	The maximum difference in output when the value is approached with (a) an increasing and (b) a decreasing analyte concentration range. It is given as a percentage of full-scale output.
Stability	The ability of the sensor to maintain its performance for a certain period of time. As a measure of stability, drift values are used, e.g. the signal variation for zero concentration. The stability can depend on temperature (which can be corrected). For a good and maintenance free sensor, the stability should be on the order of the life cycle.
Life cycle	The length of time over which the sensor will operate. The maximum storage time (shelf life) must be distinguished from the maximum operating life. The latter can be specified either for continuous operation or for repeated on-off cycles. The operating life cycle for consumer should be 2 years, for automotive 15 years and for domotics somewhere in between.

Specification	Description
Peak power consumption	Maximum power consumption during measurement (especially when a heater or light source is involved)
Average power consumption	Average power consumption in a regular duty cycle (meaningful for the targeted applications
Operating conditions	Conditions for which the sensor is specified (e.g. temperature range, humidity) under operation
Package size	Size of the packaged sensor
End-of-life	For some sensors the end-of-life properties are interesting, e.g. is it disposable, combustible, degradable…

Competing technologies: CNT, MOX (metal oxides); MOX sensors are a good benchmark (in terms of cost/performance)

Table 63: Values of an ananlogue MOX CMOS sensor. Calculated from [576].

Specification	Value
CCS801 (Ethanol, CO, Toluene)	
Sensitivity / 10^{-3}(R_{air}/$R_{analyte}$)/ppm)	13 (ethanol); 4.4 (CO); 3.7 (toluene)
Detection limit	<20ppm
Response Time	~15 ms
Peak Power Consumption	33 mW
Average Power Consumption	0.9 mW (pulsed mode, duty cycle of 2.5% on-time)
Recommended operating conditions	-5 – 50°C; 15 – 85%RH (non-condensing)
Lifetime (operating)	>5 years
Package	2 x 3 x 1 mm^3
Price (end user)	~5-7$ (pre production series)

KPI of other competing emerging sensor technologies can be found here: [540]

5.5.3.6 Biosensors

Essentially, similar KPIs are applied as in gas/chemical sensors (see Table 62). Read-out time and long-term stability are key parameters usually not too good for biosensors.

Table 64: The price of biosensor devices varies from $10 in volume applications to $1,000 in some high-end applications. This table gives a few examples. [557]

Device	Typical price
handheld diabetes detector, glucose biosensor	<10$
food pathogen analysis system	10,000$ – >100,000$
E.coli testing biosensor	>150$
SARS detection biosensor	>250$
Devices for home diagnostic applications	<10$

IVD/lab on chip requirements:

- CE or FDA approval
- Coefficients of Variation 1-5%
- sensitivity, specificity, system control
- 5-6 minutes time to results (TTR)
- Sensitivity, specificity
- Immuno-chemistry
- < 1 USD piece price
- High volume manufacture
- Room temperature stability > 1 year

Table 65: POCT vs. laboratory typical turnaround times for some key tests. [558]

Test	Laboratory turnaround time	POCT turnaround time
Urinalysis	40 min	4 min
Pregnancy	78 min	5 min
Blood glucose	10 min	6 min
Cardiac	110 min	17 min

Table 66: Typical cost of key tests (laboratory vs. POCT). [558]

Test	Centralised Laboratory ($)	POCT ($)
Blood glucose	3.5	11.5
HbA1C	3.3	6.0
Blood gas and electro-lytes	45.0	9.5
Chemistry tests	14-16	20

5.5.4 Roadmap for Sensors

5.5.4.1 Current maturity: Mostly at laboratory level

Most graphene or 2D material based sensors are still in the laboratory stage, either due to missing manufacturing technologies or due to immature prototypes.

In magnetic hall sensors graphene has already shown to be better in terms of sensitivity and power consumption by a factor of 100 compared to silicon. But this was realised with a hand-made BN-G-BN stack. So here, the manufacturing is limiting increased TRL levels. Experts think that it will take at least another 5-10 years until reasonable processes are available due to the currnet lack of large scale wafer based and transfer free synthesis, especially of BN, but also of high enough quality graphene.

Pressure sensor and force sensors are at the level of applied research. Graphene-based NEMS provide interesting opportunities but currently suffer from the missing integration scheme and reproducibility. Flexible strain and force sensors are easier to integrate and can be based on flakes/rGO and are demonstrated in functional prototypes (see also 5.6 Flexible and/or printed electronics).

Nanogenerators at the basic research level, mostly at quite early stages. First of all, the most promising type, the triboelectric nanogenerator (TENG) in general is still rather immature compared to other types. Second, the graphene-based TENG is still in its infancy. Other nanogenerators (e.g. generating energy from humidity and movement) are promising also at basic research stage.

Gas sensors are at the level of basic research. Demonstrations of potentially low cost disposable graphene-based gas sensors exist but they are still far away from consumer products (e.g. for smartphones). Lab scale gas sensors show good/better performance than state of the art, but not with respect to reliability and stability. Most applications are in the lab stage and performance needs to be shown and benchmarked, as well as stability, long term behaviour addressed. An important issue is the selectivity of the gas sensor to the targeted gases.

GFET based biosensors are available on lab scale. A major challenge is selectivity, whereas the sensitivity is already good. A benefit is that biosensing selectivity can rely on biorecognition, e.g. with aptamers or antibodies, which is extremely specific and broadly available. Furthermore, manufacturability is an issue and depends in wafer scale integration for most biosensor GFETs. Additionally, functionalization and surface chemistry is important. Other sensor concepts (e.g. electrochemical) are also on lab scale. There are already first companies currently commercializing the technology, e.g. Nanomedical Diagnostics in the US. [577] Some printed electrochemical sensors are already marketed, where graphene is used as a screen printed electrode for a sensor platform (DropSense). These electrodes are to date not functionalized and provide no selectivity, but a high surface area.

Electrical implants and body electrodes are in the laboratory to applied research stage.

5.5.4.2 Barriers/challenges (summarized)

Consumer markets:

- 10x better performance (sensitivity, power consumption) and/or 10x lower cost

Health market

- CE, FDA approval
- Reimbursement
- “cultural” barrier: paradigm shift towards prevention needed to drive POCT and biosensors

General:

- Lifetime and reliability expectations, long term stability, maintenance free
- Fragmented market and interoperability
- Focus on the right opportunities: too many different sensing types and functionalization possible so that a clear vision is hard to achieve which markets can be addressed
- Often unclear what is best for which application: single layer, double layer, few layer, doping, contact points, how they are applied
- Missing full set of KPIs (especially in terms of durability, life cycle, stability, power consumption) for most lab sensors prohibits realistic potential assessment: There is no actual market pull
- Missing demonstration in relevant environments to prove claimed benefits (also as full demonstrators with readout and data analysis)
- Unclear environmental, health and safety properties and end of life (can the promises be experimentally verified?)
- Manufacturability (wafer scale and/or printed) of devices; most sensors need wafer scale integration for mass market applications as it delivers read-out and electrical functionality; 200-300mm wafer needed with decent graphene quality (see 5.2 Electronics: Cross-cutting issues)

- SiC based graphene: most things are known, but expensive; 3” quite uniform (99.9% coverage), 6” also possible; price has gone down ½ in 2015, but is still too high to be competitive in most applications

Magnetic sensors

- Manufacturing of high enough quality graphene and hBN (wafer scale) unclear (especially for economic feasibility assessment)
- Low cost and high volume markets with many incumbent technologies
- Low maturity of 2D materials based magnetic tunnel junctions for sensing

Pressure sensors/microphones/NEMS

- Many mature technologies, unclear benefit (besides probably higher wavelength range)
- Unclear whether higher sensitivity is needed
- NEMS in general: wafer scale integration, especially for controlled multilayer membranes
- Low k-value needs to be compensated by large elongation per force
- Unclear mechanical and thermal stability

Nanogenerators

- Low cost necessary for low power energy harvesters (IoT, autonomous systems)
- Competing technologies are more mature
- Unclear cost and low maturity

Chemical/gas sensors

- Manufacturability: Reliable large scale production of GFET by wafer scale or reproducible LPE/rGO with adequate quality (depending on application and needed quality)
- contacting
- Missing proof of longer stability and life cycles (together with full set of KPIs)
- Missing proof in relevant environments of targeted applications
- Functionalization for selectivity/specificity and sensitivity is a key challenge: Finding a reliable binding site on graphene and the right one and the right amount without compromising the graphene properties
- Surface chemistry (reliable and economically feasible)
- Trade-off between functionalization/load and graphene properties: where is the optimal point for each recognition element?

Biosensors

- The same barriers/challenges as for chemical/gas sensors apply, besides the fact that selectivity is more straight forward due to the use of biorecognition elements
- High diversity of potential applications, hard to decide where to focus
- Biological recognition elements’ large variety, long development times and cost
- Surface chemistry to functionalize graphene with bio elements and to achieve optimal loading (trade-off); different recognition elements demand different chemistries
- Specificity, coefficient of variation of measurements
- Cost
- GFET sensors (high performance): wafer scale integration, others are possible without wafer scale integration (pick&place on fluidics and polymers reaches fM sensitivity with non-top quality graphene)
- Flakes/GO based sensors: reproducibility, adequate and continuous quality
- Noise due to liquid environment and biological media

- Body electrodes: graphene properties not good for stimulation.

5.5.4.3 Potential actions

If the area of graphene/2D in sensors is seen as promising for Europe and the topic is further pushed, the following potential actions, derived from the challenges, are suggested:

General:

- Build on SiC for particular applications (where current prices are acceptable or SiC can be used anyway as a substrate)
- Be honest with deficiencies, so that those can be addressed
- Carefully assess potential of graphene/2D materials in sensors and European economy on a more detailed level to find most promising applications
- Investigate long term properties, life cycles and stability of graphene/2D materials in sensors
- Determine full set of relevant KPIs (and not only e.g. sensitivity) to allow realistic and objective benchmarking with other technologies addressing the same functionality
- Demonstrate the sensors' functionality in relevant environments to create awareness of actual functionality
- Assess environment, health and safety properties for relevant applications (e.g. if food sensing or health is targeted)
- Investigate end-of-life properties if necessary for an application
- When developing demonstrators, keep manufacturability in mind (especially when addressing sensors that have already been demonstrated)

Magnetic sensors:

- Focus on manufacturing of hBN-graphene-hBN stacks
- Further investigate flexible solutions

Pressure sensors/microphones/NEMS

- Investigate multi-layer membrane manufacturing
- Investigate mechanical and thermal stability
- Benchmark with existing technologies, also for ultrasound applications

Nanogenerators

- Further explore tribological nanogenerators and other new types of nanogenerators (increase readiness level, demonstrate), keeping manufacturability in mind
- Benchmark with other technologies harvesting the same type of energy on the same scale to elaborate USPs

Chemical/gas sensors

- Show and investigate functionalization/surface chemistry for GFET and electrochemical sensors (manufacturing compatible): reliable binding sites needed (whilst keeping the graphene properties), find optimal trade-off between loading and functionality
- elaborate "toolbox" for functionalization
- Address specificity
- Improve contacting

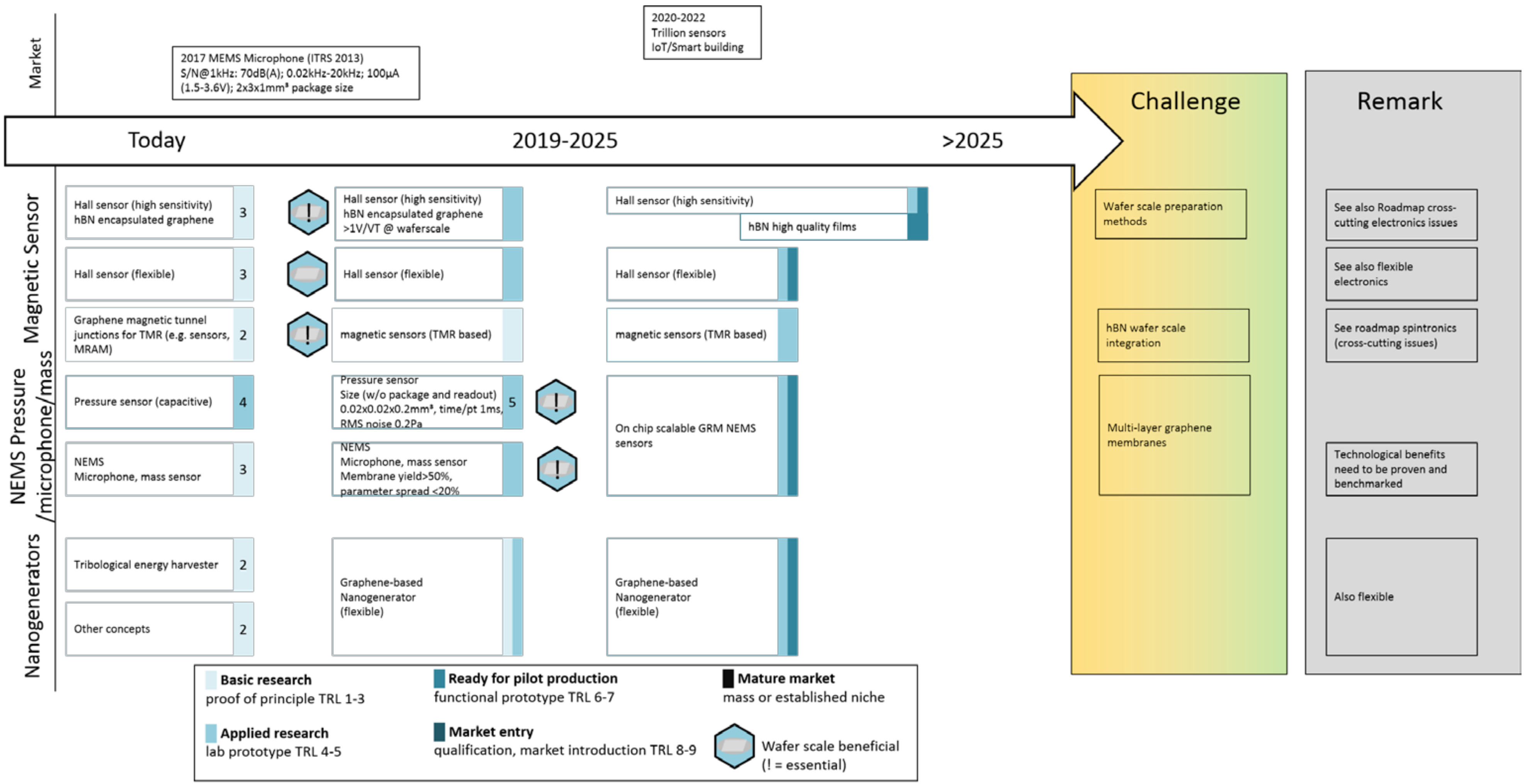
- Investigate stability and long term performance (longer lifetime could outweigh higher cost)
- Demonstrate in relevant environments with full set of relevant KPIs and benchmark with other (existing and emerging) technologies addressing the same application and analyte (e.g. MOX sensors, other nanostructured sensors)
- Benchmark results with MOX sensors and other existing technologies
- Investigate multi-gas sensing capabilities/multiple sensor arrays
- Printed could also be a solution for lower price/lower sensitivity (gas/chemical/bio)
- chemistries need to be combined, calibration and safety issues cleared

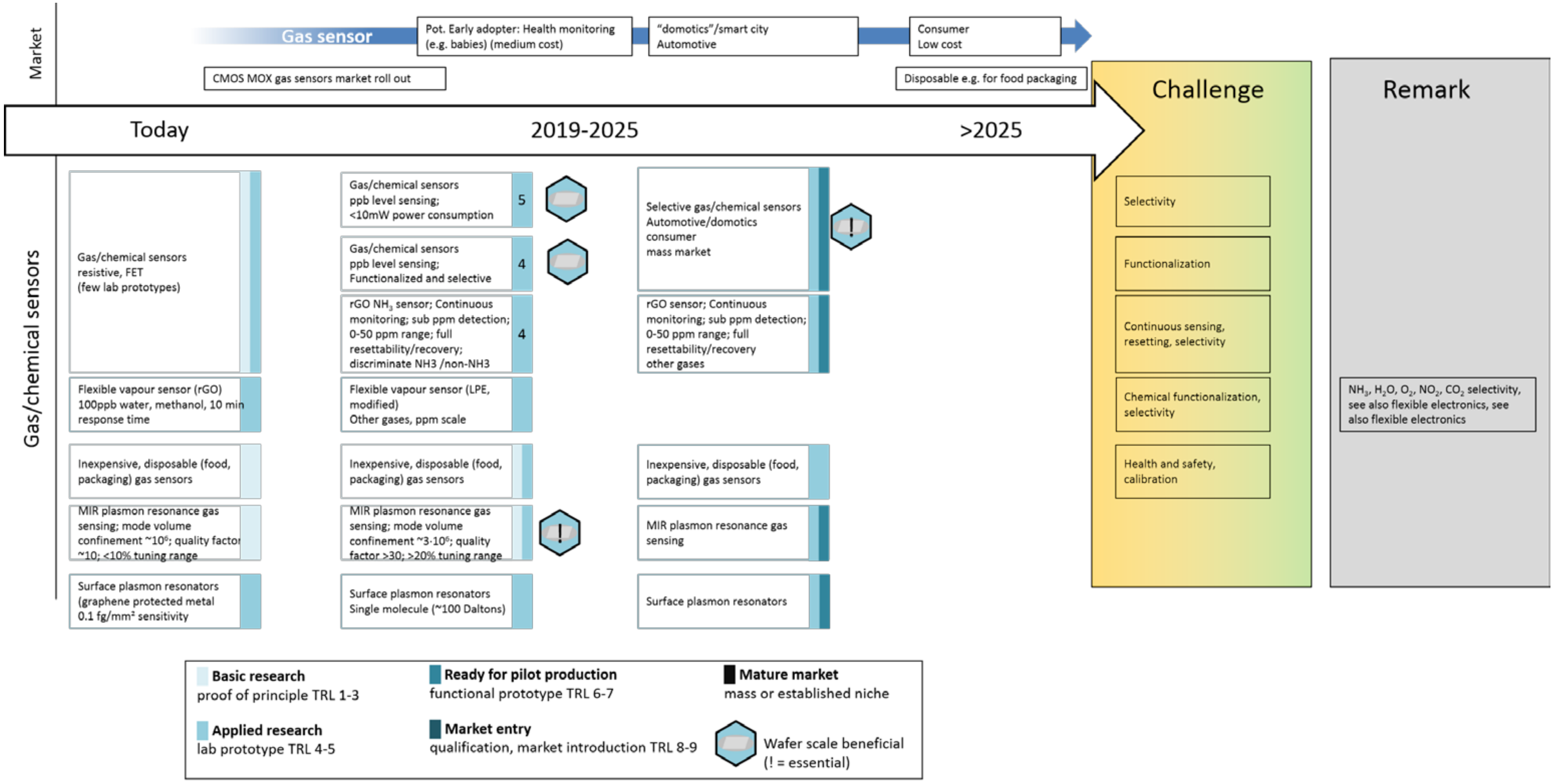
Biosensors

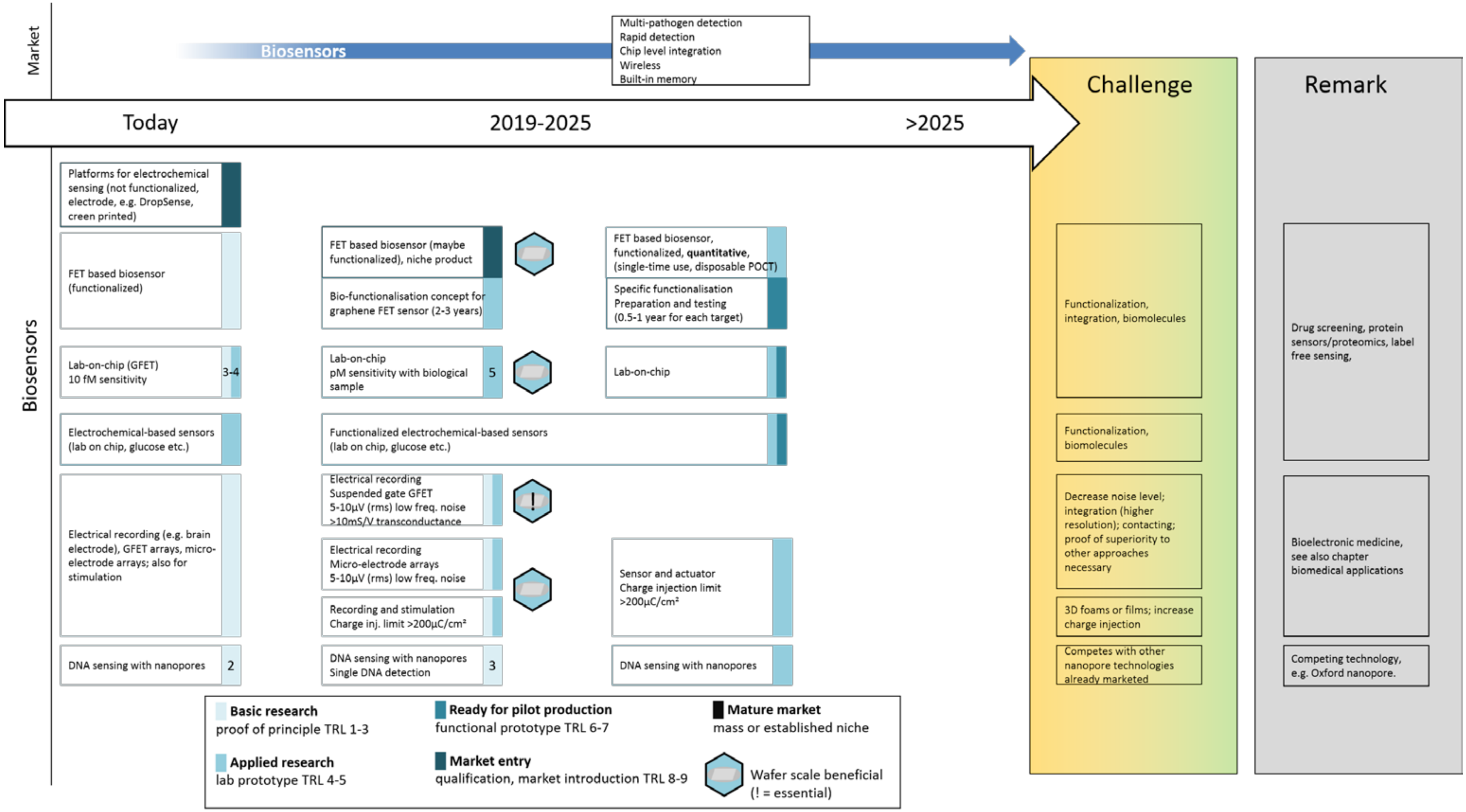
- Potential actions from gas/chemical sensors also apply for biosensors, with the differenc that biorecognition elements can be used
- Explore platform character of graphene for biosensors (toolbox of bio-elements)
- Demonstrate functionality on one promising analyte before screening too many
- Focus and benchmark with existing sensors (existing recognition elements) to proof the high performance and avoid additional costs; practically the same bioreceptors can be applied in all biosensor schemes, thus whatever is earlier developed, can be transferred to graphene when the platform is ready.
- Bioanalytics: At the present stage with a multiplicity of options for the use of graphene/GO in biosensing, it is important to focus on promising fields. Therefore it is recommended to use the already existing broad industrial basis in bioanalysis. Scientist should engage in a dialog with enterprises to get information in which areas there is a high demand for effective bioanalysis

Determine full set of relevant KPIs for targeted application and benchmark with other technologies addressing the same functionality

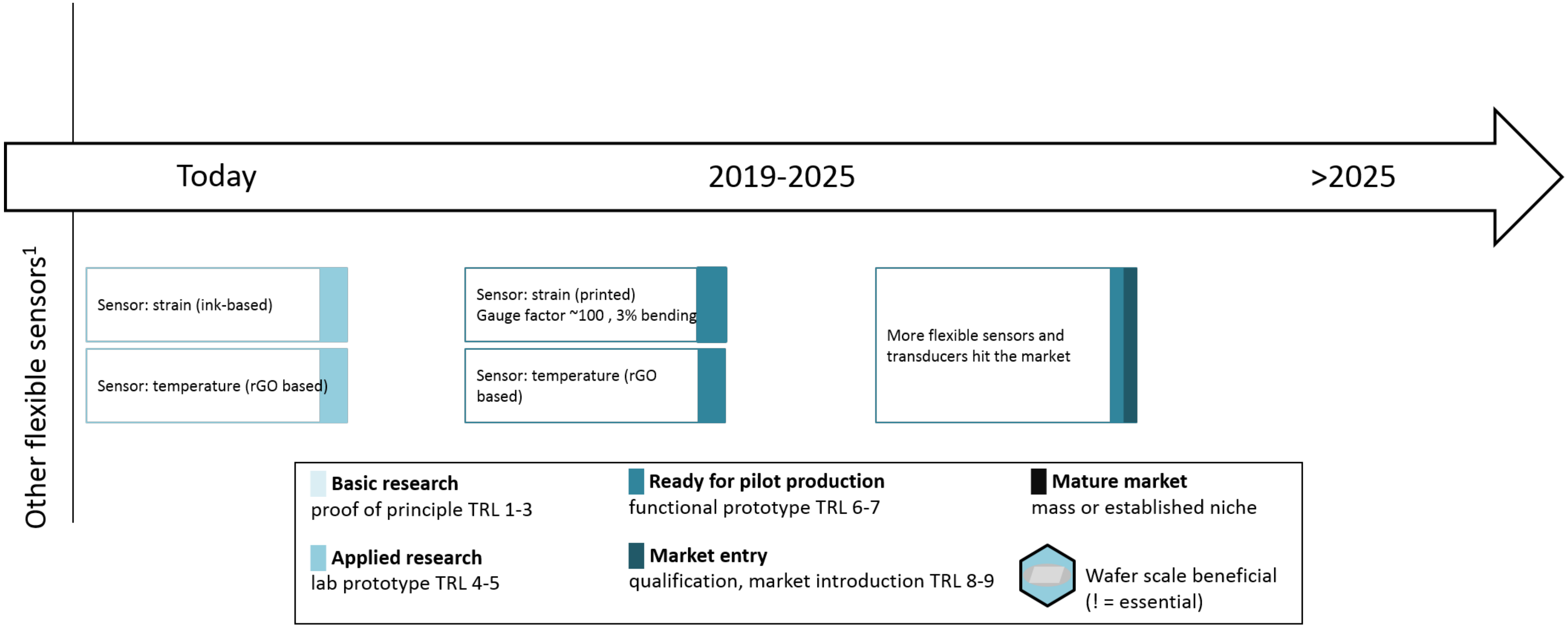
5.5.4.4 Roadmap




Market
Gas sensor
Pot. Early adopter: Health monitoring (e.g. babies) (medium cost)
"domotics"/smart city
Automotive
Consumer
Low cost
CMOS MOX gas sensors market roll out
Disposable e.g. for food packaging
Today
2019-2025
>2025
Challenge
Remark
Gas/chemical sensors
Gas/chemical sensors resistive, FET (few lab prototypes)
Flexible vapour sensor (rGO) 100ppb water, methanol, 10 min response time
Inexpensive, disposable (food, packaging) gas sensors
MIR plasmon resonance gas sensing; mode volume confinement ~10⁶; quality factor ~10; <10% tuning range
Surface plasmon resonators (graphene protected metal 0.1 fg/mm² sensitivity
Gas/chemical sensors ppb level sensing; <10mW power consumption
5
Gas/chemical sensors ppb level sensing; Functionalized and selective
4
rGO NH3 sensor; Continuous monitoring; sub ppm detection; 0-50 ppm range; full resettability/recovery; discriminate NH3 /non-NH3
4
Flexible vapour sensor (LPE, modified) Other gases, ppm scale
Inexpensive, disposable (food, packaging) gas sensors
MIR plasmon resonance gas sensing; mode volume confinement ~3·10⁶; quality factor >30; >20% tuning range
Surface plasmon resonators Single molecule (~100 Daltons)
Selective gas/chemical sensors Automotive/domotics consumer mass market
rGO sensor; Continuous monitoring; sub ppm detection; 0-50 ppm range; full resettability/recovery other gases
Inexpensive, disposable (food, packaging) gas sensors
MIR plasmon resonance gas sensing
Surface plasmon resonators
Selectivity
Functionalization
Continuous sensing, resetting, selectivity
Chemical functionalization, selectivity
Health and safety, calibration
NH3, H2O, O2, NO2, CO2 selectivity, see also flexible electronics, see also flexible electronics
Basic research
proof of principle TRL 1-3
Applied research
lab prototype TRL 4-5
Ready for pilot production
functional prototype TRL 6-7
Market entry
qualification, market introduction TRL 8-9
Mature market
mass or established niche
Wafer scale beneficial
(! = essential)



See also biomedical applications and flexible electronics. Source for market: [425]



[1]: see also flexible electronics chapter

5.5.5 Conclusion sensors

The application area of sensors is a diverse field with many potential end user sectors. The integrated sensors market in general grows above average due to drivers like internet of things, industry 4.0, mobile electronics (wearables, health) or autonomous driving. All these trends demand new kinds of integrated emerging sensors or improvement and miniaturization of existing solutions. The market and potential technology integrators are very granulated, which on the one hand creates opportunities for niche applications and early market entry, but on the other hand creates difficulties in finding the applications where graphene and 2D materials actually can have a strong benefit. Besides, there are also important industrial players for sensors in Europe.

Graphene and other 2D materials can be used in different conformations in sensors, ranging from (r)GO or flakes to high quality films. The technological barrier is for sure lowest for flake-based technologies (e.g. strain sensors, some electrochemical sensors) compared to high quality films which usually require wafer scale integration and/or embedding in other materials (e.g. 2D boron nitride in the case of magnetic hall sensors). Due to the high fragmentation of the market, sensors is an interesting field for early commercialization. There are already first graphene-based sensors approaching the market in niche areas. However, other materials and technological approaches are also advancing, so that the overall competition of technologies is high and the USP towards these competitors or state of the art technologies needs to be clearly and objectively elaborated. In summary, the technological potential for 2D materials in sensors is there, although issues such as functionalization or production need to be resolved and the actual potential needs to be shown with commercially feasible production methods and in relevant environments.

Table 67: Assessment of market and technological potential of graphene/2D materials use in sensors on a scale - -, -, 0, +, ++.

Sensors	**Current technological potential (USP)**	**Market potential (EU perspective)**
Pressure sensors/microphones/ NEMS	0/+	++
Magnetic sensors	++	+
Mechanical force/stress/strain/ mass sensors	0/+	+
Gas/chemical sensors	+	+
Biosensors	+	++
Nanogenerators/micro-energy harvesters	0/+?	+

5.6 Flexible and/or printed electronics

This area deals with flexible and printed electronics (sometimes also called wearable electronics or large area electronics). It is a cross-lying area with elements from the other applications areas but with a particular focus on unconventional flexible/conformable substrates. Besides pure flexibility, stretchability is also increasingly important as a USP towards other technologies. In this chapter we refer to stretchability separately and consider flexibility only as the possibility to bend/flex a device. However, the overall term “flexible electronics” is defined to contain also stretchable devices.

This area covers:

- CVD/vacuum deposition flexible electronics
  - Transparent conductive films and touch sensors
- printed electronics and conductive inks

Typical applications of flexible electronics in general are

- Flexible conductors and antennas (e.g. NFC, RFID), printed circuit boards, also electrodes for bioelectronic medicines
- transistors for flexible ICs
- Flexible memory applications (in particular flexible resistive memory, RERAM)
- Flexible sensors and transducers, e.g. mechanical force/stress/strain sensors but also all other types of sensors
- Flexible displays

Flexible batteries/supercapacitors (see also chapters 4.3 and 4.4, electronics cross-cutting electronics issues (5.2), telecommunication, optoelectronics and photonics (5.3), computing/logic (5.4) and sensors (5.5). This chapter treats only the flexible subset of the applications with a focus on the special opportunities, threats, strengths and weaknesses of graphene/2D materials when it comes to flexible electronics. This distinction is made because flexible electronics usually addresses different markets than rigid electronics and the requirements are also different. Of course it would be desirable to have flexible devices that compete with rigid devices in terms of performance. From a current technological perspective this is, however, wishful thinking and, if at all, a very rare case in the foreseeable future. Therefore flexible electronics will have an own market and will not compete with rigid CMOS electronics soon.

Uses of graphene and 2D materials in flexible electronics are summarized in Table 68.

In this chapter we will distinguish bulk graphene/2D-flake based (printed) electronics that can be used for antennas, conductors, as well as in sensors, and high quality graphene materials that can be used for sensors and logic and higher performing flexible electronics applications. This differentiation is especially important for the strengths and weaknesses.

Table 68: Uses of graphene/2D materials in flexible electronics

Application	Graphene/2D use	Recent review/ publication
Antennas (RFID, NFC), circuit boards, electrode	Flexible conductor, conductive ink, transparent conductive film	[578, 579]
Transistors	Channel material (e.g. GFET, TFT), electrode, for logic and RF transistors	[386, 580]
Memory	RERAM (resistive material as storage bit), carbon memory, tunnel memory	[581–583]
Sensors	Electrode for flexible electrochemical sensors, GFET, optical sensing elements, photodetectors, strain gauges, magnetic sensors, biosensors	[584]
Displays, OLEDs, photovoltaics	Transparent conductive film; PV is not addressed in this chapter but in chapter 4.4	[580, 585, 586]
Energy storage	Electrode material for flexible batteries/supercaps, nanogenerators	[587]

5.6.1 Market perspective: graphene/2D materials in flexible electronics

In 2014 products including flexible, organic and printed electronics with a value of $23-24 billion were sold with growth rates of more than 20%. The biggest product group are OLED displays, accounting for 2/3 of the revenues. The major pioneers in adopting flexible electronics technologies are automotive, consumer electronics/white goods, packaging/advertising and pharmaceutical and healthcare industries. More and more Flexible, lightweight and/or mobile products hit the market in these areas. [588] The market for printed and potentially printed electronics, including organics, inorganics and composites, will have grown to more than $26 billion in 2016 (see Figure 105) and is expected to extend to $69 billion in 2026. [20] The massive expectations from the early 2000s have not been met, but the technology is now approaching the plateau of enlightenment in the hype cycle and has become an actual growth industry, although it is still young. True mass markets only exist for OLED displays and healthcare applications right now. [20, 588] Besides displays, the largest markets are sensors and actuators, mostly healthcare electrodes, glucose strips, and conductive inks, mostly inorganic materials, all printed. [20]. However, flexible/conformal electronics still have a much smaller market of less than $10 billion (Figure 106) and printed electronics add up to $9.3 billion (Figure 107).

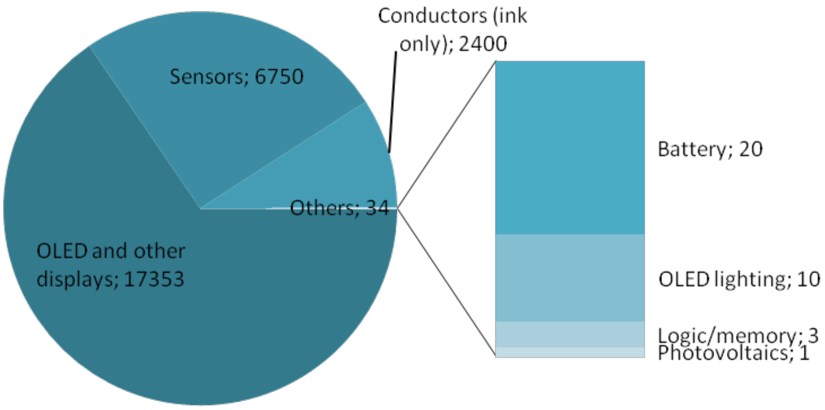


Figure 105: Flexible, printed and organic electronics markets by application, expected sales of products integrating the technology in million US$ in 2016. [20]

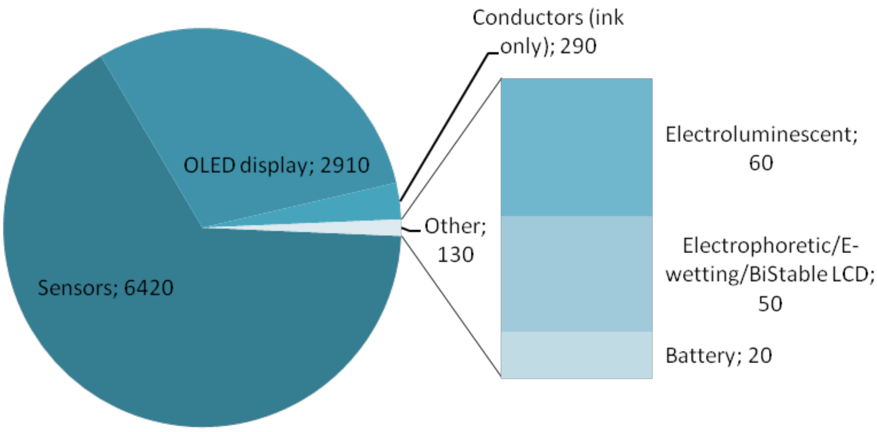


Figure 106: Flexible electronics markets by application, expected sales of products integrating the technology in million US$ in 2016. [20]

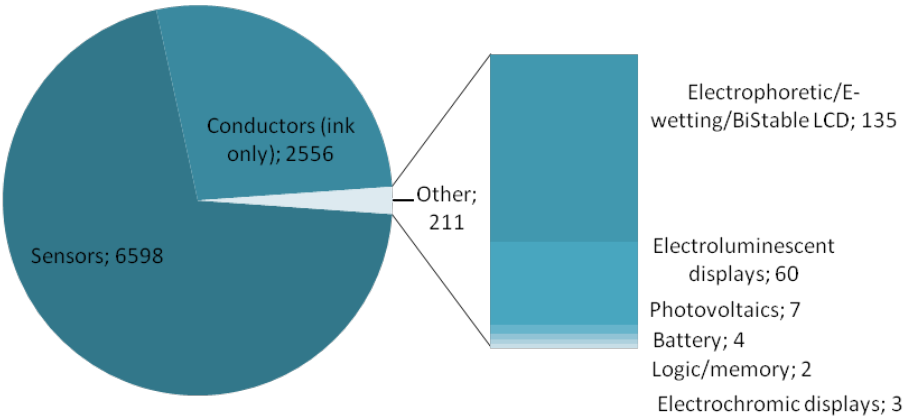


Figure 107: Printed electronics markets by application, expected sales of products integrating the technology in million US$ in 2016. [20]

Conductive inks

The conductive inks and pastes based products market is a multi-billion dollar market ($1.5-3.5 billion in 2016, depending on definition and source) expected to grow at a CAGR of 3-5% in the next decade. [20, 589–591].

The market is dominated by metal pastes, especially silver. Nanoparticulate pastes are approaching the market and become increasingly competitive, but will only get a small market share in the next 5-10 years. Largest applications are PV bars and automotive (e.g. window heater) and RFID. Antenna printing for mobile phones is increasingly interesting, i.e. 3D shape printing for better form factors. [590]

Transparent conductive films (flexible)

The market is expected to reach $1.2bn in 2025 at film level (for intermediate products, not including ITO on glass). It is dominated by ITO, but emerging solutions like silver nanowires (expectation $126m in 2025) and metal mesh (expectation $191m in 2025) increase their market share in the next years to cover ¼ of the market due to better processability and flexibility. [592]

Looking at all transparent conductive coatings, the market was ~$2 billion 2013 and is expected to reach $5.9 billion by 2020. Asia dominates this market with more than 50% market share, Europe only has 10%. [593]

RFID

The global RFID tags market is estimated at $4-5 billion in 2016. It has been growing rapidly in the last years (~29% CAGR). But growth is settling to 3-5% reaching a market of $7 billion in 2026. [590]

The RFID related markets (including tags, passive and active, readers and software/services for RFID cards, labels, fobs and all other form factors) are estimated to be ~ $10 billion in 2015 . It is projected to grow to >$13 billion in 2020 (CAGR >5%). The largest application markets for RFID are automobile/transportation (1/3). Healthcare & Medical is assessed to be the fastest growing end use sector until 2020 (CAGR of 21%) with a market share growing from ~1% to a few percent. [594, 595]

Sensors

The printed and/or flexible sensors market is estimated to be close to $7 billion in 2016 and expected to grow to $8-10 billion by 2020 (CAGR ~5%); dominated by glucose stripes (accounting for >95% of the market). Growth is driven by an increasing demand for printed/flexible electronic devices in sectors such as medical & healthcare, industrial and consumer electronics. [20, 596]

Looking at the markets beyond glucose sensors, a next generation of printed, flexible, and organic electronic sensors could enable new medical and athletic wearable devices. The market for those sensors is still open ranging from $100 million to $1000 million in 2024, the likeliest being ~$400 million. The largest market at this time is expected to be a $244 million market for wearables used by athletes and medical patients. This area is seen as highly interesting for new flexible sensors to successfully compete with CMOS sensors. Smart food packaging or monitoring store inventory accounts for another major part of $117 million. The rest is made up of flexible sensors for transportation and building sectors. [597]

Logic and memory

There is hardly any logic/memory device printed and/or flexible at the market (excluding OLED transistor backplanes). The estimated revenue in 2016 is $3 million, generated with mostly prototypes and demonstration samples and very few commercial products. It is expected to grow to $240 million by 2026. It is not expected that it will compete with silicon at some point in the next 10-20 years. [20]

Flexible batteries and supercapacitors

The flexible battery market is estimated to be $70 million in 2015 and expected to reach $300 to >$600 million by 2020 (CAGR ~53%). The packaging segment was leading the market with a ~30% share in 2014. Advancements in consumer electronics are expected to drive the market in the future. [598, 599] Flexible supercapacitors are also an interesting opportunity, as they are so far not commercially existing.

Wearable electronics

Wearable electronics are essentially all electronic devices that can be worn on the person. It is not a very precisely defined market or segment and therefore, the global wearable electronics market is estimated to be worth $16-30 billion in 2016, depending on source and definition. Growth rates of 10-20% in the next years are expected and the market is projected to reach >$100 billion in the next ten years. [600, 601]

Products are expected to shift towards high value wearable electronic products. Major applications are virtual reality, augmented reality/mixed reality devices, specialty medical devices and smart clothing / e-textiles. The value proposition for wearable devices in medical and healthcare is very strong and the sector is the largest at the moment. The growth rate is expected to be modest due to many new revenue opportunities. This segment is expected to reach over $31.6 billion by 2026. Smartwatches and fitness trackers sales have increased rapidly since 2012/13, with the total market reaching over $6 billion in 2015. The growth rate is expected to rapidly decrease so that there will be a market consolidation. [601] E-textiles were a ~$100 million market in 2014 expected to grow to >$ 600 million 2019. 1/3 of the market is addressed with electronic inks. E-textiles are mostly used for sports and fitness apparel. Japan and China are dominating the market. [590]

Smart packaging

The smart packaging market for electrical and electronic packaging excluding chemical smart packaging and RFID generated a revenue of ~$75 million in 2013. It is expected to grow to sales of $200 million in the next five years and then to >$1.4 billion in 2025. [20]

Actors

Europe is a major player for flexible electronics and many first movers come from Europe, also due to a strong political support. [20] The automotive industry as an important integrator of flexible electronics is also very strong in Europe. However, some other typical application industries and integrators (wearables, consumer products) are not in Europe.

5.6.1.1 Market Opportunities

5.6.1.1.1 Broad addressable markets for platform technology with many niches

Flexible electronics can be seen as a platform technology for new kinds of electronics products. Eventually, it could penetrate the whole electronics, lighting and power sector and thus address hundreds of billions of dollar markets. [20] Nowadays, there are several developments and emerging markets driving the need for flexible and lightweight electronics solutions, for instance Internet of Things or wearable electronics. The fact that a market is not yet developed can be an advantage for new technologies to enable it and push it forward. This is a huge opportunity for graphene/2D materials if they can provide lower cost, better reliability, functionality, processability and higher performance than other flexible electronics materials.

Flexible electronics address broad and versatile markets with many niches, e.g. logistics, smart packaging, brand protection, ticketing, advertisement, health, apparel, consumer electronics, energy, automotive. Applications can range from semiconductors/transistors, sensors to simple flexible conductors or flexible conducting layers for EMI/ESD (see chapter 3.3). Flexible sensing elements, batteries or other functionalities have a large potential and functional flexible devices have higher value than just flexible conductors. New markets could also be created by enabling ubiquitous electronics in walls, fabrics or windows for the electronics industry towards the vision of “electronics everywhere”.

There are three possibilities how flexible electronics can be implemented: [20]

1. Replace a whole existing electronic / electrical product
2. Replace or do something simple in existing electronics/electrics

3. Replace nothing – create new products

Especially the latter demands new design rules.

There is no “killer application” for flexible electronics available, but the breadth of applications does not necessarily call for a killer application. It is a more likely scenario for this platform technology that market penetration increases incrementally in a variety of areas. [588]

The flexible electronics platform can provide integrated functionalities and the combination of different devices in one production on one substrate is very appealing and an important opportunity.[588]

The initial volumes of printed/flexible electronics products are low and address niche markets, e.g. special promotional items with volumes between several to max hundred thousand. [20] Mass markets do not exist yet, except for OLED displays for mobile phones. In recent years, however, it is observed that market penetration is increasing. The OEA expects strong growth in the coming years, depending on progress in the fields of material, equipment, processes and device design. Some of these areas still demand progress and even breakthroughs. [588]

5.6.1.1.2 Hybrid approaches are possible on short term

Especially in the short and medium term, hybrid solutions of flexible/printed parts with small and rigid silicon chips are a way forward and offer a great opportunity. For instance, a flexible sensor element, antenna, etc. can be combined with a small rigid silicon chip. This is essentially the principle of most flexible electronics products on the market at the moment, where the flexibility is used for the conductor and the actual electronics is rigid. This approach is expected to gain more interest as a primary path to further commercialization in the coming few years. [588] Especially flexible logic and battery applications are still way behind rigid solutions, so that those are nowadays and in the near future expected to be realized in a rigid format (coin cell battery and Si ICs) combined with flexible other elements (conductors, transducers). The biggest challenge there is related to the seamless integration of flexible and rigid electronics to have highest flexibility and in a commercially efficient and mass production compatible way avoiding manual steps (chip bonding, contacting, pick and place). [20]

5.6.1.1.3 Often lower performance requirements than for rigid electronics

The biggest opportunity for current fully flexible electronics technologies is where conventional electronics cannot be used, where e.g. lower requirements on performance (speed, quality of material, tolerances) are needed for ICs combined with high flexibility and ruggedness. Due to the flexibility, lower performance in some application cases is acceptable, because for instance other form factors and designs can be used. However, the business cases will be better, the better the performance. Lower requirements can be also achieved with organic semiconductors etc.

Silicon cannot provide low temperature processes, form factors, design options and CMOS performance on flexible substrates, which is why other materials such as 2D materials have a chance in replacing Si there. The question is how far silicon can take it in (partially) flexible electronics.

5.6.1.1.4 Flexibility and customizability as an added functionality

Flexibility is more and more acknowledged as an added functionality and a good selling proposition, especially nowadays with emerging IoT and wearables. The industry appears to be more and more open and realizes the value of flexibility. Other strength of flexible electronics are its thinness, potential for large area (interesting for e.g. sensors) and better integration into small sized products due to the flexibility in form factor. Printed/flexible electronics can actually deliver added values by realizing competitive advantages in terms of promotion and differentiation from other products and packaging. Besides that, completely new market opportunities are enabled by the technology. Flexibility offers more freedom of design and different form factors making new products possible (e.g. intelligent packaging). This even sometimes justifies premium pricing. [20, 588]

Further awareness creation of the real potential of flexible/printed electronics is needed and it is a matter of time to create a stronger market pull. There are already many end users who investigate printed/flexible electronics and invest money in research, prototyping and testing. But to actually convince internal selling and marketing, the arguments are mostly not good enough yet, e.g. because of too low volume or too high cost. [20]

For 2D materials and their combinations, the inherent functionality of flexibility combined with other functionalities (e.g. sensing, transparency, conductivity) is an opportunity to become part of the flexible electronics toolbox. For instance, the flexible transparency of graphene can be combined with flexible sensor elements from graphene or other 2D materials.

Customizability is also an important asset. Silicon electronics is usually only cheap when large volumes are produced (due to volume independent costs of lithography masks and equipment). Flexible electronics and printed electronics have the opportunity to be rather low cost also at smaller batch sizes.

5.6.1.1.5 Flexible electronics often good at lab scale but not on industrial scale

For flexible electronics there is often a gap between lab results and industrially relevant processed devices (e.g. p-type: 20cm²/Vs published for lab results, <5 cm²/Vs reached with industrially compatible process). This is on the one hand a threat, as lab results are not pointing towards real performances. On the other hand, it is an opportunity for graphene solutions, which might be able to perform similarly at lab scale and at larger scale.

Besides the performance it is very important that materials are improved in terms of processability, uniformity and stability, also including issues such as patterning. [588]

5.6.1.1.6 End-of-life and sustainability as a potential opportunity

Flexible electronics also offer opportunities in terms of sustainability. They address the trend towards green technologies and can offer sustainable production (e.g. low temperature, less material use) and eventually reduce the CO_2 footprint. [588] But the restricted use of chlorinated solvents or other hazardous materials is also important.

Besides flexibility and sustainability, organic, printed and flexible electronics can and in some areas (e.g. packaging) need to provide biodegradability, combustibility or simple recycling as USPs.

The sustainability is often not addressed, but companies demand sustainable products to improve the reputation and avoid being branded. Especially for batteries and Si chips, it is not desirable to send them to landfills. [20] Furthermore, some organic and inorganic electronics use rare materials (e.g. silver, or sometimes even rare earths). [20] Replacing these materials with more abundant (e.g. replace silver with copper) and proven environmentally friendly materials is a wish from industry.

Therefore it is a good opportunity for 2D materials to address the sustainability and end-of-life properties as additional USPs. Using non-chlorinated solvents and no rare or harmful materials during production can thus be an opportunity.

5.6.1.1.7 No dominating material for flexible electronics identified yet

Although there are many competing materials (see threats) for printed and flexible electronics, there is no clear winner at the moment. There is still an important need for new materials to improve overall performance, life time, encapsulation, efficiency and frequency [588].

5.6.1.2 Additional market opportunities: printed electronics and conductive inks

5.6.1.2.1 Conductive inks market exists and grows

The conductive inks market is a several billion dollar market (2-3b$ per annum). It is dominated by metal inks, especially based on silver (silver pastes had an overall market of ~$2.7 billion in 2013, this includes not only the flexible applications [20]). Conductive inks can be seen as a platform technology with broad range of applications, such as sensors, flexible conductors/interconnects, antennas (RFID, NFC), heaters, etc. 1/100Ω/□ sheet resistance are necessary/sufficient for a broad usability in most of these applications.

The greatest short term opportunity lies in the applications that currently are addressed by carbon inks or where silver inks over perform. Additional cost savings are possible when just one print is needed instead of e.g. 5 to reach the desired conductivity.

Conductive inks can be easily integrated into existing productions if the ink formulation is tailored to the need. Large volumes and simple processes are possible and in contrast to silver, graphene offers the potential to be disposable (combustible).

5.6.1.2.2 Developing printed electronics market

The printed electronics market is currently developing. Printed electronics address the need for low cost/lower performance flexible products in IoT, smart sensors, embedded energy harvesting etc. More and more products enter the market in various application areas and the industry approaches a phase of realistic growth and with significant revenues. [588] All printable electronics is already a well-designed niche.

5.6.1.2.3 Disadvantages of dominating metal inks or carbon inks

Typical metal-based inks, especially the widely used silver flake inks and pastes are rather expensive and suffer from corrosion problems. They usually also demand higher temperature annealing steps. Lower temperature processes are sought for, e.g. for automotive polycarbonate windows. Furthermore, the end-of-life properties are not very good and there is a need for metal-free conductive materials being recyclable, environmentally friendly, sustainable and corrosion resistant. But they are very well conducting, the basic functionality of a conducting ink. There is, however, an opportunity to address and replace silver-inks with graphene enhanced inks, in applications where silver ink is too expensive and “too good” or in corrosive environments.

Besides, carbon inks cover the other side of the spectrum, being corrosion resistant and cheap but offering a much lower conductivity.

The largest opportunity of graphene-based inks is in the space between silver inks and carbon inks, where it can be well suited in terms of cost and conductivity. Furthermore, graphene-enhanced carbon inks can lead to cheaper processing when you have to print once instead of 5 times to reach the desired conductivity.

Last but not least, a transparent graphene-based conductor without CVD could be a huge opportunity (e.g. based on printing).

5.6.1.2.4 Conventional printing as a large opportunity

Especially in packaging and advertisement, there is a need for cheap solutions compatible with standard print markets, so that the existing print industry and equipment can be used.

The good scalability of printing processes and the roll to roll processes offer large volume and simple integration of inks.

5.6.1.2.5 Additive manufacturing and 3D printing synergies, in-mold electronics

Another important trend that can be addressed by conductive inks is additive manufacturing/3D printing. Using different printing processes (e.g. stamp/aerosol) 3D objects can be coated with conductive layers and functionality can be added. Furthermore, printed and flexible electronics can be used for in-mold electronics, a more and more pursued way to integrate electronics on complex 3D objects.

5.6.1.3 Additional market opportunities: high quality 2D films for flexible electronics

5.6.1.3.1 High performance flexible CMOS currently not possible with available materials

Higher performance flexible CMOS is not possible with existing flexible n- or p-type materials, as no flexible semiconductors reach the performance of bulk semiconductors. This is an opportunity to fill this gap with 2D semiconductor materials. However, for instance graphene is not well suited for flexible logic but rather for flexible sensors and optoelectronics. But other organic semiconductors are also improving and CNTs are also suitable for flexible applications, so that the possibility is not unique and the race for the best materials is still open.

So far there is no reproducible processable semiconductor for flexible substrates achieving CMOS compatible performances. The search is especially ongoing to find a reproducible and processable n-type semiconductor which can be used together with p-type materials. [588]

5.6.1.3.2 Higher performing flexible sensors

There are hardly any high performance sensors on flexible substrates (hall, photodetectors, gas sensors), so that there is a potential opportunity to address these markets, where flexibility is of great importance.

5.6.1.4 Additional market opportunities: flexible (resistive) random access memory

5.6.1.4.1 Potential low end market, e.g. for smartcards

There is a potential market for non-volatile, cheap and low storage capacity markets, e.g. on smart cards or for packaging. This low-end market addresses new smart cards, maybe disposable products, health and point of care cards. These application only need ~80kB storage capacity.

5.6.1.5 Additional market opportunities: flexible batteries and supercapacitors

5.6.1.5.1 No satisfying solutions available yet, batteries a major problem for miniaturisation and flexible devices

Flexible batteries only exist in niche markets. They suffer from limited capacity and large footprints due to the limited energy density and existing material systems. Furthermore they have lower power density, higher degradation and costs compared to coin cells. [602] Therefore, flexible batteries are in need of new concepts and materials to become competitive and interesting for a broader market.

Supercapacitors are not available in conformable versions. If they can compete with batteries and reach high enough capacity and low self-discharge, supercapacitors or hybrid solutions with flexibility could have an interesting business case.

5.6.1.5.2 Interesting add-on in conjunction with other flexible devices: Interesting battery business case for Europe

Electronic devices are getting smaller, thinner and lighter and along with that the need for smaller and conformable power sources increases. Thin, flexible and printed batteries are a missing piece for smaller and flexible electronics. [20]

The trends in wearable technologies, medical/fitness devices and internet of things demand small/thin batteries with special form factors as energy sources (in conjunction with nanogenerators).[602]

For developers of flexible electronic devices (e.g. senors, antennas, etc.) it is interesting to also pursue the development of flexible batteries, although batteries are not necessarily the core business. This could eventually allow the production of a fully integrated device including a power source. Thus, although the battery/cell market is highly dominated by non-European actors, flexible batteries can still be an interesting field for Europe.

5.6.1.6 Market Threats

5.6.1.6.1 Strong players and industrial basis, especially for consumer products, mostly not in Europe

Major markets and industrial players for consumer products are currently in Asia (Samsung, LG) and US. The strongest European application industry is by far the automotive industry, but also more general sensor applications (e.g. in healthcare, machinery and special electronics) are relevant.

5.6.1.6.2 Conventional electronics seen as competitor

Conventional electronics also address wearable, portable and cheap applications. Although not flexible, very small rigid chips perform well in electronic and can be integrated into fabrics or other flexible devices just because of their size. These standard electronic chips usually set the standards and expectations in terms of cost and performance. The further miniaturization make them a moving target finding their way into more and more "flexible" applications and there is and will be a competition between truly flexible and conventional electronics, despite the lack of conventional electronics not to provide actual flexibility and performance at the same time. Conventional electronics build on a large and existing industry. For truly flexible electronics a new infrastructure, new designs, new products and new markets are needed, which increases the barrier to switch to this technology. It is also a matter of awareness and acceptance. [588] Currently it is hard to find an application which cannot be realized with standard semiconductors. In this case it is less flexible but still lives up to its purpose.

A way forward is the hybrid integration which combines the benefits of both approaches. Conventional silicon will be used combined with flexible electronics parts (e.g. sensor and antenna printed/flexible, readout and data processing in a standard silicon chip. [20] The goal is not to replace functionalities that are easier, better and cheaper made with silicon electronics (ICs), but rather add flexible functionality in form of a flexible conductor, sensor or antenna.

5.6.1.6.3 Competition of materials and technologies remains high – many different technologies under development

Flexible electronics is not seen as an established technology and is still often compared to silicon, although silicon is not really a competitor in terms of flexibility and performance at the same time. Still, silicon is often used in applications where true flexibility might be valuable but is neglected due to the availability of small silicon chips (see argument above). Or lower performing partially flexible amorphous or poly-silicon implementations are used.

Although flexible electronics is not yet an established technology, there is also competition with and between other (more mature) not Si-materials (organic semiconductors, CNT, nanowires, etc.). A clear winner is not yet seen and will probably not be, as different materials have different strengths. There is a wide range of other materials available that can increase performance and open chances in high performance applications.

Low performance and high flexibility can be also achieved with other materials, which have been under investigation for a longer time, are more mature and have not yet enabled the flexible electronics market to flourish. But the mobility and performance of organic semiconductors still increases and approaches levels to be competitive at least with poly-Si. [588]

5.6.1.6.4 Juvenile market of printed/flexible electronics and credibility gap

Although organic and printed electronics has become a growth industry with significant revenue, especially due to the OLED business, [588] and there are various flexible products on the market, the market has not picked up considerably. Conductive inks, sensors and displays are markets were some stakeholders can already work profitable. [20] It needs to be clear that the market is still juvenile, emerging and volatile, and that market and technology expectations are based on assumptions and uncertainties and only a short record. [588] In particular the market is not yet living up to its promises and expectations, which scares off investors and leads to a lack of strategic investors. This can be summarized in a credibility gap which needs to be narrowed. The technology and market were expected to improve faster, but still fail to live up to these expectations. [20]

5.6.1.6.5 Performance, lifetime and reliability perception

The credibility gap exists in market and technology expectations. The common perception of poor performance of flexible electronics changes slowly. Demonstrators are needed that show that it actually works and can live up to the expectations. And still then it is a long way until the credibility gap is fully closed.

Other concerns are related to lifetime and reliability. The lifetime problems are to a great extent solved and often not an issue, especially when the business case is tailored for the lifetime expectation of the device. Absolute reliability is very important for credibility. [20]

Until the credibility gap in terms of performance, lifetime and reliability can be closed technological breakthroughs are still needed in processes, encapsulation, materials and standards and regulations. Especially the poor availability of low cost, flexible encapsulation is a major threat to address lifetime and reliability issues for organic electronics. [588]

5.6.1.6.6 Solely low cost promise dangerous

Especially printed electronics is often promoted with being cheap. This might also eventually become true but initially this is a problem, as it is often a challenge for a new technology to only compete or enter via lower cost promises. The first market entry usually is only possible with higher cost and higher prices and costs come down with time and development until cost competition is achieved. In some cases higher costs for first generation low volume products are unavoidable [588], so that the technologies need to deliver an added value that customers are willing to pay for (adequate cost-performance, where performance also related to the added value proposition, e.g. flexibility). Lower costs are more likely to become a USP for a more mature technology that has already entered the market in niches where the higher prices are paid for a USP. When costs are decreased new markets can be opened up with the cost argument.

5.6.1.6.7 Sustainability and health and safety perception and concerns

Companies demand sustainable products as customers and regulation more and more demand them. They for instance wish to avoid sending coin cell batteries and Si chips to the landfill. [20] So sustainability of flexible electronics needs to be proven and can actually be turned into an added value.

Especially for nanotechnology products, the perception of integrity/durability and environment, health and safety are important issues. For graphene, the toxicity is often perceived similar as CNT, although this is potentially not true. To avoid the threat of being perceived as toxic, it is best to address it openly and pro-actively. Health & safety concerns especially regard the release of graphene, contact with graphene, handling in production and solvents used. Measurements of release and possible exposures are needed. In particular if the material is used for health and wearable products which are in direct contact with the environment or body, or even body fluids, a safety assessment is needed.

5.6.1.6.8 New value chains needed and not yet established

Although truly flexible and organic electronics address similar products as conventional electronics as well as completely new products, the value chain is different and is not really fully existent yet. This is especially the case for printed electronics. Current supply chains for flexible electronics are diffuse and exist in niches (besides the established ones for OLED). The existing value chains are strongly push related with not so much pull from users. [20] To fully exploit the potentials of flexible electronics in general, creative design companies need to get involved and the industry needs more exchange with end users. [20] Most importantly there is a lack of integrators. End users see the potential benefit of flexible electronics but do not want to become integrators themselves. Instead, they rather want to buy simply integratable components, prototypes and solutions. This shifts the development work to integrators. [20] Besides, different parts of the value chain are at different maturity levels and there is no overview of European actors in the flexible electronics area and their capabilities.

To support the innovation to market process, these challenges need to be addressed for the overall industry (independent of graphene). This, however, is not only a threat to 2D material's role in flexible electronics but also an opportunity, as the space is still open for new (venture) companies and SMEs to address and establish new markets [588]

Standards are also related to the establishment of a reliable supply chain needed to address large and regulated markets (such as automotive or healthcare). The different quality and variety of available materials (for all applications) calls for common standards. It is still an open challenge to develop standards suitable for organic electronics. [588]

It further appears that there is an imbalance between “front end” and “back end”. There are many effort to produce flexible components, but the assembly (e.g. pick and place, flip chip), contacting and packaging as well as quality control is not addressed likewise. This can especially be a cost driver and outweigh a potential cost advantage of for instance a printing process.

5.6.1.7 Additional market threats: printed electronics and conductive inks

5.6.1.7.1 Conductive inks market complex and competitive

The conductive ink market is an established, complex and competitive market dominated by metallic inks and pastes. Depending on the needs of an application (conductivity, cost, production method, substrate) many different materials are used in inks. Besides the high performance and high cost silver flakes there are conductive inks from carbon, CNT, copper, conductive polymers (e.g. PEDOT:PSS) and metal nanowires and –particles. Finally, the inks also compete with other technologies, such as sputtered metals. Copper inks are seen as an emerging competitor to silver inks having a similar maturity as graphene inks. For flexible applications it is most important to have a preparation which does not need high temperatures.

Customers usually do not care which ink is used, as long as the functionality and cost/performance is adequate, as it does not change the experience of the product. Benefits and arguments for a particular technology can be (besides the performance and properties in the product) in the production process, e.g. when a single coat is needed instead of multiple coats. Therefore customers will not buy an ink because it is made of graphene, but only because it is better suited and functional in the addressed application.

Another threat is that printed electronics might be too complicated, which increases the barrier for usage. In reference [20] an example is presented where a packaging company needed more than 40 additional production steps to deposit a fully printed light with a switch on corrugated cardboard.

5.6.1.7.2 Low cost applications addressed: difficult entry scenario for a new technology

Printed electronics usually addresses low cost applications, where also a poorer functionality is accepted. Systems can be very simple but they must be cheap. Thus, the product needs to be low cost high volume, to be more than a nice to have. Some applications require costs of a few cents (e.g. in packaging). So the cost constraints are substantial. However, printed electronics remains expensive despite cost being the main potential attraction. [20] But it is hard for a new technology to enter a market only via cost arguments, as it is usually not easily possible to come up with a large scale very cheap product in the first place. The profit margin of those applications is usually low and a very high volume is needed to become profitable. Therefore, the USPs of graphene-based inks need to be seen as a whole and potential future cost reductions is only one amongst them. If product cost will be decreased in the first place, it will most probably be via production cost or reduced cost of ownership (e.g. less material needed, less coating steps), etc.

Competing technologies addressing similar applications are also very cheap, e.g. a silicon RFID chip can be made for 1 cent. This is a threat and prohibits new technologies in these markets. [20] Also the RFID antennas made with aluminum are very cheap (less than one cent per inlay), but suffer from sustainability issues.

It is therefore more likely to be successful in areas where the added functionality (e.g. corrosion resistance) is paid for and the other applications can potentially follow afterwards. It appears to be more promising to focus on customizability in conjunction with lower cost, rather than mass production and lower cost (see opportunities). Another area where printed devices can find particular niches with USPs is the flexible sensors area.

5.6.1.7.3 Perception of 2D materials in printed electronics

Graphene-based inks are currently seen as a slightly better but more expensive carbon ink. Some actors perceive that graphene material inks will not be a game changer for printed electronics at the moment, as the added value of GRM is not yet clear. The printed electronics expectations for graphene are not so high, as the USPs are somewhere between silver and carbon.

It needs to be made clear, that graphene material inks at the moment should not be seen as drop-in for high performing silver inks in terms of conductivity. If this is not the case, it is a threat that graphene does not fulfil the expectations. They, however, can have a USP where for instance corrosion resistance is more important than conductivity.

5.6.1.8 Additional market threats: high quality 2D films for flexible electronics

5.6.1.8.1 Competition with rigid electronics

High quality films particularly compete with small footprint rigid electronics (see also 5.6.1.6.2 Conventional electronics seen as competitor).

5.6.1.8.2 TCF competition: strong incumbent, markets and players not in Europe

The TCF market is dominated by Indium-Tin-Oxide (ITO). Where lower cost, higher thermal and chemical stability is needed, fluorinated Tin-Oxide is the material of choice. China, Japan and the Republic of Korea are the world's major ITO producers and user, mostly due to the display panel production. The TCF technologies for ITO and FTO are very established and used since many years. A new technology needs to fit into the current production process so that it can be taken up in the nearer future. The price of ITO depends on the indium price, which was fluctuating but not heavily increasing in the last 10 years. Increasing prices will lead to increasing drivers for new materials.

There are upcoming novel materials besides graphene, e.g. metal meshes, nano-wires or CNT. However, ITO is expected to remain the dominant materials used for at least the next decade, followed by metal mesh and silver nanowires.

For TCFs transparency and optical properties, conductivity (low sheet resistance), etchability (property to allow simple patterning), price and substrate/flexibility and for OLED/solar cells efficient charge extraction/injection across the electrode/organic interface are very important aspects.

A major drawback of ITO is the poor performance on flexible/conformable substrates and the optical properties. All new technologies therefore also address the search/need for ITO replacement with this added functionality of flexibility or optical properties (e.g. lower reflectance). Although a TCF application of graphene has been already demonstrated (Wuxi [603] and Chongqing Morsh Technology), it is still not clear whether the potentially graphene-based TCFs are commercially viable. Due to the advancement in other competing new technologies in terms of cost/performance and the current lower levels of conductivity in graphene, graphene materials might come too late for TCF (narrowing window of opportunity). All in all, graphene based TCFs are more likely to be successful in flexible or stretchable applications (see chapter 5.6 Flexible and/or printed electronics) or as additive for enhancing other TCF technologies, or in certain niche application such as UV-LEDs (see box on page 317)

However, there are rumours that graphene TCFs might be used in OLED displays due to an optical advantage. [604] The potential use in OLEDs is also matter of research of a EU project GLADIATOR. [605]

Besides, the major player for TCFs are not in Europe, so only for particular niches there might be a chance to gain ground in this market. Another opportunity is to license technologies to the major manufacturers.

5.6.1.9 Additional market threats: flexible (resistive) random access memory

5.6.1.9.1 Competition with other materials and low end markets require very low cost

The flexible resistive memory is also possible with other nano-carbon materials and the material will succeed which offers the best performance with a low-cost process.

5.6.1.10 Additional market threats: flexible batteries and supercapacitors

5.6.1.10.1 Flexible batteries are on the market

There are already thin film flexible batteries on the market, even with a nano graphite material. However, the market is not yet profitable and the batteries are only successful in small niche applications. Still, the maturity of existing thin film batteries is higher. But graphene could be used as an additive to improve the performances enabling to address new markets.

5.6.1.10.2 Coin cells are mature, small, cheap, have higher power density and are broadly used

Coin cells or button batteries are a success and hundreds of millions of these batteries are used in many applications from gift cards, active RFID tags, hearing aides, wristwatches to car keys and calculators. Laminar and flexible batteries are only used, where the need for thinness and flexibility is extreme. But in most cases coin cells are used, eventhough thinness would be desirable. An important reason for that is the much higher cost for thin film batteries compared to coin cells as well as the poorer performance, reliability, etc. [20]

5.6.2 Graphene/2D materials perspective: current strengths, weaknesses and challenges for the use in flexible electronics

5.6.2.1 Current strengths for graphene/2D materials use in flexible electronics

5.6.2.1.1 Multifunctionality and intrinsic flexibility as a key proposition for flexible electronics

2D materials are ultrathin bendable materials with charge carrier mobility larger than in most other materials already available (>40 $cm^2 V^{-1} s^{-1}$). [510] They can be printed as inks, usually made from LPE/GO flakes leading to lower performance devices, but much simpler to produce and apply, even on large area; and transferred as high quality films, leading to higher performing devices but with the problem of a much more sophisticated transfer and preparation.

The intrinsic flexibility and stretchability of 2D materials is a major USP for flexible electronics. Although for printed and bulk-material based devices the boundary between flakes, the binders and ink formulation are determining the performance under binding to the larger extent.

Besides the electrical properties and intrinsic flexibility, 2D materials offer additional functionalities, such as amphiphobicity, (anisotropic) thermal/electrical conductivity, barrier, anti-reflectance, corrosion resistance. This multi-functionality makes the material class very interesting for flexible electronics. Especially the combination with the barrier properties is very interesting for combination with other flexible electronics. Bio compatibility (with environment, tissue and body) and end-of-life properties, in terms of combustibility and environmental compatibility, of graphene could be also beneficial. This, however, needs to be shown for the different material types and flake sizes.

Furthermore, functionalization offers an additional degree of freedom in particular interesting for printed/flexible sensor, batteries, etc.

Especially where the combination of the different functionalities are required, a unique added value and competitive advantage could be generated that might actually justify the initial cost. For instance, transparent conductive surfaces have been achieved with tunable wettability. [193]

5.6.2.1.2 First demonstrators are promising and first products are entering the market

Especially graphene flake and GO based applications are already quite mature. Conductive inks are on the market (Sigma, Vorbeck) and lie between carbon and silver inks in terms of conductivity.

The potential of graphene for flexible electronics is shown in the lab (proof of principle devices) for sensors, antennas, conductors, etc. Issues such as degradation on flexible substrates are already addressed. First tests look promising but a full investigation of degradation is pending. The graphene flagship is developing a toolbox of technologies and processes for a GRM flexible electronics platform.

There are even first devices based on conductive inks (antennas, RFID, glucose sensors) announced to come to the market soon. The devices that are already on the market are, however, no blockbusters yet.

5.6.2.1.3 Printing or CVD are possible: wide range of applications

Depending on the requirement of an application, graphene and most other 2D materials can be used either as flakes in inks, transferred high quality films or in best case low temp CVD grown. Also the compatibility and use of both types of graphene/2D materials (ink/flake and film) in a device should be possible and might be interesting for integrated devices.

The transfer of lab results to industry-scale and compatible processes is not fundamentally problematic, but improvements need to be achieved. Especially for high quality films, the wafer scale integration assessment is valid (5.2 Electronics: Cross-cutting issues).

Cost could also be eventually a USP, as lower temperatures are needed and a higher yields are possible with time and increasing efforts.

5.6.2.1.4 Electronic, thermal and barrier functionality at the same time: addresses needs for most flexible electronics materials

Flexible electronics usually need encapsulation and barrier materials. Graphene and 2D materials can be an active component and a barrier at the same time. This added functionality is an interesting property of graphene, although the preparation needs to be cheap enough, because especially for encapsulation the price pressure is usually quite high. Using graphene as barrier and e.g. electrode might relax the cost constraints a little bit, as additional steps can be avoided. Still, large scale high quality graphene transfer would be needed or the ink film quality needs to be good enough to avoid edge effect or impurities that reduce the properties. Also 2D materials such as hBN can be used for encapsulation without electrical conductivity, see chapter 3.3 for more information on barrier materials.

5.6.2.2 Additional strengths: printed electronics and conductive inks

5.6.2.2.1 First marketed inks available based on graphene

First graphene based inks are commercially available on the market (e.g. from Sigma Aldrich or Vorbeck). They perform better than common carbon inks in terms of conductivity and already now have a better price point than metallic nanowires and silver inks.

5.6.2.2.2 Filling the gap between carbon and metal inks in terms of price and performance

As mentioned above, graphene bases inks are cheaper than metal inks but also have lower conductivity. The inks are positioned between metal inks and graphite inks (in terms of performance and price). The business idea is fill the gap between carbon and silver/other metal inks and to replace metal inks as a cheaper alternative, where metal over-performs but graphite inks under-perform. They are also better than conductive polymers and directly competing with CNTs and metal nanowires. Thus, for this space between graphite and metal inks, graphene inks are one out of a few in terms of uniqueness.

Current graphene material based inks are ~30% better than carbon inks, but will never be as good as silver inks, which is also not the goal. The flexibility/stretchability is better compared to metal and carbon inks.

In terms of prices, silver inks are about one order of magnitude more expensive already today (~200-1000€/kg depending on density and quality). Carbon inks are priced at 40-45€/kg plus the cost of some 5% graphene. Usually at least 3l are needed for a large scale printing process (to also account for dead volume). Besides, less process steps might be needed when silver is replaced which can lead to additional benefits.

However, the question is still open to which extent this area in between metal and carbon inks is economically interesting. This needs to be further investigated before it is clear whether this actually is a strength.

5.6.2.2.3 Additional USPs: corrosion resistance and chemical resistance

The USP of corrosion resistance is very interesting for graphite and graphene based inks, as silver inks are usually prone to degradation and corrosion. So graphene does offer something that cannot be offered by another material, i.e. chemical and corrosion resistance similar to graphite but with a higher performance. Therefore graphene inks might be especially interesting where combination of these properties is needed and a better conductivity than graphite inks is desirable.

5.6.2.2.4 Potential to replace/enhance conventional carbon-based inks

Carbon black based inks are used as conductive inks in areas where conductivity does not need to be high and where low cost is priority. Graphene-enhanced carbon inks perform better than standard carbon-based inks and are expected to be almost cost competitive in the near future.

In the last few years, a massive improvement in conductivity has been achieved for pure graphene material conductive inks and processes (from kΩ/□. to <1 Ω/□, e.g. 1.4 Ω/□ at 25µm thickness [579]). There are no critical technical challenges/limitations anymore regarding the conductivity.

When the electronic design of flexible circuits, antennas and devices is adjusted to these achievable conductivities, the inks can even compete in application areas where metal inks are normally used. With adjusted processing, design and thickness, even flexible NFC antennas can be realized.

However, the pure conductivity of printed graphene is not a game changer at the moment. Only the full package of process, cost and performance might eventually become a USP. It remains an open question whether the sheet resistance be further reduced and to which extent especially the processing can be adjusted to achieve highest possible sheet resistances with for instance one print. It is therefore necessary to look at Ω/□/mil or /print. 1 Ω/□/print is already possible.

In summary and as mentioned above, graphene inks or graphene-enhanced inks can address the market and replace silver inks for applications where silver inks are too expensive and too good, e.g in touch sensors, or where carbon/graphite inks are performing not good enough.

5.6.2.2.5 Added functionalities beyond pure conductivity

Functionalization offers further technological opportunities for graphene and 2D material based printed electronics. Graphene/2D materials offer a broad range of functionalities beyond pure conductivity: 2D printed systems can be for instance used for temperature sensors, humidity sensors, RF circuits, pressure and strain sensors, gas and bio sensors. This opens up the potential to have a 2D materials toolbox for flexible/printed electronics to create flexible systems combining the functionalities. In that respect, the combination of flexibility with several functionalities can create an USP for these materials.

5.6.2.2.6 Substrate independence

It has been shown that graphene inks can be used on various substrates, even on porous ones. Similar to other printed electronics materials, any substrate is possible with proper engineering. Even tissues and textiles are possible to be used, still reaching a quality compatible with NFC antennas.

5.6.2.2.7 Printability and simplification of integration processes

Conductive inks based on graphene/2D materials can be printed with standard equipment and there is a good integratability in existing printing systems. This process is much simpler compared to transferred high quality CVD graphene. Thus, a shorter time to market is possible for printed electronics and inks.

Different printing/coating techniques are in use and possible, e.g. bar/rod coating, screen printing and flexographic printing. It is possible to produce/print multi-layer structures and heterostructures, which increases the freedom of design and the potential applications.

Using graphene inks in the conductivity space between carbon and metal inks can reduce the effort of printing, e.g. through the need of just one printing unit instead of two for printed touch sensors (replace silver ink). This also offers the chance to print a device in a single step or very few steps instead of multiple coats.

Furthermore, although higher performing graphene inks need post processing (e.g. compression, laser treatment), there is potentially no overall heat curing needed.

Graphene has also the potential to become eventually cheap enough to allow broad use and to bear the dead volume of ordinary printing machines (several litres).

5.6.2.2.8 Potential environmental properties as USP towards metal inks

Similar to carbon inks, the potential environmental properties of graphene-based inks, i.e. recycling, combustion, biodegradation, lower environmental impact, are better than for most metal inks. However, not only graphene materials influence the EHS properties, but also the binders and residual additives in the films.

5.6.2.2.9 Ultimate goal: printed and transparent electrode

So far, a purely printed transparent and sufficiently conductive film has not been achieved with graphene. The question remains open whether it is possible to print a transparent conductive layer e.g. from single layer graphene (oxide). The realisation of such a printed TCF would be a very interesting opportunity. Some stakeholders do not expect it to be possible due to the difficulty to achieve percolation in thin (one layer) films.

5.6.2.2.10 Other 2D material inks could enable flexible (printed) electronics

Other 2D material inks (e.g. MoS_2, WS_2, MoO_3) and their combination have the potential to become key enabler of flexible electronics, if they can be manufactured and applied in a controlled way. There is a potential for all-inkjet printed heterostructures by sequential printing of graphene and other 2D materials. But the maturity is still rather low and many challenges need to be addressed, e.g. the role of grain boundaries in printed structures. [606]

5.6.2.3 Additional strengths: high quality 2D films for flexible electronics

5.6.2.3.1 High quality semiconducting 2D materials as good candidate for flexible electronics: Essentially all devices can be made flexible

High quality 2D materials are better suited for higher performing flexible electronics. Possible applications are hall sensors, photodetectors, RF electronics/transistors, and logic. For logic other 2D materials, such as MoS_2 or SnS_2 are more promising due to the intrinsic bandgap.

If large-area deterministic materials growth is successful, 2D materials technology could enable a new generation of flexible electronics for wearable and bendable systems. MoS_2 or other 2D materials could be n-type or p-type semiconductor with sufficiently high mobility.

Essentially all devices that are mentioned in this electronics chapter (also in the sensors, logic, RF/telecomm and optoelectronics chapters) can in principle be made on flexible substrates (if the preparation uses limited temperatures <200°C). This is a great strength and opportunity for graphene electronics to leave the competition well behind . Flexibility is one of the very clear USPs of graphene based electronics. Please refer also to the other electronics chapters depending on the application of interest.

5.6.2.3.2 CVD graphene/2D materials with high quality can reach better performances than flakes

CVD graphene is more likely to be used for higher performing for end products, but only if low temperature direct growth or transferability is controllable (see wafer scale assessment in 5.2 Electronics: Cross-cutting issues). For flexible applications also direct roll to roll or sheet to sheet transfer (deposition of flexible substrate on graphene, before Cu delamination/etching) is already established and could become economically viable, reducing the dependence on the wafer scale integration success. CVD processes and high quality films are better suited for higher performance/electronics (transistors, sensors) and transparent applications. In particular the transparency is a potential selling proposition. Interesting for future fully integrated devices is also the potential compatibility of high quality films and ink-based components.

5.6.2.3.3 Substrate independence

Once lamination/transfer of high quality films works, one is essentially independent on substrate (only dielectric needed). But the specific interaction of graphene with the substrate needs to be considered. If graphene is encapsulated, e.g. in BN, substrate independence is essentially given.

5.6.2.3.4 TCF: good flexibility and optical properties

The optical properties and the flexibility of graphene based TCFs is better than for the incumbent ITO and can compete with other emerging technologies. The downturn is the complex preparation and not so good conductivity compared to other solutions.

5.6.2.4 Additional strengths: flexible (resistive) random access memory

5.6.2.4.1 Multi-storage per bit potentially possible

Simple configurations (printed) of graphene oxide sandwiched between two contacts can be used as RERAM. The CareRAMM project investigated graphene-oxide RERAM and realized switching speeds of 10ns and sizes of 100x100 nm^2 per bit. [607]

With RERAM, multi-storage is in principle possible, i.e. more than two stages are available per “bit”.

5.6.2.4.2 Rather simple preparation method based on flakes

A simple version of the memory can be prepared with spray gun (that is also used for supercaps) or by piezo printing, both roll to roll processes. Water can be used as solvent and plasma for patterning, which only needs 100°C.

5.6.2.5 Additional strengths: flexible batteries and supercapacitors

5.6.2.5.1 Simple use of graphene materials

Graphene materials can be easily used as an additive for graphite electrodes (e.g. in form of GO). Besides that, the strength of graphene in batteries as provided in chapter 4.3 can be applied. Vorbeck materials already introduced the first graphene-enhanced flexible battery.

5.6.2.5.2 Graphene is the only material enabling flexible supercapacitors

So far, graphene is the only materials that potentially enables conformable supercapacitors. This might be a unique opportunity.

5.6.2.6 Current weaknesses and challenges for graphene/2D materials use in flexible electronics

5.6.2.6.1 Compatibility with different processes and technologies

One of the main challenges for flexible low cost GRM ICs is the compatibility between different processes and technologies (printed, transferred, CMOS, substrates, other materials, etc). This also refers to the compatibility of high quality graphene films and printed graphene films based on inks.

5.6.2.6.2 Exploiting the full potential of graphene/2D materials with economically feasible processes compatible with flexible substrates

The extraordinary microscopic properties (e.g. high mobility) of graphene have gathered a lot of attention for flexible electronics. First companies are offering conductive inks and it is still explored for many applications as semiconductor and conductor in flexible electronics (as high quality film and printed ink). One of the key challenges is to maintain the microscopic and highly interesting properties of pure graphene sheets after converting the material into a processing form, i.e. an ink or a scalable grown film and transfer. [608]

Besides, the production processes are partially not easily scalable and thus drive the cost. For instance, currently often non-scalable sonication and centrifugation processes are used and high temperature annealing. However, new scalable production methods (e.g. microfluidization) are developed. [609]

5.6.2.6.3 Maturity of flexible applications beyond conductive inks is still rather low

Graphene-based or enhanced conductive inks are used in consumer products such as flexible RFID or security labels [610]. First products are about to hit the market.

Besides the rather simple use as slightly better carbon ink for conducting layers, the maturity of flexible applications with graphene/2D is still low. Graphene based "real flexible electronics" solutions are still far away from commercialization.

There is no established GRM based IC platform for large area flexible electronics available at the moment. There is still some lack of fundamental knowledge about the GRM properties in flexible applications and a better understanding of the material and preparation is needed. Key challenges are to improve the material mobility, the development of roll-to-roll fabrication processes and the development of device/circuit fabrication technologies [510]. Finding an efficient way to make a system out of the materials/modules is a limiting factor.

Another challenge is reproducible, reliable and homogeneous doping and functionalization: For some applications doping is needed and it remains yet unclear how to do that uniformly on large scale. The quality demand of course demands on the application. Disposable devices for instance have lower requirements than multi-use sensors/devices.

In particular for sensor applications more knowledge on functionalization is needed (surface chemistries, processes and influence/optimization of functionalization on performance).

The amount of potential application of GRM materials in flexible electronics is very large. This is of course an opportunity, but also makes it hard to figure out and decide on which applications are worthwhile exploring more deeply. So far there is no “quick win” foreseeable and it is not a fast-selling item in terms of technological and non-technological properties combined with the still open questions on processing and applications.

5.6.2.6.4 Reliability, long term stability need to be proven

For non-disposable products, the long term performance and durability is often still unclear and needs to be proven (also in air and different ambient conditions). More efforts on reliability are needed. For disposable products, the shelf-life needs to be investigated.

5.6.2.6.5 Other 2D materials need more attention

Graphene has already gained quite some attention in terms of production and demonstrators. Other 2D materials are gaining more and more attention, especially for electronics. On MoS_2 already a lot of work has been done, but it is still very far away from being assessed on its potential properly.

There are opinions stating that for flexible electronics the efforts on MoS2 are currently too low and other 2D materials do not get the same attention as graphene. On the other hand, if graphene proves to be viable in a flexible electronics product it might pave the way for other 2D materials.

Competing materials (e.g. organic electronics) are more mature, but also have constraints. The frequency of operation is lower than for printed inorganic materials. The yield and matching to other components for or graphene and pinted electronics in general is still open. Multiple manufacturing techniques have to be investigated for best performance, number of transistors and lifetime. The competition with ultra-small silicon chips needs to be taken into account. [20]

5.6.2.7 Additional current weaknesses and challenges: printed electronics and conductive inks

5.6.2.7.1 Is positioning between metal inks and carbon black inks a sweet spot for graphene?

Graphene conductive inks are positioned between graphite inks and metal inks in terms of performance (conductivity) and cost. The conductivity in comparison to silver is a factor of 100 lower (and processing dependent) and the improvement towards graphite inks is some 30%.

The conductivity achieved today is good enough for RFID and even NFC antennas with reasonable range. It is, however, not good enough for a one to one replacement of printed circuit boards. One intrinsic problem of graphene is the low charge carrier density, which in part counteracts to a certain extent the high mobility for conductivity applications.

The technological USP is still somewhat vague, although the rather non-technological USPs as corrosion resistance and potential environmental properties appear promising combined with the expectations of falling prices. Still, the cost/benefit advantage is not yet clear enough. To compete in this area on a broader basis the inks need to be rather low cost and high volume and there is probably nothing in between, because else metals or carbon inks could do the job better or cheaper. If this is not met, it will remain in a niche product for special applications, such as in corrosive environments.

Several companies are in the business (e.g. Vorbeck in the US since several years) but so far none seems to have reached the breakeven point.

5.6.2.7.2 Graphene alone is not the key enabler of printed electronics

Graphene is potentially one component among others in printed electronics and it is neither a driver, nor an enabler for printed electronics. Depending on the application, graphene material based inks do not technologically enable things that cannot be done with carbon and silver inks, only the price and non-technological benefits (corrosion, end of life) can be an argument at the moment and the positioning between metal and carbon inks (see above).

The black colour/lack of transparency of graphene inks could be a disadvantage in applications where the colour or appearance is important.

In combination with other 2D material inks, graphene might become more important for heterostructures.

5.6.2.7.3 Engineering knowledge needed, especially expertise in ink formulation needs to be involved

The conductivity of graphene and 2D materials based films made from conductive inks not only depends from the material itself, but to a great extent from the ink formulation, binders, surfactants, additives (all tailored for the targeted printing process), the printing process itself and post processing. The type of flakes and their influence on printability need to be considered as well. Furthermore, the targeted application requirements (also non-technological), e.g. in terms of shelf lives, need to be regarded alongside with the type of substrate. 0.1-1 or 2µm flakes are stable and shelf lives of several months have been achieved.

The further improvements demand considerable engineering efforts and engineering knowledge on ink formulation and a lot can be learned from the ink community. The following challenges remain:

- unknown adhesion between different substrates and inks (wear resistance…), find the most suitable substrate
- better understanding of particle interfaces, bridge/reduce contact between different flakes needed to allow influencing structure of film and interfaces
- Need to find a formulation that increases the conductivity of carbon inks whilst not changing the printability (rheology, viscosity)
- Ink formulation and tuning of properties, stability: maturity not yet far enough, but in principle manageable with enough effort
- Stable dispersion without losing target properties of graphene
- Use industrial standard tests for the targeted application (e.g. for RFID, sensors, etc.)
- Stability/lifetime of the devices
- Contacting of devices

5.6.2.7.4 Challenge: building the value chain and providing consistent supply

Many companies are already active in the bulk graphene business. Most of them also offer a conductive ink. However, there is a poor current availability of reliable, consistent and stable inks, especially for larger volumes. Although the ink provided by one supplier might be stable and reproducible, it is hardly possible to change form one supplier to another. This introduces a barrier, as many industries demand second sources.

It is a challenge to find the right supplier who has the ink with the required properties. Especially in Europe, the supply is still unsatisfactory.

Also in terms of consistency and volume of bulk graphene material supply (at 100kg scale) there are many differences between suppliers. In this case the consistency of one supplier is usually high enough (at least from one or the other), but again the change to another supplier is hardly possible. The quality of bulk graphene depends on the synthesis route and can even depend on the raw material graphite quality for certain routes.

Missing material standards and a lack of standard characterization tools for quality control of large volume of material (powders, inks) accompany this problem. For inks, standards are there and have to be addressed when developing inks that should be sold to the market. It appears that in the current situation, companies have a better chance of success when they cover the value chain up to where standards exist (e.g. ink supplier).

5.6.2.7.5 Some printing techniques might suffer with larger sheet size

For some printing techniques (e.g. inkjet) the wear of printing heads and nozzles from large size sheets is unknown. For larger sheets, some printing techniques (especially inkjet) might not be suitable as clogging could appear. This is not relevant for screen/flexo printing.

5.6.2.7.6 Yield, performance and market differentiation

Not only on ink level, but also on applications level, the USPs are often not yet clear enough – compared to competing technologies addressing the same functionality – for a company to invest in the material. For instance for flexible/printed sensors, the yield, performance and market differentiation are unclear. For flexible conductors, the cost and conductivity are challenges. [20]

5.6.2.8 Additional current weaknesses and challenges: high quality 2D films for flexible electronics

5.6.2.8.1 Challenge for integration processes: wafer scale or transfer free

The largest challenge for high quality films is economically viable preparation and transfer to the flexible substrate with sufficient quality. The overall assessment for this process is comparable to wafer scale integration and can be found in chapter 5.2 Electronics: Cross-cutting issues. Direct sheet to sheet or roll to roll transfer is also an established option for flexible electronics. A flexible substrate can be deposited (laminated or printed) on graphene where the requirements and the barrier is somewhat lower compared to wafer scale like transfer processes. The process is already quite mature, but economical feasibility is not yet sure.

The best case would be a low temperature (<100°C) CVD transfer-free process for uniform and large sheets with reasonable properties, which at the moment appears to be rather illusionary. Therefore a feasible transfer process from CVD grown graphene seems to be more likely at the moment. But the feasibility of this process also needs to be shown (especially in terms of quality and economical viability).

The scalability of these processes for large samples is not yet clear and an industrial compatibility/manufacturability is not available yet. This is an important bottleneck for lab demonstrators to be scaled up. GRM need to perform very well compared to other materials in the lab, and the applications need to be compared with other devices addressing the same functionality to justify the effort for scale up and integration.

Due to the multiple risks of unclear performance, competitiveness, production yield and cost, there are no larger investments on company level at the moment to address high quality flexible electronics with graphene/2D materials.

5.6.2.8.2 TCF: conductivity and overall value proposition not good enough

Currently graphene is not seen as an important competitor for the incumbent ITO. Ag nanowires and metal meshes are assessed to be more promising. Graphene offers good optical properties and flexibility. However, the preparation technique makes it too expensive at the moment and also the electrical properties are not good enough. It requires doping mechanisms, which need to be applied homogeneously, which is an additional step besides transfer that makes it too process intensive at the moment. Based on the current knowledge it is therefore assessed to remain a niche product in the next years.

5.6.2.9 Additional current weaknesses and challenges: flexible (resistive) random access memory

5.6.2.9.1 Maturity still low and reliability uncertain

The maturity of GO RERAM is still quite low and it is at the basic research level. Issues such as the contacting and approaching of the storage pixels need to be solved avoiding cross-talk. So far only 300 read/change/write cycles have been demonstrated (need: >10000).

5.6.2.9.2 Other carbon materials similarly promising

Other carbon base memories are similarly promising. For instance, amorphous carbon performs well in resistive memory [611]. There are also many other non-carbon technologies addressing this area.

5.6.2.10 Additional current weaknesses and challenges: flexible batteries and supercapacitors

5.6.2.10.1 Good enough?

Environmentally friendly versions of flexible batteries are low power for a given area and cost. E.g. they are a magnitude more expensive than coin cell batteries which have higher power [20]. The question remains whether the use of graphene can push the properties of flexible batteries far enough to become more attractive and feasible for more applications and interesting as competitor to coin cells.

The same is true for flexible supercapacitors, which so far are only researched at laboratory level, if at all. It is not clear to which extent they can compete with small batteries or coin cells.

5.6.3 KPIs for flexible electronics

In general KPIs for flexible devices can often be poorer than for rigid applications (but this depends on actual application and cost). Expectations for flexible devices are usually not that high. Besides, the types of KPIs used in flexible applications are essentially the same as in rigid applications. The following application KPIs are of particular relevance and importance for flexible electronics (adapted from [588]):

- Flexibility/bending radius: key selling point of flexible electronics is the flexibility, i.e. the ability to bend, roll or fold the device without damage/degradation. The requirements can range from rigid but robust to rollable/foldable.
- Complexity and density of circuits: reliability, applicability and production yield are influenced by the complexity of circuits (e.g. number of transistors) and the number of different integrated devices – i.e. sensors, switches, power supply, logic – on the same substrate.
- Lifetime / stability / homogeneity / reliability: operational lifetime, shelf life, stability against the environment, other materials and solvents, and homogeneity of the materials are important for successful applications.
- Power efficiency: is important for many applications, especially mobile and light weight ones. the conversion efficiency of light to electricity or electricity to light is key for photovoltaics or LEDs, respectively.
- Environmental and toxicological safety: “environmentally friendly electronics” can be an important USP. This includes no or limited use of toxic materials in the production processes and products, the latter especially for disposable products. Also lower energy consumption and resource need in production and product are relevant. Products in contact with the environment (e.g. soil/drinking water/food) sensors) and in contact with the body, e.g. clothing, healthcare, wellbeing, fitness need to avoid any materials with toxicological issues or environmental, health and safety (EHS) conformity needs to be assessed and proven.
- Cost: costs have to be low enough, but premium can be charged for added functionalities. E.g. for rollable displays, a cost premium over conventional rigid displays may be accepted. In some applications low cost will be a major driver or barrier, e.g. in packaging. Typically it is rather tough to bring a new technology to the market only by cost arguments.

KPIs in terms of technology, processes and material are (adapted from [588]):

- Electrical performance: Operating frequency/switching speed, energy (conversion) efficiency, brightness and/or energy storage capacity are products performance indicators that depend on charge carrier mobility and bandgap of the semiconductor, conductivity of the conductor and/or the dielectric properties of the dielectric materials. Thus, mobility, efficiency, conductivity, operating voltage, current density, on/off currents are major electrical performance parameters. See the application focused chapters for more information.

- Barrier properties / environmental stability: depending on the sensitivity of the material to oxygen and moisture, barrier properties and protective layers can be relevant. The necessary barrier properties vary for the different applications and use cases over several orders of magnitude, depending on expected life time, shelf life, stability, reliability, purpose and context of use etc.
- Resolution / printing registration / uniformity: reduced feature sizes and accurate overlay layers are important for printed and transferred devices and can be relevant for certain applications (e.g. when miniaturization and small footprints are needed). For high performing applications also high uniformity and defect free layers over large areas are critical.
- Processing and process parameters: The process conditions are important aspects for the later cost of a product as well as for the barrier to integrate or use a technology. Speed, needed temperatures, used solvents, necessary ambient conditions, vacuum, inert gas atmosphere, etc. are relevant process parameters that need to fit to the targeted applications. Adjustment and compatibility of the process parameters for different materials is important for working flexible systems and devices. Improving process characteristics can be decisive for the success of a material/technology. Reaching better/fitting processability is so important that industry even seeks it at a certain expense of improving mobility or sacrificing device performance.
- Yield: Yield is strongly correlated to processing and a high yield production is prerequisite to achieve high volume and low cost. Safe and reliably processes with either a known and certain range of process parameters (safe parameter space) and/or a good process control , in-line quality control, tailored materials and circuit designs are cornerstones of high yield processes.

5.6.3.1 Flexible electronics (transistors/active components)

Felxible transistors are usually thin film transistors (TFT)

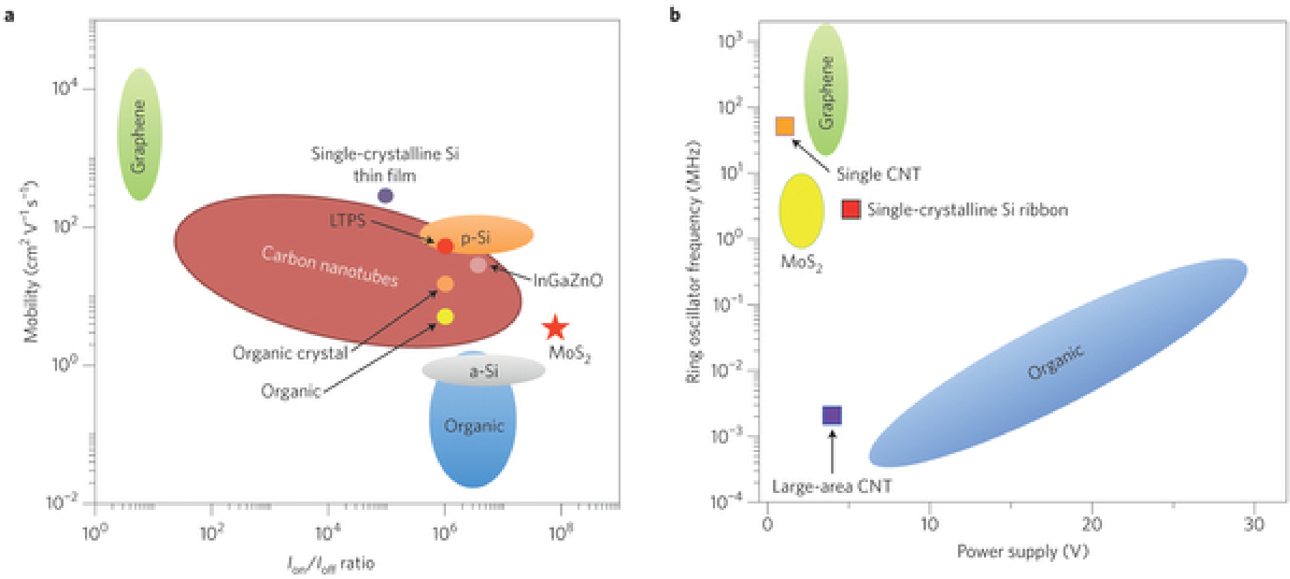


Figure 108: Figures of merit for flexible electronics transistors and comparison of different competing materials. From [510].

RFIC, flexible radio, flexible HF electronics/transistors, photodetectors: see 5.3.3 KPIs for telecommunication, optoelectronics & photonics.

Flexible sensors (gas, bio, magnetic): see 5.5.3 KPIs for sensors.

5.6.3.2 Flexible transparent conductive films (TCF)

For TCF: conductivity (Ω/□), transmission spectrum, patterning/etchability, flexibility, optical properties, roughness.

Prices of the incumbent (ITO) are 18-23 $/sqm in 2015 (reduced prices since 2013, before that it was 25-35 $/sqm. [592]

Table 69: KPIs of several competing TCF technologies.

Material	Transmittance	Sheet resistance /(Ω/□)	Remark
ITO	80-85%	60-200	on PET
Metal Mesh	>85%	5-30	PolyIC
Ag nanowire	>90%	10	Cambrios ClearOhm, wet process
CNT/CNB	95-98%	100-300	Canatu CNB Flex
PEDOT	85-95%	100-350	Agfa, better performances under development
Graphene	90-97%	~30-125	[586]

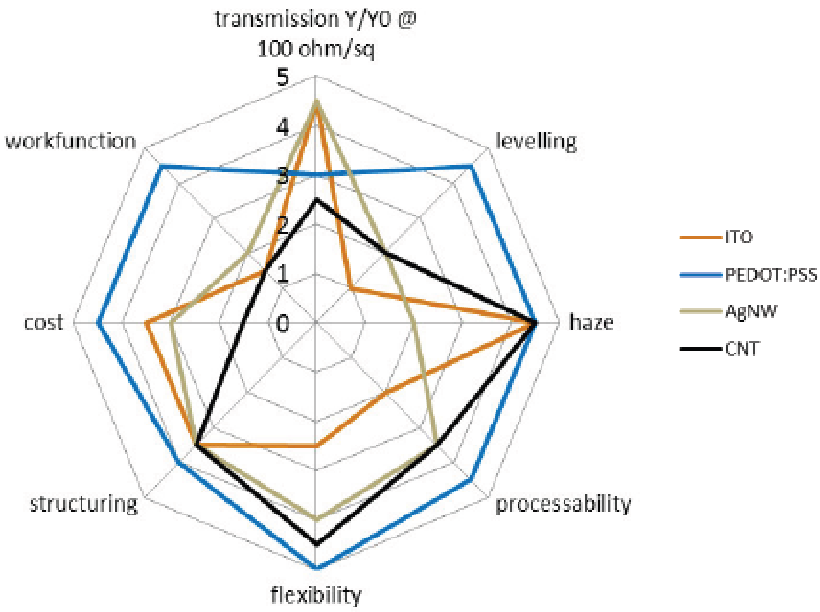


Figure 109: Key properties of competing technologies for TCF. [588]

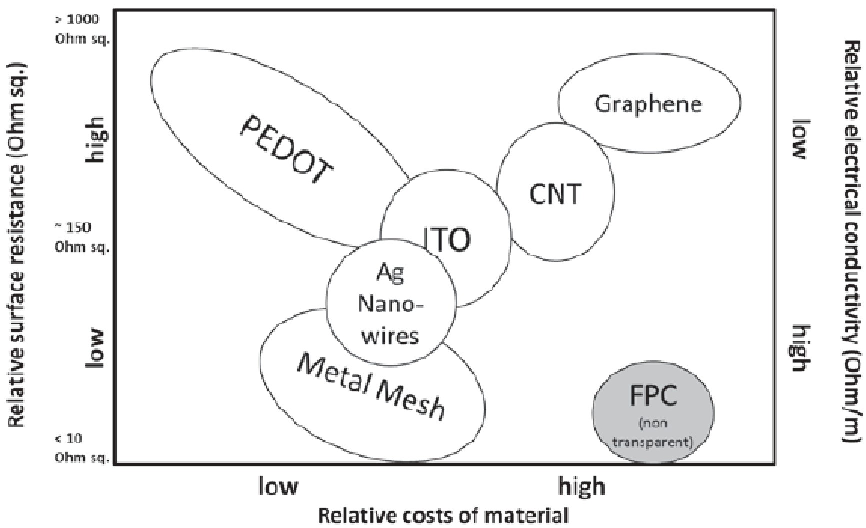


Figure 110: Performance vs. Cost of several materials. [588]

5.6.3.3 Printed electronics & cond. inks (conductors)

Cond. Inks and printed conductors:

- Printing on 3D objects (e.g. aerosol), in mold
- Ω/□/mil or Ω/□/print; 1 Ω/□/print has been achieved by Vorbeck 3 years ago
- Silver inks: >10^6S/m, <0.1Ω/□ (25µm film thickness)
- Carbon inks: ~50Ω/□ (25µm film thickness)
- First graphene inks (on market), best performance: ~10-50 Ω/□ (25µm film thickness)

- solar cell interconnect: 1/100Ω/□ necessary
- Flexibility: 100k cycles with bending radius to thickness ratio of 100

Typical prices:

- pure Silver metal: ~400€/kg
- pure polymer: 16€/kg
- pure graphite: 0,5-2€/kg
- pure solvent: 1€/kg
- 1l high grade silver ink retail: 1000€/kg

Table 70: Typical material cost of conductive inks. Typical content: 40-60%. Adapted from [612]

	Conductivity	Raw material cost /kg
45% Ag content	30-45 mΩ/□ @10µm	~190€
65% Ag content	30 mΩ/□ @10µm	~120€
45% carbon content	15 Ω/□ @1mm	~2.5€

5.6.3.4 Flexible memory

80kB storage for smartcards, 10000 read/change/write cycles

KPIs are: manufacturing cost, production capacity, disposability, retention time, envrion-mental stability and bit error rate. [588]

Important material characteristics are: memory film uniformity, memory cell drive voltage, endurance, , compatibility with (flexible/printed) transistor, preparation/printing method, electrode conductivity, production conditions (inert atmosphere, …) [588]

5.6.3.5 Flexible batteries and supercapacitors

For a full set of KPIs please refer to the batteries and supercapacitors chapter (0 and 4.3, respectively).

Application KPIs are: Energy density, power density, voltage, (peak) current, lifetime, cycles, temperature range, bending radius [588]

Important material parameters are: layer thickness, ionic conductivity, thermal stability, encapsulation/gas permeation, flexibility [588]

5.6.3.6 E-textiles, functional textiles

Use for functional textiles: Performance requirements in terms of stretchability, adhesion and washability (>50 washing cycles) are very important and stringent.

5.6.4 Roadmap for flexible electronics

5.6.4.1 Current maturity: 'lab demonstration for real flexible electronics, marketed conductive inks and flexible conductors'

Conductive inks are on the market (e.g. Heraeus graphene-based conductive inks, Vorbeck, Sigma Aldrich and others), but still have potential to be improved.

Flexible sensors are marketed, but only where inks are used as a conductor. There are no marketed flexible products where graphene/2D materials actually provide active electronic functionality.

TCFs are to a certain extent marketed in China (Wuxi), but it is questionable if these are commercially viable and the broad use in a device is pending. There are rumours that graphene might be used in OLED displays in the next few years. However, issues of doping and long term stability and the production process are still not resolved yet.

CVD based films are not commercially mature or feasible at the moment.

The majority of flexible electronics based on graphene is at the lab demonstrator stage. Memory and more comprehensive applications (transistors, high quality film) have a lower maturity than printed conductors.

Other 2D materials and their heterostructures have promising properties and first lab scale demonstrators of flexible high quality or printed devices exist. However, the maturity is much lower than for graphene, although the overall prospect for these materials to become an enabler for flexible electronics is not so bad.

5.6.4.2 Barriers/challenges (summarized)

Value chains:

- Completely new value chain needed with typically different stakeholders than in conventional electronics
- Seamless value chain for flexible electronics in general and for graphene/2D materials does not exist yet
- Different parts of the value chain are at different readiness levels
- Missing material standards and characterization tools

Markets:

- Markets are broad, but finding the most promising application is tricky and demands on the one hand broad screening, on the other hand focussing of resources

- Conventional electronics/batteries as strong incumbent hinder new technologies (although the new technology might fit better to certain applications)
- Credibility gap: flexible electronics has not lived up to its promises yet. Besides it has not yet delivered the "cheap and high volume" products that are often promised.

Devices/Production:

- Transformation of lab scale results to relevant production environments without losing too much performance. The gap between performance and processing limits and slows down application development, industry interest and commercialization [588]
- Maintaining the microscopic properties of graphene on flexible substrates
- Low maturity of flexible electronics besides flexible conductive paths
- Process optimization is crucial and as important as demonstration of devices
- Unclear conductivity depending on frequency (especially in the GHz range) for ink based and CVD based (important for antennas and other RF applications, CVD graphene is currently not conductive enough for antennas, inks can create the conductivity via the thickness)
- Other 2D materials (inks and films) are potentially promising (e.g. for flexible logic, sensors) but the maturity is still quite low and it is yet unclear how actual performances compare to other materials
- Missing (stable) logic/comparison electronics is one of the major bottle necks in the emergency of flexible large area electronic devices
- Functionalization with processes compatible with the production of the original material (seamless integration) needed
- Hybrid electronics: seamless integration and packaging (pick and place, bonding)
- Reliability, lifetime, shelf life, long term stability not proven
- Compatibility between different processes and technologies (integration of printed, transferred, CMOS etc.)
- Contacting of films/devices
- In line control and characterisation tool missing

End of life and sustainability

- Usage of hazardous materials
- Unclear end of life properties (biodegradability, recycling, etc.)
- Unclear health and safety properties, perception of nanomaterials as dangerous

Conductive inks

- Flexible conductor: no principle/fundamental technical challenge/limitation at the moment but still further engineering and market assessment needed
- Need for large area (roll to roll) processes to achieve good processability and good conductivity
- Complex market and unclear value of "niche" between metal inks and standard carbon inks
- No replacement of metal inks (but expectations are often that it can replace metal inks)
- Ink formulation knowledge, property tuning and engineering knowledge for optimization (i.e. regarding substrate adhesion, better performance and processability, stability and shelf life)
- Understanding of particle interfaces/contact between flakes
- Value chain and consistent supply in sufficient amounts

High quality films:

- Addresses areas with strong incumbents (e.g. TCF)
- Reliable and larger scale preparation and transfer of high quality films on flexible substrates (wafer scale integration related challenges for flexible substrates)
- Other 2D materials: lower efforts and less knowledge
- Clear elaboration of USP and benchmark

Flexible batteries

- Increased capacity (per footprint) and decrease cost
- Competition with incumbent (rigid) coin cells
- See batteries chapter

Flexible memory

- Contest with other emerging technologies (e.g. amorphous carbon)
- Low maturity
- Increased storage density and read/write cyclability
- How to address the single pixels without cross-talk

5.6.4.3 Potential actions

If the area of graphene/2D in flexible electronics is seen as promising for Europe and the topic is further pushed, the following potential actions, derived from the challenges, are suggested:

General

- benchmark with common and emerging technologies (flexible and **not flexible**) by means of processability and functionality; depending on the targeted application, non-flexible solutions (e.g. small logic chips for a few cents) might be the competitor rather than other flexible approaches
- Explore different applications and focus early on most promising applications
- Investigate the potential of other 2D materials and heterostructures, focus on the ones that are easy to produce/integrate and have a higher potential for industrial manufacturing (also in terms of stability in air, etc.)
- Explore stretchability
- Engage with printed and flexible electronics community and build on existing efforts, many challenges are similar and actions can be combined (e.g. packaging, hybrid integration, pick and place etc.)
- Link with design companies and creative product designers, demonstrate capabilities
- Engage with researchers that address the markets (e.g. fibre/textile researchers, automotive researchers, design)
- Analyse existing and potential value chains and how graphene/2D materials can fit into them
- Address USPs besides potential cost reduction, e.g. added value through lower cost for lower customized volumes
- Address existing standards and identify gaps where additional standards are needed
- Investigate in-line quality control, measurement and characterisation
- Address processability, which is as important as demonstrators and prototypes
- Investigate interfaces and grain boundaries, electrical and mechanical properties under different conditions (frequency, environment)

- Demonstrate compatibility with different processes (also in terms of compatibility of high quality films and inks and the related processes)
- Explore/prove reliability, lifetime, shelf life and long term stability of devices and materials
- Investigate process compatible functionalization methods
- Explore end of life properties (recyclability, combustibility, health & safety), explore especially process that avoid hazardous substances

Conductive inks

- Address ink standards/application standards
- Further develop cost efficient roll to roll processes
- Investigate printing on 3D objects (aerosol printing), in mold electronics
- Engage with researchers with printing/ink expertise, gain formulation expertise
- Further explore large area printing (with adequate resolution)
- Address USPs towards metal and carbon inks
- Address shelf life and stability in solution as well as in the device
- Investigate film forming and compatible post processing

High quality films:

- Further explore possibilities beyond conductive films (e.g. transistors, RF, etc.) and elaborate clear USPs and benchmarks
- Further investigate other 2D materials for flexibl electronics (preparation and process technologies as well as demonstrators based on those)

Flexible batteries_

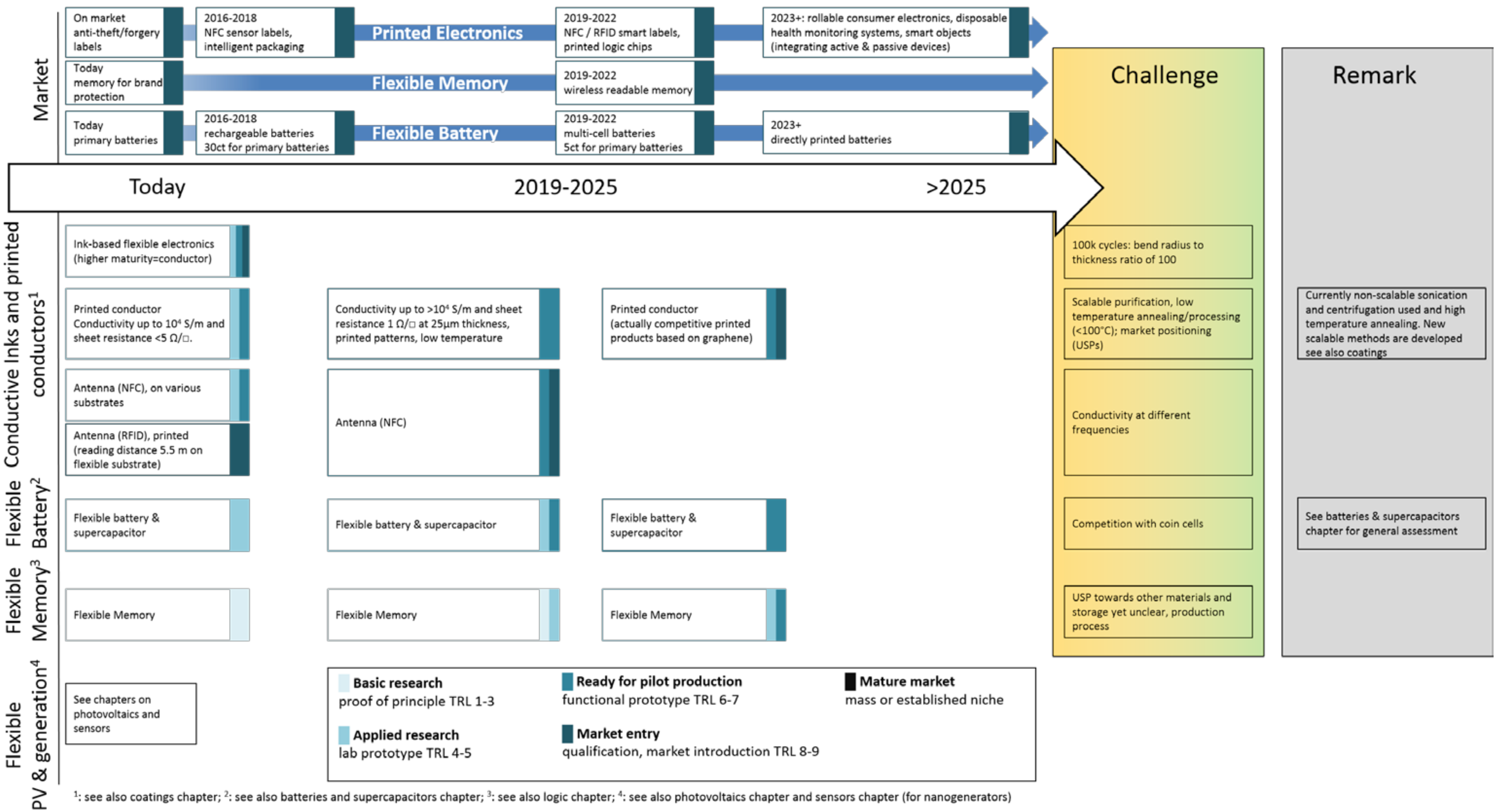
- Benchmark with coin cells

Flexible memory

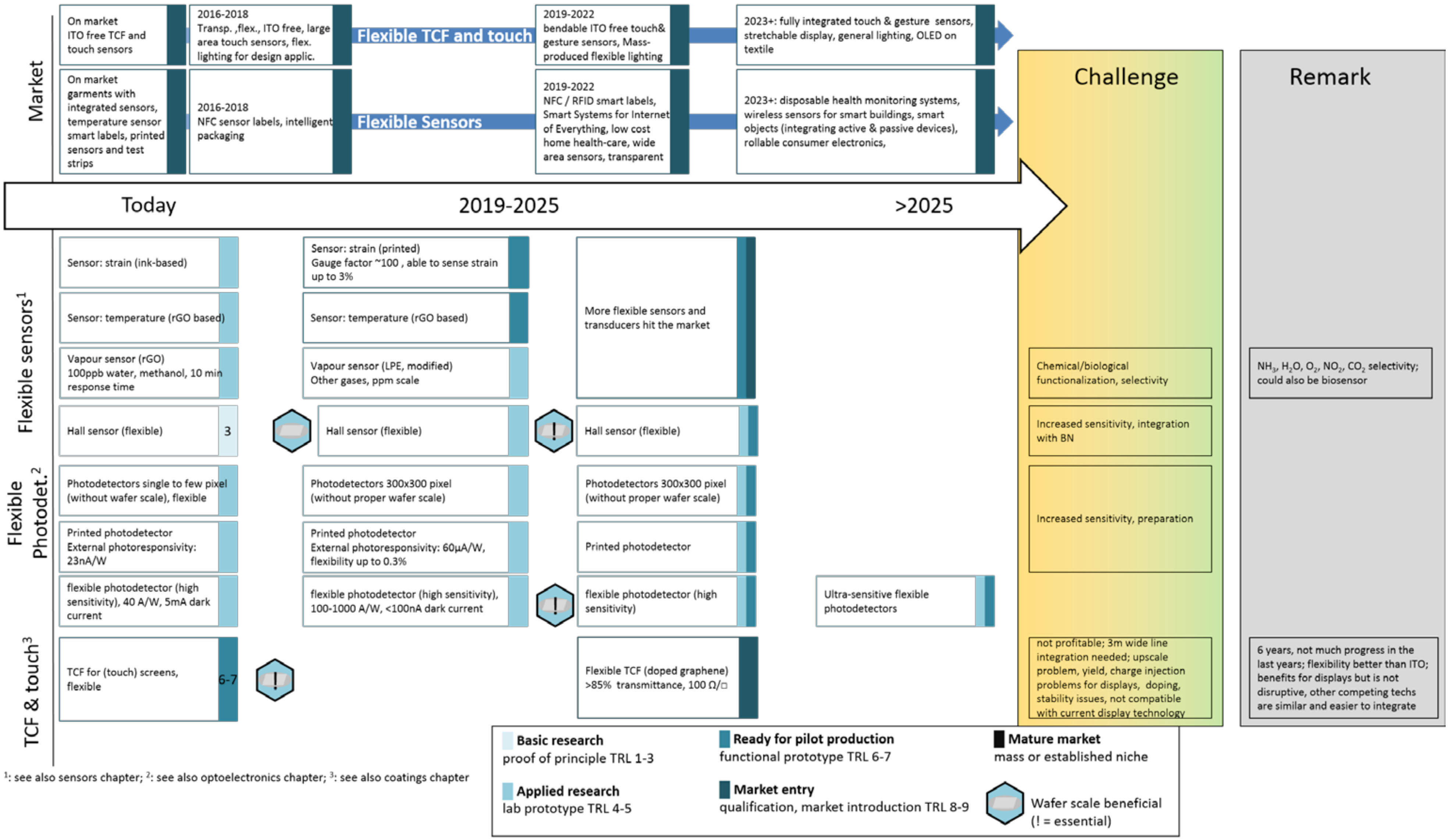
- Investigate whether graphene/GO is a better material than competing ones
- Increase maturity, investigate possibilities to increase storage density and read/write cycles
- Figure out best way of preparation
- Investigate contacting and cross-talk

5.6.4.4 Roadmap

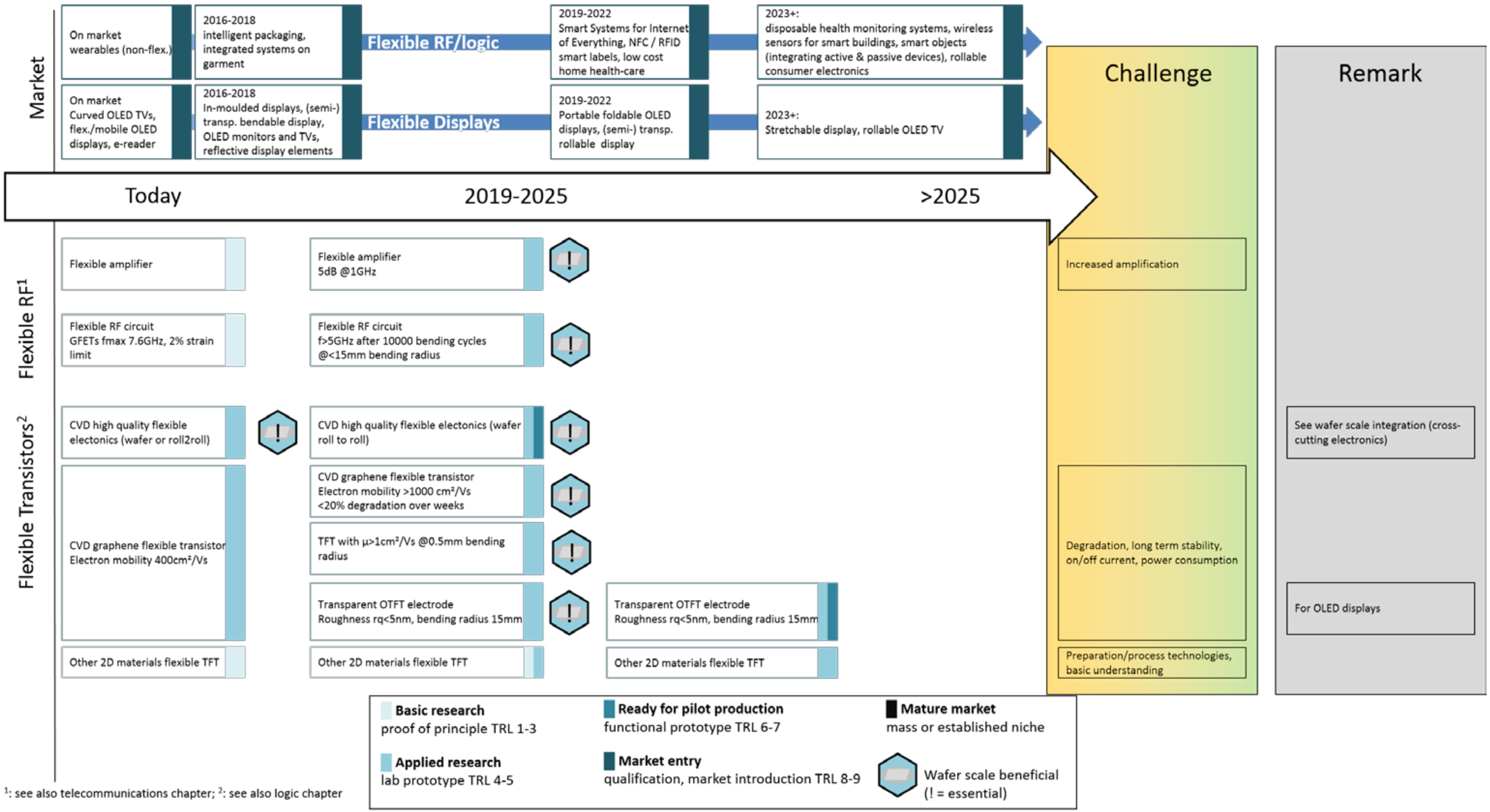
The proof of concept of fully flexible integrated systems (TRL4/5) is expected by 2019.



Market sources: [20, 588]



Market sources: [20, 588]



Market sources: [588]

5.6.5 Conclusion flexible electronics

Flexible electronics is cross-lying to all electronics applications. The potentially added functionality of flexibility is one of the key propositions of 2D materials. Therefore, 2D materials have a better technological potential for any application that requires flexibility.

As the actual flexible/printed electronics market (besides printed circuit boards and OLED displays) is still juvenile, there are chances of early entry. But many of the targeted applications are consumer electronics related where the actual integrators are quite often not in Europe. On the other hand, another strong integrator sector is automotive, where Europe is strong. Besides, many first movers of flexible electronics are in Europe and the political support is strong.

In terms of printed electronics, conductive inks are already on the market, also made of graphene. They are positioned between carbon black inks and metal inks in terms of pricing and conductivity. The market chances in this void between carbon black inks and metal inks are still not absolutely clear, but there are some indications that it might be an interesting market position. The actual applications in that area need to be identified. Many applications are already solved with metal inks (although the conductivity is higher than needed), e.g. RFID antennas made of etched aluminium or copper reach low prices. Other technologies are also emerging (e.g. metal nanoparticles, CNT). 2D material based inks can only compete, when they have an additional added value (e.g. added (electronic) functionality, substrate independence, simpler preparation, corrosion resistance, recyclability, lower cost).

For more advanced applications beyond conductive paths (i.e. transistors, sensors) lab demonstrators are available and need to be further developed to assess the industrial compatibility and commercial viability (printed and high quality films). Printed 2D heterostructures, e.g. for logic, might become an enabler, because there is currently no reliable material solution for flexible and printed logic. However, these 2D material inks are still at an early stage of development and it is yet unclear whether they can live up to the expectations. Flexible solutions often do not need to meet highest performances and the technological requirements are often lower than for non-flexible solutions. This lowers the barrier of entry. On the other hand, there are many other, more mature materials (conductive polymers or small molecules) that are already entering the market. Also silicon based rigid chips are available with very small form factors and for very low prices, so that introduction onto flexible structures is possible.

The upcoming and growing wearables and internet of things markets are the major drivers for flexible and lightweight electronics solutions, sometimes with rather simple functionalities. Broad markets are addressed, such as logistics, smart packaging, advertisement, health, apparel, consumer electronics). These trends create a strong market pull for conformable solutions, however, some of these markets are also very price sensitive. On the other hand, these markets also offer many niches for early market introduction.

In conclusion, the high quality film based applications often promise larger technological added values but have a higher barrier for integration, whereas flake-based mass applications (e.g. printed electronics or composites) have a lower barrier for integration but usually lead to less disruptive and smaller technological improvements.

Table 71: Assessment of market and technological potential of graphene/2D materials use in flexible electronics on a scale - -, -, 0, +, ++

Flexible electronics	Current technological potential (USP)	Market potential (EU perspective)
Flexible TFT	+	0/+
Flexible HF electronics	++	+
Flexible sensors	++	++
Printed electronics/conductive inks	0/+	+
Flexible antennas	0/+	+
Flexible transparent conductive films	0	-
Flexible memory	0	+
Flexible batteries	0/+	+
Flexible logic (e.g. TMDs)	+	-/0

5.7 Summary electronics & photonics

Due to the interesting electronic and optical properties of graphene and 2D materials, it is obvious that many different applications are possible in this field. It is additionally a field that often deals with thin films and layered materials, although the change from bulk to 2D materials actually reflects a paradigm change. The market perspective is generally very interesting, as large and typically growing markets are addressed. Especially trends like wireless networks/5G and beyond, ubiquitous computing, wearables or internet of things create demands for new technologies in electronics, optoelectronics, power supply and sensors. However, the market is also highly competitive and there are stronger industries in USA and Asia (especially Korea and Japan). Europe is particularly strong in More than Moore technologies and special logic applications, e.g. for vertically integrated markets, such as automotive, energy, security, smartcards, industrial electronics and data processing electronics. European companies possess leading positions in sensors and MEMS markets. Besides that, Europe has strengths in virtual components and low power processors, and in the supply of equipment, materials and IP (Intellectual Property) into the value chain. First movers in the flexible electronics area are in Europe and the political support is strong, so that this emerging field appears to be also interesting from a European perspective.

A major obstacle for many applications is economically feasible wafer scale integration and scalable high quality preparation of graphene and other 2D material films with sufficient quality and yield. Open questions regard contacting, delamination, transfer processes, quality and yield. If these processes are not viable, many applications will only remain in niche and low volume applications, if at all. Only a few applications in sensors, flexible memory, flexible batteries and flexible conductors/electronics are currently possible with printed solutions and thus do not need wafer scale integration. On the other hand, if wafer scale integration works, many applications suddenly become interesting and viable.

A first proof is needed for a simple demonstrator prepared by viable processes, so that the risk for industry to take up the development is lowered. This risk is currently too high and there is no reliable ecosystem available, although interest exists from end users and OEM companies to investigate graphene further. However, they will not integrate the material and as long as no pilot production is demonstrated feasibly, no company or foundry will invest heavily. Usually a 10x performance improvement and/or 10x cost improvement (or a mixture of both) along with a realistic integration scheme is needed so that an investment into a new technology is realized (in contrast to most bulk applications, where usually both cost and performance need to be improved at the same time). This is not a fundamental problem, as many questions are still open and under investigation due to the novelty of the 2D material technology. But at the same time it is not yet foreseeable for graphene/2D materials, whether the threshold of performance/demonstration and viable production can be met. The incumbents are very strong and everything that can be realized with silicon and existing technologies will be realized. Usually new materials/technologies need more than 10 years until broader diffusion in the electronics industry.

In terms of applications from a functional point of view, hybrid approaches with silicon appear promising, where graphene is added in the back-end-of-line or back end to deliver additional functionalities (e.g. optoelectronics, THz, sensors). Besides that, flexible applications appear to be very interesting for 2D materials, especially as there is no leading incumbent (silicon does not perform well) and there is still a need for new materials. Flexible solutions often have lower requirements than non-flexible solutions, which reduces the barrier for commercialization.

Niche markets for early adoption and potential later scale up are possible in sensors, THz, radar applications and photonics applications (lasers). Logic and HF transistors typically address larger volumes and need scalable processes. From a technological point of view, especially flexible HF electronics appear interesting. In optoelectronics especially optical switches/modulators, ultrafast photodetectors and hyperspectral imaging detectors are promising from a technological point of view. Furthermore, 2D materials in general have a particular advantage in all kinds of sensors due to the high sensitivity of electrical properties on the surrounding.

For beyond CMOS applications in logic and memory, the silicon era will reach limits in the next 10-15 years. To address this window of opportunity, breakthroughs in novel technologies have to be available on lab and probably pilot scale in the next 5 years. TMDs recently had such a breakthrough making them a reasonable candidate. For completely new concepts, such as spintronics, graphene or 2D materials might have an opportunity.

Major common challenges throughout all electronics applications are functionalization/homogeneous doping and contacting. Reliability, lifetime and end of life properties, as well as health and safety assessments are recurring topics to be addressed. USPs towards competing, emerging and state of the art technologies need to be clearly and objectively elaborated based on the targeted functionality.

Table 72: Summarized assessment table of all electronics and photonics application areas primarily sorted by European market potential and secondary sorted by USP.

Cross-cutting electronics	**Current technological potential (USP)**	**Market potential (EU perspective)**
Flexible sensors	++	++
Photonic networks	++	++
Biosensors	+	++
Wireless communication	+	++
Pressure sensors/microphones/NEMS	0/+	++
Photodetectors/Imaging systems/Spectrometers	++	+
Magnetic sensors	++	+
Flexible HF electronics	++	+

Cross-cutting electronics	Current technological potential (USP)	Market potential (EU perspective)
Optical switches and modulators	++	+
Electronics in general	+	+
Wafer scale CMOS integration	+	+
Laser/photonics	+	+
Gas/chemical sensors	+	+
Mechanical force/stress/strain/mass sensors	0/+	+
Printed electronics/conductive inks	0/+	+
Flexible batteries	0/+	+
Flexible antennas	0/+	+
HF transistors	0/+	+
Nanogenerators/micro-energy harvesters	0/+?	+
Equipment (wafer scale)	0	+
Flexible memory	0	+
Resonators	+	0/+
Antennas (large area, unobtrusive)	-	0/+
Flexible TFT	+	0/+
New transistors (novel charge-based transistors, TFET, GBT)	0	0/+(low power)
Interconnects	+	0

Cross-cutting electronics	**Current technological potential (USP)**	**Market potential (EU perspective)**
Thermal material	+	0
Barrier material	+	0
THz/sub-mm wave components	+	0
Flexible logic (e.g. TMDs)	+	-/0
Spintronics	+	-/0
2D channel FET (MoS2)	+	-
GFET	-	-
Flexible transparent conductive films	0	-