Report on Future Technologies for Advanced Functionality

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Responsible partner: Fraunhofer IISB
Lead Author: Markus Pfeffer

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Executive Summary

Ubiquitous intelligence in the form of the deployment of smart devices in a myriad of possible scenarios – from the smart wearables and smart appliances to the electrified autonomous vehicles, industry 5.0, smart grids and digital healthtech – is based on the functional diversification of semiconductor technologies. A key challenge in the development of smart systems is that a "one size fits all" approach is not possible. In this context, International cooperation is essential for accelerating technological innovation and strengthening semiconductor value chains and is in line with the objectives of the EU Chips Act

Key drivers for research and development include digitalization, which enables immediate digitization of analog measurements, and wireless connectivity that facilitates the low-cost installation of Internet of Things (IoT) devices. Besides energy-efficient power management and low-power devices, the need for energy harvesting systems is increasing, particularly in autonomous applications that reduce reliance on disposable batteries. Additionally, advancements in new sensor technologies and Edge AI enhance the utilization of data from sensors, while data fusion allows for smarter insights by combining information from various sources. Ensuring data security and reliability is also critical. The development of eco-friendly materials and environmental sustainability through the full lifecycle of the smart systems are also a significant drivers.

The investigation covered various topics, including the challenges in sensor design, the significance of III-V semiconductors in photonics, and the need for environmentally friendly materials in energy harvesting. International collaboration is vital for progressing power devices used in industrial and automotive sectors, along with research into high-temperature applications and emerging materials like ultra-wide bandgap materials. Overall, such cooperation is pivotal for driving future advancements in semiconductor technologies.

1 Overview

1.1 Purpose

The purpose of this deliverable is to present the findings from the analysis of existing international roadmaps (e.g., IRDS, IPSR-I, ECS-SRIA, NEREID) and their connections to other relevant CSAs (e.g., those focused on graphene and quantum computing), as well as insights from previous studies, knowledge from the consortium and partner network, desk research, and brainstorming sessions. This analysis focuses on future technologies in advanced functionalities that hold potential for exploitation through collaboration. Additional objectives include creating a comprehensive map of international research on future technologies and comparing the European status with that of other leading countries in areas identified as critical for Europe.

1.2 Responsibilities

The partner organization, Fraunhofer IISB, is responsible for collecting information from all ICOS partners in task 3.2 and compiling a comprehensive report on future technologies for advanced functionality.

2 Future Technologies for Advanced Functionality

International cooperation is vital for accelerating technological innovation and enhancing the resilience of semiconductor value chains, which aligns with the objectives of the EU Chips Act. This collaboration is crucial for presenting emerging technologies in advanced functionalities and groundbreaking innovations, while also addressing the expected impacts on global cooperation.

In the domain of Advanced Functionality, key technological advancements have been collected and categorized to create an overview of current trends and challenges. The identified drivers for research and development are:

- **Digitalization**: Analog measurement results are immediately digitized on-site.
- **Wireless connectivity for IoT devices**: Facilitates easy, low-cost installation of sensor devices.
- **Autonomous systems**: Wireless connectivity and the (desired) freedom from disposable batteries increase the need for energy harvesting.
- **Development of new sensor technologies fused with advance in material science** will increase functionality, render them fit-for-purpose and open up new markets.
- **Access to powerful computation (Edge AI)**: Increases the usage of data-producing sensors.
- **Fusion of sensor data**: Combining data from different sources enables new, improved, and smarter data for users.
- **Data security and reliability**: Data should be accurate and reliable, and protected from unauthorized access.
- **Electrification of transportation and energy conversion**: Requires efficient power devices.

The following topics were investigated in the following section of this report:

- **Sensors**: Designing sensors requires advanced design tools, including multi-physics simulation at challenging geometrical dimensions and scales. Sensors are often sensitive to packaging and interferences, and material properties are sometimes not well enough understood. Additionally, some packaging technologies and materials are not easily available in Europe. The market for sensors is fragmented into segments, making the cost of sensor design, manufacturing, and packaging prohibitively expensive in some cases. Key challenges also remain in developing sensors that are fit-for-purpose in many different market applications. Increased sensitivity and functionality are expected to be derived from combining new sensors architecture and miniaturization with materials chemistry.

- **Semiconductor-based photonics**: III-V semiconductors are still essential for light sources due to their superior optical properties. However, photonic packaging remains challenging and expensive, contributing to long product development cycles.
- **Energy harvesting**: Improving energy harvesting (EH) performance and efficiency is as important as developing environmentally friendly materials. This includes replacing toxic or rare materials currently in use, such as lead-based piezoelectrics, Bi2Te3 for thermoelectrics, and NdFeB (neodymium) for electromagnetic conversion. The use of nanotechnologies is expected to enhance the performance of these concepts overall. Additionally, developing flexible and low-cost approaches for wearable applications, such as e-health, is crucial. A comprehensive system design that combines all aspects of the fabrication process, harvester structure, power conversion circuits, and storage will be essential for increasing power generation efficiency.
- **Power devices**: International cooperation is key to accelerating technological innovation, especially in smart energy research and development. In the field of power semiconductors for future technologies, various devices for industrial and automotive applications are already on the market. However, cost pressures and technological innovation are driving performance to the next level. Research needs and gaps have been identified to make further progress in smart energy.
- **Others**: Additionally, research activities in other areas, such as high-temperature applications and emerging materials like ultra-wide bandgap materials, e.g., AlN, were discussed.

2.1 Sensors

As of 2024, there are approximately 18.8 billion connected IoT devices globally and is expected to reach approximately 32.1 billion by 2030. The role of edge-of-the cloud devices and the generation of big data are expected to drive the creation of new ecosystems and include 11% of the world economy by 2030. The compound annual growth rate (CAGR) for the smart sensors market is expected to be around 19.0% between 2024 and 2030. North America/Canada having the largest share of the market followed closely by the Europe, Asia and the rest of the world. The largest sectors globally that employ smart sensor technology: healthcare, automotive, environment, agriculture, smart cities, and energy applications.

The Technology market are shown in Figure 1 which is expected to be dominated by

1. MEMS (Micro-Electro-Mechanical Systems): This segment is expected to hold a significant share of the market, driven by its applications in consumer electronics, automotive, and industrial sectors estimated to reach $35 billion by 2030
2. CMOS (Complementary Metal-Oxide-Semiconductor): CMOS sensors, primarily used in imaging applications, are anticipated to grow substantially estimated to reach $25 billion by 2030
3. Optical: With the increasing demand for miniaturized and integrated sensor solutions estimated to reach $20 billion by 2030

Figure 1: Global Smart Sensors Market is expected to reach $109.4 billion by 2030 source Data bridge

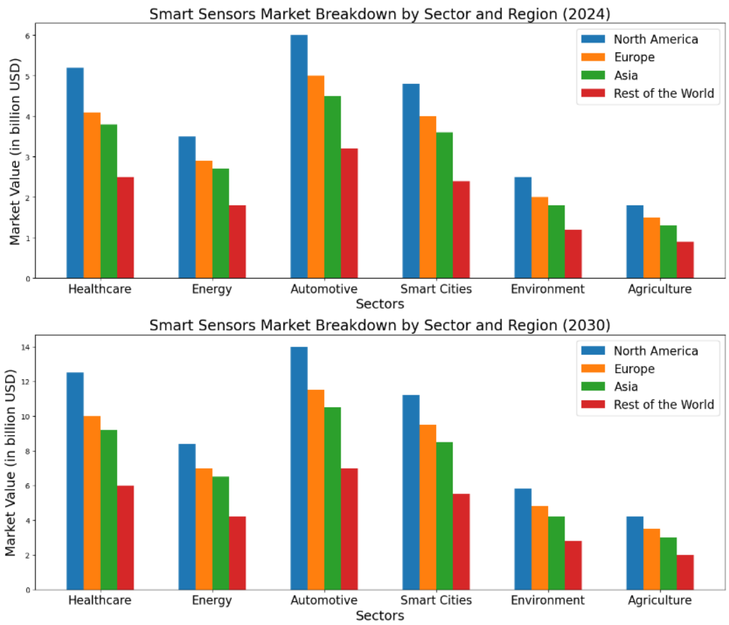


Figure 2: Global Smart Sensors broken down by sector and geopolitical area

The sensor technology market can be further broken down by sector with considerable growth forecast: Healthcare: from $15.6 to $37.7 billion, Energy from $10.9 to $26.1 billion; Automotive $18.7 to $43 billion, Smart Cities $14.8 to $35 billion, Environment from $7.5 to $17.6 billion, and Agriculture from $5 to $15 billion and also by geo-political area, see Figure 2. These data represent considerable growth for the entire smart sensors market. However, the development of smart sensor systems faces challenges due to the diverse deployment scenarios across different applications. This complexity necessitates the creation of tailored solutions rather than a "one size fits all" approach.

The discussion on sensor concepts has evolved over the years. Initially, the focus included motion and pressure sensors, advanced drive assistance systems, environmental sensors, and agri-food sensors. The latest concepts for 2024 introduce additional categories, such as energy sensors and sensors specifically designed for smart cities. These innovations reflect the growing demand for versatile and adaptable sensor solutions.

Amidst this evolution, challenges remain prominent. The landscape of smart sensors has shifted, leading to an increased emphasis on environmental sustainability. As a result, there is a pressing need for highly sensitive and versatile sensors that require the development of advanced, sustainable materials. This research is being driven by policy such as the European Green Deal, the Nitrates Directive and the Water FrameWork Directive and fourth watchlist. Consequently, research is increasingly directed toward controlling molecular interactions at the nanoscale, which is essential for enhancing sensor performance and sensitivity.

One noteworthy initiative is the Horizon Europe BioSensei Project, which focuses on utilizing living cells as indicators of target molecules. This project aims to develop multi-modal sensing modules that integrate and package live cells sustainably. Real-time, cell-based monitoring systems are expected to provide valuable data directly to end-users, enhancing the responsiveness and effectiveness of sensor applications (see fig 2.1.1).

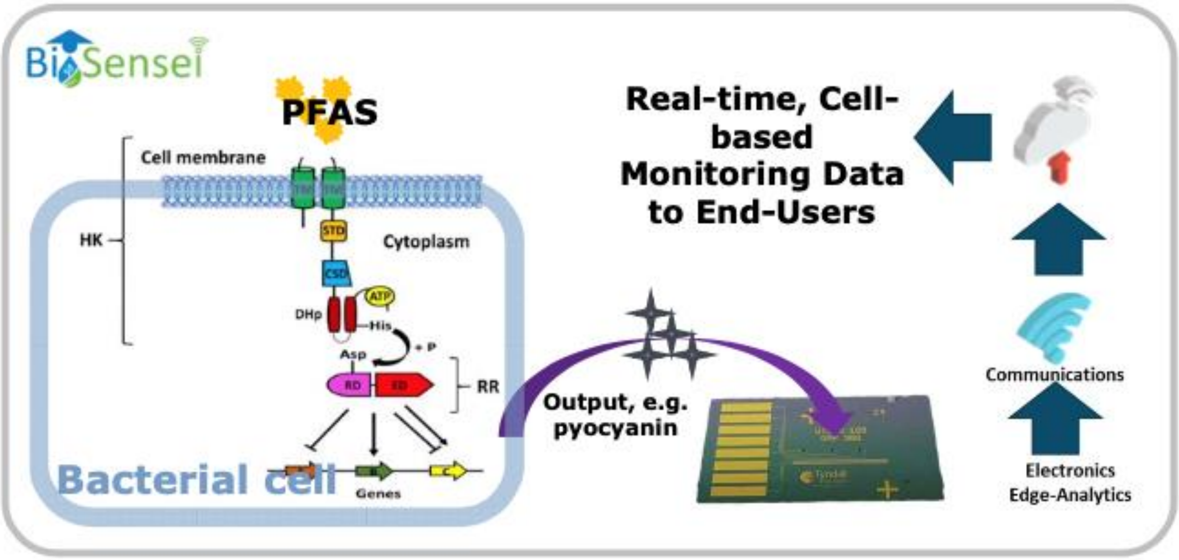


Fig. 2.1.1: Real-time, cell-based monitoring systems to provide valuable data directly to end-users

In conclusion, the global smart sensor market continues to expand at an impressive rate, driven by the increasing proliferation of IoT devices and a strong focus on sustainability. While the challenges identified in earlier assessments remain relevant, there is a clear trajectory toward innovation in sensor technology and materials integration. The future of smart sensors is poised to transform various sectors, enhancing efficiency, sustainability, and the overall quality of life.

2.2 Energy harvesting

The recent discussion on emerging technologies in advanced computation, advanced functionalities, and ground-breaking technologies highlighted the significant market growth of connected devices, particularly in the Internet of Things (IoT), healthcare, wearables, and home automation. A crucial aspect of this growth is the need for energy supply, especially in the range of milliwatts to micro-watts, as traditional batteries often prove inadequate due to cost, complexity, and environmental constraints.

Among various energy harvesting (EH) methods (e.g. solar, RF, etc.), mechanical and thermal energy harvesting, were explored. Mechanical energy harvesting usually exploits 3 different principles: Electrostatic, Piezoelectric and Electromagnetic effect. The piezoelectric conversion in particular utilizes mechanical resonators. Current trends in this area include the investigation of porous materials and nanostructured materials, such as ZnO nanowires (See Fig. 2.2.1), to enhance performance.

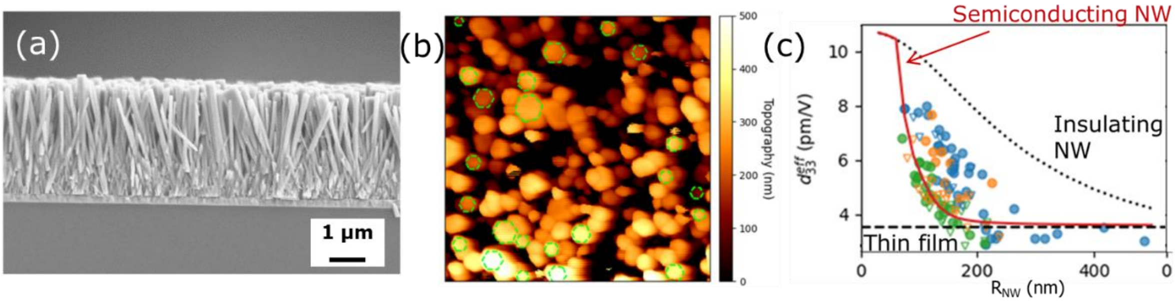
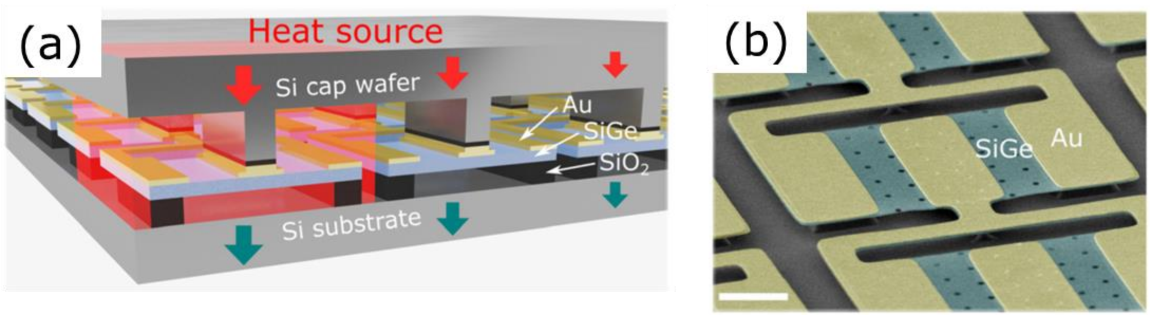


Fig. 2.2.1: (a) SEM image of vertically grown ZnO NWs. (b) AFM topographic image of the same NWs. (c) d33 coefficient (performance parameter) of ZnO NWs in function of their radius [edited from [1]].

In thermal energy harvesting, the Seebeck effect generates voltage from temperature differences. Emerging trends involve using silicon and silicon-germanium thin films (See Fig. 2.2.2) as environmentally friendly alternatives to toxic materials like Bi2Te3, thus ensuring compatibility with CMOS technology.



[1] Jalabert, T., Pusty, M., Mouis, M., & Ardila, G. (2023). Investigation of the diameter-dependent piezoelectric response of semiconducting ZnO nanowires by Piezoresponse Force Microscopy and FEM simulations. *Nanotechnology*, *34*(11), 115402.

Fig. 2.2.2: (a) Schematic of a thermoelectric device integrating a thin suspended film made of SiGe. (b) Photo of the SiGe suspended film with electrodes [edited from [2]].

Additionally, advancements in energy storage, particularly in micro-batteries, were discussed. Innovations like 3D structures and low-temperature fabrication techniques allowing the integration of batteries into flexible substrates (See Fig. 2.2.3) are being explored to improve energy density and power options while reducing costs.

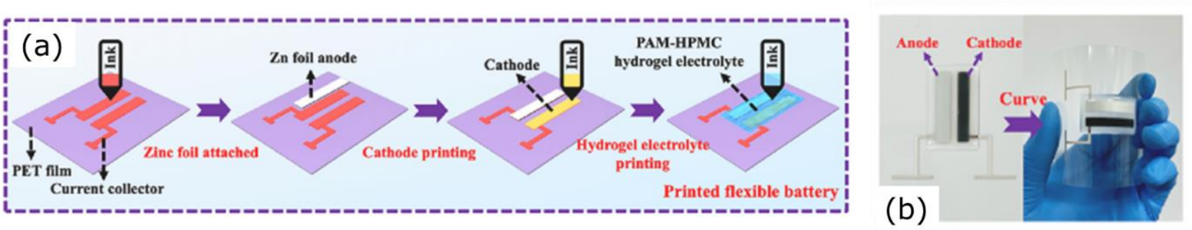


Fig. 2.2.3: (a) Schematic of the fabrication of a fully 3D printed flexible battery. (b) Photo of the actual device [edited from [3]].

In conclusion, enhancing energy harvesting performance and efficiency is as critical as developing environmentally friendly materials. The integration of nanotechnologies is expected to significantly boost overall performance. There is also a pressing need for flexible and low-cost solutions for wearable applications, especially in e-health. A comprehensive system design that incorporates all aspects of the energy harvesting process will be essential for improving power generation efficiency. The contributions of various organizations and individuals involved in the research and development of energy harvesting technologies underscore the importance of collaboration and innovation in this field.

2.3 Power Devices

In the realm of innovative materials for power devices, international collaboration is essential for research and development in smart energy technologies. Ongoing activities in the EU and globally focus on semiconductor advancements for industrial and automotive applications, identifying research gaps necessary for future progress.

Power devices are responsible for managing at least 50% of the world's electricity consumption, making them essential for enhancing energy efficiency, which is crucial for the European Union's objectives in reducing carbon dioxide emissions.

[2] Jalabert, T., Pusty, M., Mouis, M., & Ardila, G. (2023). Investigation of the diameter-dependent piezoelectric response of semiconducting ZnO nanowires by Piezoresponse Force Microscopy and FEM simulations. *Nanotechnology*, *34*(11), 115402.

[3] Lu, Y., Li, Z., Wang, X., Wang, Z., Li, M., Hu, X., ... & Wang, Y. (2024). 3D printed dual network Cross-Linked hydrogel electrolytes for high area capacity flexible zinc ion Micro-Batteries. *Chemical Engineering Journal*, *490*, 151523.

The discussion highlighted a range of materials, with a specific focus on wide-bandgap (WBG) semiconductors such as silicon carbide (SiC) and gallium nitride (GaN). These materials are increasingly favored in power electronics due to their superior performance characteristics compared to traditional silicon technologies. For instance, WBG devices can achieve up to 10% greater efficiency and show excellent performance under partial load conditions (see fig 2.3.1).

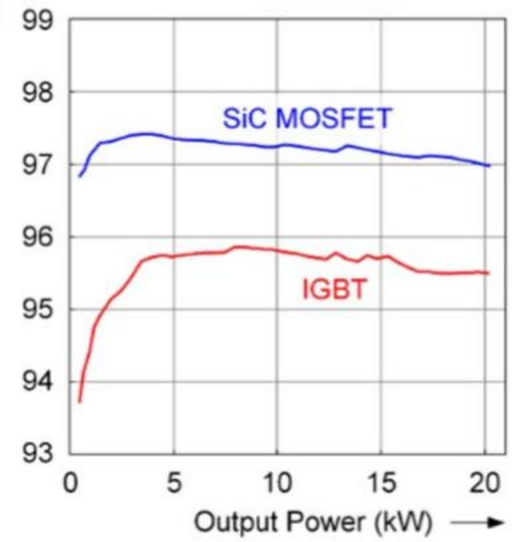


Fig. 2.3.1: Device efficiency in % vs. output power in kW [4].

The properties of WBG materials (see fig 2.3.2), including their ability to operate at high voltages and temperatures, as well as their high thermal conductivity, make them ideal for various applications, including electrical conversion, renewable energy systems, and electric vehicles.

[4] M. Nitzsche et al., PCIM 2019, Nuremberg

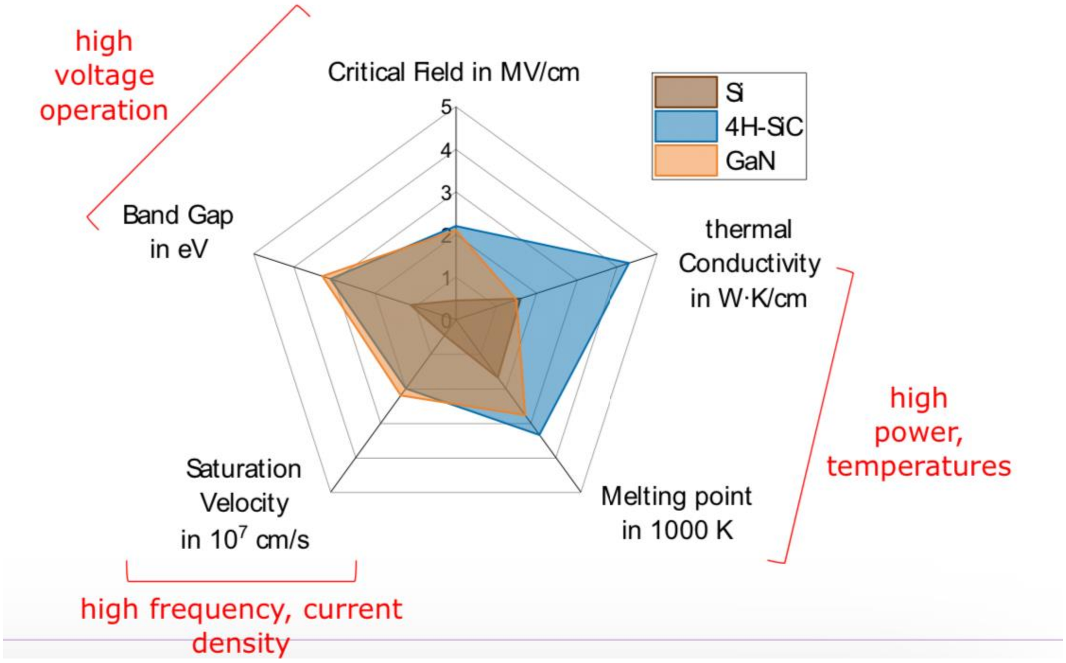
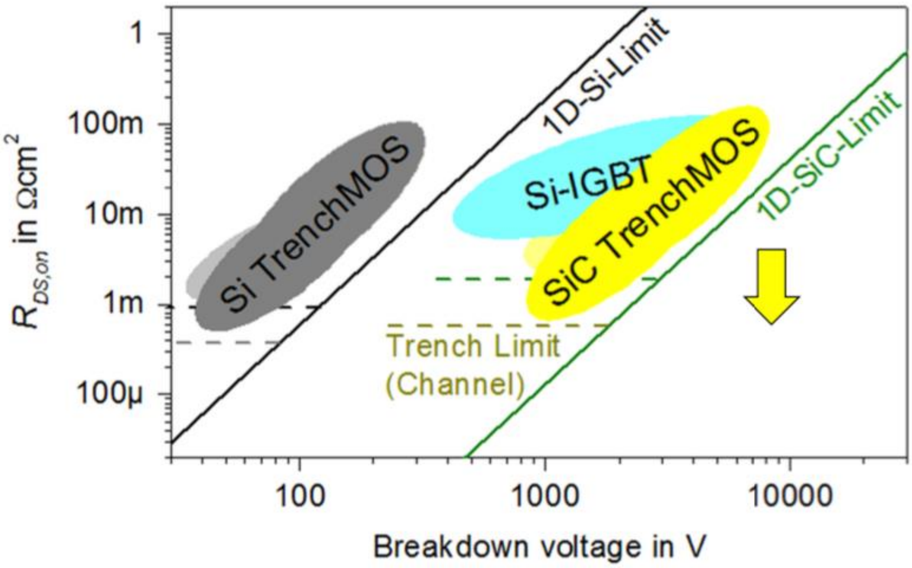


Fig. 2.3.2: Properties of WBG materials

The evolution of power MOS technology was thoroughly examined, focusing on the critical task of reducing on-state resistance (see fig 2.3.3) to minimize die size and manufacturing costs. The implementation of advanced trench gate structures in SiC MOS devices was highlighted as a significant improvement, enhancing channel mobility and overall electrical performance. This evolution is essential for meeting the increasing demands for higher efficiency and power density in modern power devices.

Fig. 2.3.3: Technology limits for different technologies



Market outlooks presented during the discussion revealed substantial investments in the semiconductor sector, particularly in the development of WBG technologies. Major industry players, such as Bosch and Renesas, announced significant capital allocations aimed at expanding their WBG capabilities. Bosch, for instance, is set to invest €3 billion in its semiconductor business by 2026, with plans to expand cleanroom facilities to accommodate the production of 200 mm SiC wafers.

The European Union's Chips Act was also a focal point of the presentation, emphasizing the EU's ambition to become a leader in semiconductor technology. The Act outlines plans for establishing pilot lines dedicated to advancing semiconductor technologies. These pilot lines aim to bridge the gap between laboratory research and commercial production, particularly in four strategic areas: extending Moore's Law to the angstrom scale, scaling down to 7 nm technology, integrating heterogeneous technologies, and developing next-generation wide-bandgap materials.

The potential of ultra-wide bandgap (UWBG) semiconductors was explored, with a particular focus on materials like gallium oxide (Ga2O3) and aluminum nitride (AlN). UWBG semiconductors offer the promise of higher efficiency, compact designs, and the capability to operate in extreme environments. The anticipated benefits include simpler cooling systems and reduced overall costs at the system level.

The WBG pilot line initiative aims to achieve two key outcomes: to enhance the maturity of existing SiC and GaN technologies and to delve into less mature UWBG materials. Research and development efforts will cover the entire supply chain, from crystal growth to front-end processing, testing, and back-end technology. This comprehensive approach is essential for improving the efficiency and power density of WBG-based devices (see fig 2.3.4).

		WBGs		Ultra WBGs		
	Silicon	4H-SiC	GaN	Ga2O3	Diamond	AlN
Bandgap E_g [eV]	1.1	**3.26**	**3.45**	4.85	5.47	6.2
Melting Point [°C]	1420	-	-	1795	-	-
Electron Mobility μ_n [cm^2/Vs]	1350	900	1000	150	4000 (th.)	500
Dielectric constant ε	11.8	9.7	9.5	9.9	5.5	9.1
Thermal Conductivity k [W/cmK]	1.56	**3.7**	1.5	0.1	25	3
Critical Electrical Field E_{cr} [10^6V/cm]	0.2	**3.2**	**3.3**	8	10	16.6

Fig. 2.3.4: Comparison between properties of WBG and UWBG materials

Looking ahead, the planned timeline for the development of AlN suggests that it will serve as a next-generation semiconductor with applications across various sectors, including automotive, aerospace, and quantum electronics. Its potential applications include electronics designed for extreme conditions, energy-efficient power electronics for data centers, and power transistors for RF communication.

In conclusion, the landscape of advanced power devices is rapidly evolving, driven by global research and development efforts, increasing investments, and a robust market for WBG and UWBG materials. The establishment of pilot lines is a crucial step in facilitating access for universities, small and medium enterprises (SMEs), and emerging companies, fostering innovation and collaboration in this vital field. As the technology matures, it is expected to enable significant advancements across multiple industries, contributing to a more sustainable and energy-efficient future.

2.4 Photonics

Photonic Integrated Circuits (PICs) play a crucial role in optical communication, yet their potential is still largely untapped. Scaling PIC technology is essential, requiring the development of complex circuit architectures and new materials to enhance performance across various applications.

The European Silicon Photonics Alliance (ePIXfab) aims to strengthen the silicon photonics ecosystem by advocating for collaboration among academia and industry, providing training, and representing the interests of stakeholders.

Photonics is defined as the manipulation of light on a microscopic scale, with a wide range of applications including fiber-optic communication, sensing technologies, and quantum optics. Semiconductor technology plays a critical role in enabling these applications. Key devices such as CMOS imagers, LEDs, vertical-cavity surface-emitting lasers (VCSELs), and photonic integrated circuits (PICs) are fundamental components of the photonics landscape (see fig 2.4.1). PICs consist of essential building blocks like lasers and modulators integrated onto a single chip, interconnected via waveguides to facilitate efficient light transport.

The silicon photonics market is experiencing significant growth, with projections indicating that by 2040, it could capture over 1% of the semiconductor market, buoyed by a compound annual growth rate (CAGR) of approximately 44%. Currently, applications primarily focus on transceivers, with data rates evolving from 100-400 Gb/s to over 800 Gb/s as technology advances.

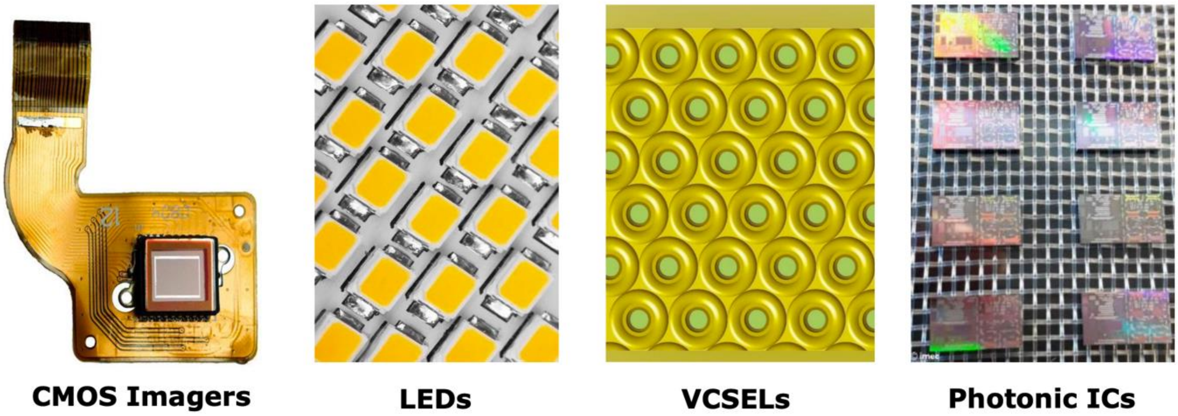


Fig. 2.4.1: Different classes of photonics devices

Despite the progress, several challenges hinder the broader adoption of photonic technologies. Low production volumes remain a concern, necessitating the development of more diverse applications to justify increased manufacturing capacity. Additionally, the quest for superior materials is ongoing, as heterogeneous integration—combining various materials (see fig 2.4.2) at the wafer scale—emerges as a critical area of research to enhance device performance.

The design and fabrication cycles for photonic chips are lengthy and costly, often exceeding one year. This situation underscores the need for rapid prototyping solutions that can streamline development processes. Packaging is another significant challenge, accounting for over 80% of the total cost of photonic chip products. Thus, developing cost-effective methods for fiber attachment and standardizing form factors is essential for reducing expenses and improving efficiency.

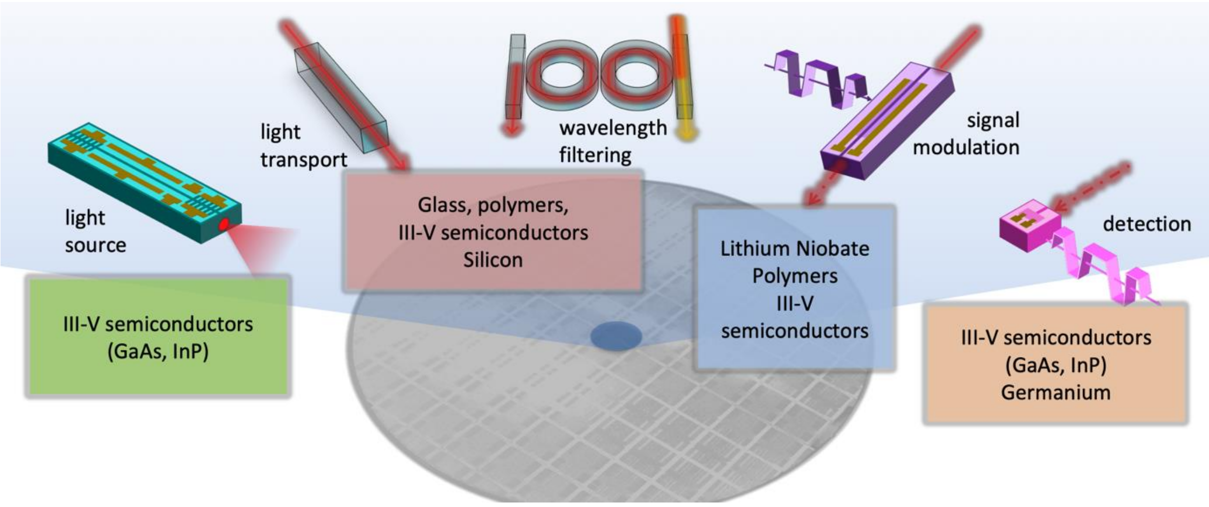


Fig. 2.4.2: Different materials for photonic integrated circuits

The integration of photonics and electronics is crucial for achieving high-bandwidth interconnects and effective control systems. While standards exist within the photonics domain, the current focus is on accelerating time-to-market rather than establishing uniform protocols.

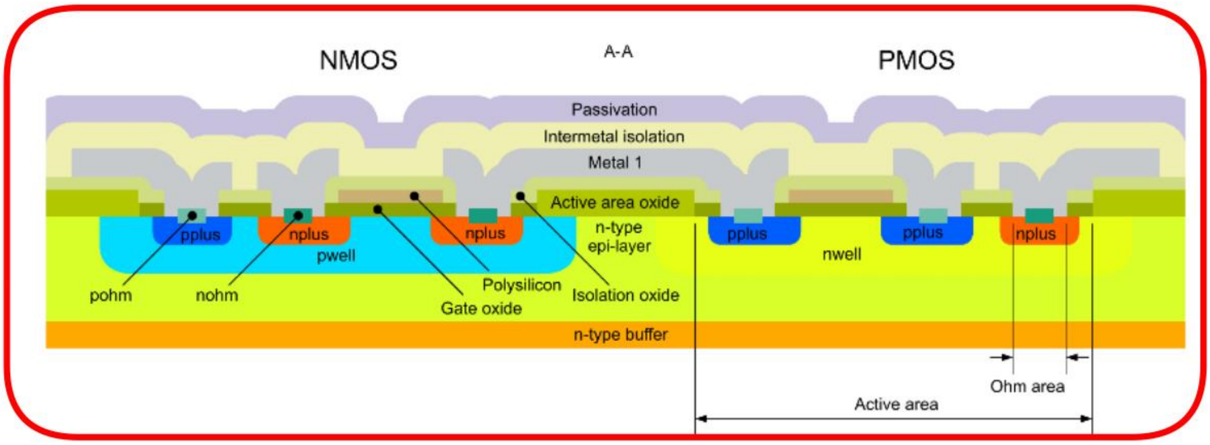
Looking ahead, initiatives such as PhotonDelta and AIM Photonics are working to create technology roadmaps for photonic chips, identifying key future developments and addressing bottlenecks in the supply chain. The objectives include establishing reliable supply chains for wafer-scale light source integration and enhancing the performance of high-speed modulators and detectors.

In conclusion, photonics plays a vital role in supporting the information society, particularly in areas such as telecommunications and artificial intelligence. While established foundries with increasing capacity are available, the journey toward enabling a broader array of applications is gradual. Mechanisms to expedite design and prototyping, coupled with the introduction of standards, could significantly enhance the scaling and integration of semiconductor photonics, paving the way for innovative solutions across various sectors.

2.5 Others

SiC CMOS technology is specifically engineered for high-temperature applications, capable of functioning in environments exceeding 500°C. The focus is on developing high-temperature circuits, including CMOS inverters that can operate reliably up to 550°C. This technology integrates digital and analog circuit blocks, providing a comprehensive solution for various applications. One notable aspect of this technology is its ability to facilitate smart system integration (see 2.5.1).

Fig. 2.5.1: Principle schematic of a SiC CMOS technology



The technology encompasses various process options tailored to meet specific application needs. These include modules for customized implantations, which enable the creation of application-specific devices, as well as low-temperature metallization techniques that improve electrical performance. Furthermore, there are provisions for wafer back thinning and the integration of vertical devices, which can significantly enhance device efficiency and performance.

Ongoing research within this domain is dedicated to the advancement of power devices that can withstand harsh environmental conditions. Additionally, investigations into quantum sensing and computing, particularly through the utilization of silicon vacancies in silicon carbide, highlight the potential for groundbreaking developments in these areas.

Overall, this innovative SiC CMOS technology offers a robust platform for power, mixed-signal, and sensor applications, paving the way for advancements in electronics designed to operate in extreme conditions (see fig 2.5.2).

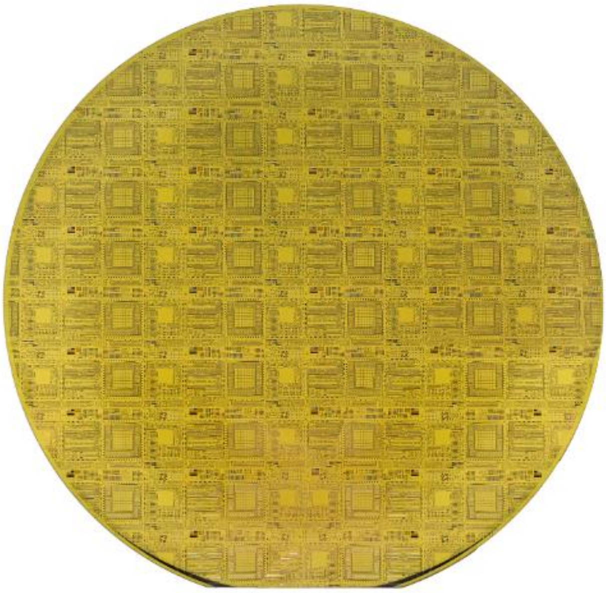


Fig. 2.5.2: Fully processed 150 mm wafer with SiC CMOS technology

3 Conclusion

The "Report on Future Technologies for Advanced Functionality" underscores the vital importance of international cooperation in the semiconductor sector, particularly in the context of emerging technologies that promise to drive significant advancements in various applications. The underpinning functional diversification of semiconductor technologies is a major deviation from the “one size fits all” and points to an interconnected global landscape where fostering collaboration among nations, research institutions, and industry leaders is essential to accelerate technological innovation and strengthen the semiconductor value chains. This alignment is not only crucial for meeting the objectives of the EU Chips Act but also for ensuring that Europe maintains its competitive edge in the global market.

The report highlights several key drivers of technological progress, including digitalization, which facilitates the immediate conversion of analog data into digital formats. This capability is paramount for the widespread adoption of Internet of Things (IoT) devices, which require seamless connectivity and low-cost installation. Furthermore, the growing emphasis on energy harvesting reflects a shift toward sustainability, as industries seek to reduce reliance on disposable batteries and embrace autonomous systems. Innovations in Edge AI and data fusion technologies are also transforming how data is utilized, enabling smarter insights and enhancing decision-making processes.

In the realm of sensors, the report notes the rapid growth of the smart sensor market, driven by diverse applications in healthcare, automotive, and environmental monitoring. However, challenges remain, particularly in sensor design and manufacturing, where fragmentation can lead to increased costs. Addressing these challenges through advanced design tools and collaborative efforts can significantly enhance the efficiency and effectiveness of sensor technologies. New policy frameworks addressing environmental sustainability will also drive (bio)materials innovation and integration in new, highly sensitive and more versatile sensors.

The exploration of energy harvesting methods, such as mechanical and thermal techniques, is critical for developing sustainable energy solutions. The focus on environmentally friendly materials and nanotechnologies can further improve performance, especially in wearable applications. As industries expand their use of connected devices, the demand for efficient energy supply solutions will only grow, making this area ripe for innovation.

Power devices are also at the forefront of this technological evolution, with wide-bandgap semiconductors like silicon carbide (SiC) and gallium nitride (GaN) emerging as key players. These materials offer superior performance and efficiency, crucial for meeting the increasing energy demands of modern applications. International collaboration is essential in advancing research and development efforts in this field, ensuring that new technologies are effectively integrated into existing systems.

Photonics technology, while promising, faces challenges in scaling and adoption. The report emphasizes the need for collaboration between academia and industry to develop new materials and circuit architectures that can enhance performance. Efforts to streamline design and prototyping processes, along with standardizing protocols, will be vital for overcoming existing barriers and unlocking the full potential of photonic technologies.

Lastly, the report highlights the ongoing research into high-temperature applications and ultra-wide bandgap materials, which could pave the way for groundbreaking developments in various sectors. The integration of these innovations will significantly impact industries such as automotive, aerospace, and energy.

To summarise, key Advanced Functionality‘ topics for EU to be active are:

- Innovation in new, highly sensitive and more versatile sensors requiring more advanced sustainable (bio)materials innovation and integration
- For energy harvesters the improvement of the performance/efficiency is as important as the development of “green” materials
- Wide band gap (e.g., SiC, GaN) and ultrawide band gap materials (e.g., AlN, GaOx, diamond) for power devices
- Heterogeneous integration of best materials for target application
- Hybrid integration of various functional chips
- Advanced design tools, including multi-physics simulation for first-time-right modelling capabilities
- Rapid prototyping to bypass long chip iteration cycles (e.g., PDK, ADK availability)
- Packaging that meets multiple design requirements such as optical, electrical, mechanical, thermal, RF, (bio-)fouling etc.

In conclusion, the findings of this report illuminate semiconductor technologies that may benefit from international collaboration. By leveraging shared knowledge and resources, stakeholders can address existing challenges, drive innovation, and create a sustainable future in the semiconductor industry. The commitment to research and development in sensors, energy harvesting, power devices, and photonics will not only enhance technological capabilities but also contribute to a more resilient and efficient global economy.

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International Cooperation
On Semiconductors

icos-semiconductors.eu

@ICOS_horizon

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