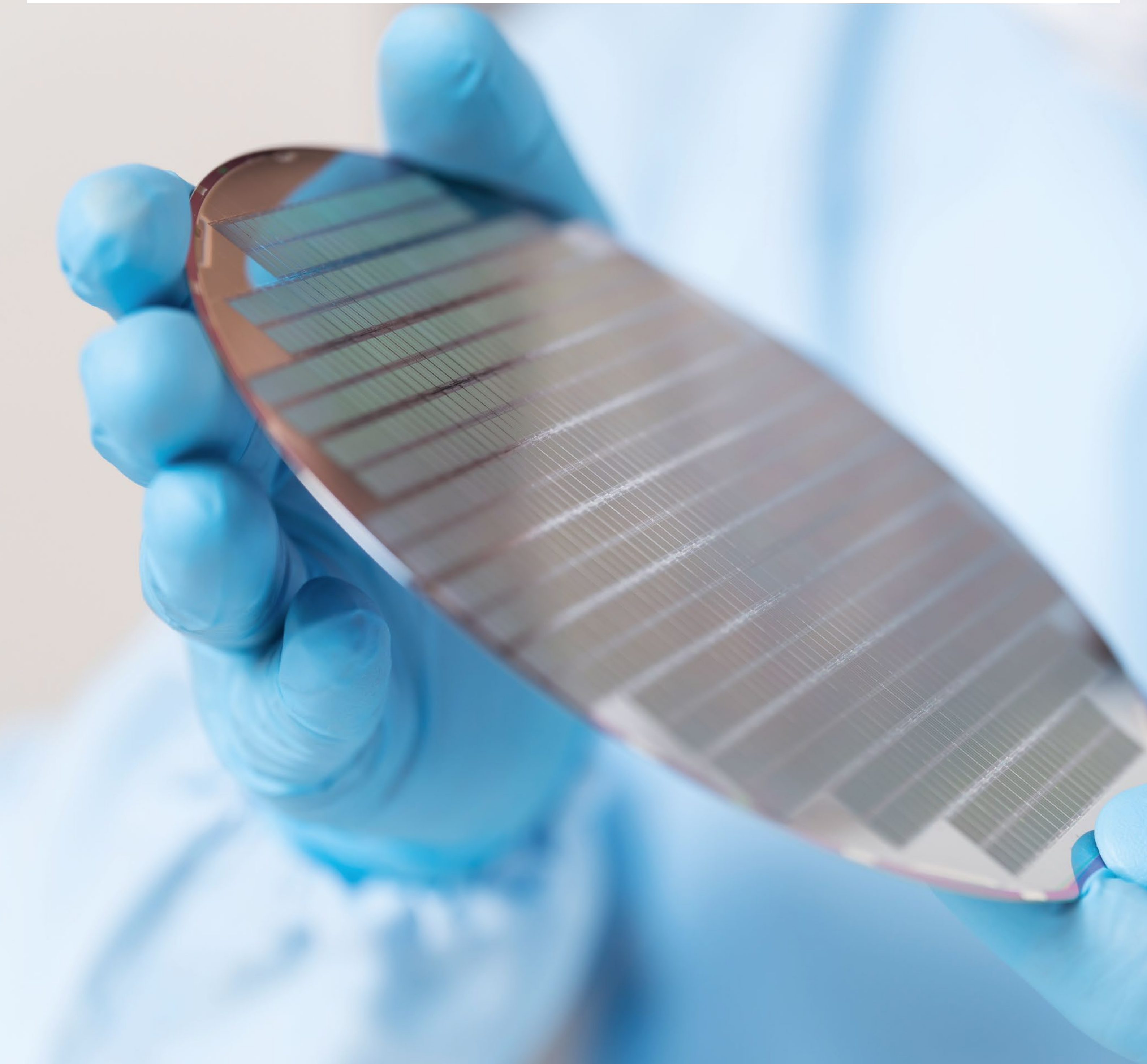
Federal Ministry
of Education
and Research

Microelectronics.
Trustworthy and sustainable.
For Germany und Europe.

The German Federal Government's Framework Programme for Research and Innovation 2021–2024



Contents

Foreword

Self-driving vehicles, production machines, medical technology, and telecommunications – none of these are possible without innovative electronic systems. We are keen to ensure that these systems continue to come from Germany. To this end, our focus is on the strengths of our research and development – the foundation of our innovative potential. This is why in the years 2021–2024 the Federal Government will continue to place particular emphasis on supporting research and innovation in microelectronics.

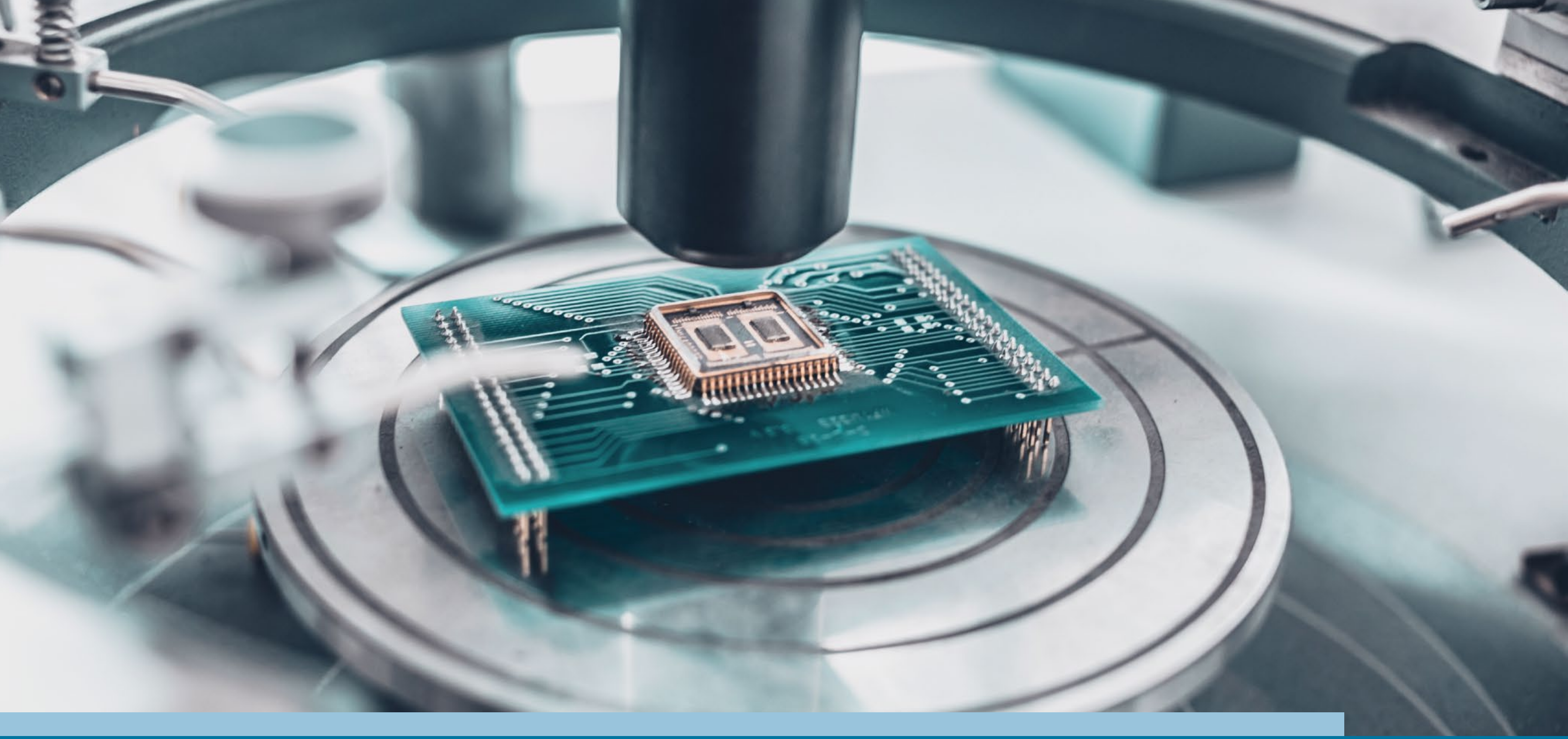
The issue at stake is the competitiveness of Germany and Europe in the world. But it is also a matter of trust. In future, anyone using a self-driving vehicle must be able to rely on it getting them safely to their destination. And it is not only here that trust is an issue. Today's innovations are increasingly digital and based on electronic systems.

For electronics to be trustworthy, we need to understand it. We can only do this if we have cutting-edge expertise in industry and the scientific community and develop this continuously. The more we design, develop, manufacture advanced electronics ourselves and ensure their safety and security, the better we will understand what third-party electronics can and cannot do. This enables us to work on an equal footing worldwide and to enforce requirements for electronic systems we use or operate. Sustainability plays a part in this. We need digitalisation and hence electronics that work in line with our climate goals instead of further increasing the consumption of resources.

We are striving for Europe's technological sovereignty and, at the same time, we are eager to engage in cooperation. Given the highly networked knowledge and value chains in electronics, cooperation is both necessary and advantageous. In this context, we give priority to collaborations in the European Single Market and the European Research Area based on shared values. We thus support the development of European electronics expertise in research and production so that Europe can continue to be strong as a community in international competition.

We are committed to turning ideas into innovations that are successful worldwide and benefit people. Whether as researchers, users or consumers: with this programme for research and innovation in electronics, we are strengthening our technological sovereignty and, in turn, the prosperity of our country.

Anja Karliczek
Member of the German Bundestag
Federal Minister of Education and Research



1 Introduction

Digitalisation is on the march and electronics are increasingly pervading our everyday lives and workplace environments. Electronics are not only found in mobile phones, tablets, and office computers, they also regulate our power supply, control the data streams for our mobile internet, and enable secure connected, automated mobility. Electronic processors are also the brain in which artificial intelligence (AI) takes place. In sectors such as healthcare and industrial manufacturing, electronics ensure that services and products from Germany meet the highest standards of functionality and quality. This makes (micro)electronics an important basis for prosperity in the age of digitalisation: by providing services that improve the quality of life and ensure sustainable value creation and jobs in Germany.

We need technological sovereignty so that we can continue to do this in the future and be able to manage digitalisation in keeping with our values and ideas. We understand technological sovereignty to be a commitment and ability to (co)design key technologies, i.e. to define requirements for technologies, products, and services according to our own values and to co-determine corresponding standards on the global markets. Therefore, the aim of technological sovereignty is explicitly not isolation, but international cooperation on an equal footing. It is important to understand that technological sovereignty in electronics is only possible as part of the European Single Market and Research Area, not on a purely national level. The present programme has therefore been designed in synergy with the European Research Framework Programme Horizon Europe, which likewise focuses on sovereignty in digital technologies. Other world regions are undertaking massive efforts: the USA, for example, is promoting the establishment of new chip factories, including through the use of state incentives. China is also investing public funds in its own microelectronics capabilities in order to catch up with the world leaders and reduce dependencies. The same is true for Europe: it can only keep up and create a level playing field by having its own competencies.

The growing importance of electronics poses major challenges. Germany and Europe are involved intensively in global value chains and partnerships in the field of microelectronics and electronic systems (Figure 1). European companies are both suppliers and purchasers of chips and electronic components, and as such are both exporters and importers. In order to establish a leading position in these global value chains and be able to manage digitalisation in keeping with our values, we need trustworthy electronics. We need to know exactly what these electronics do, understand how to manufacture them, and be able to check their functionality so that we know they are safe and reliable. To achieve this, we need to understand and deploy all the key electronics technologies. And we must remain able to react flexibly to the challenges in global supply chains by having our own economically viable microelectronics production in Germany and Europe.

The rapid spread of electronics is just as much an opportunity as it is a challenge. For one thing, smart digitalised solutions could frequently save resources. However, the electronics sector itself is consuming increasingly more resources. Information and communication technologies (ICT) accounted for 3.7 % of global greenhouse gas emissions in 2019, while energy consumption by ICT increased by 9 % per year between 2015 and 2020, which would be equivalent to doubling every eight years if continued.[1] To reduce CO_2 emissions in the current electricity mix, we therefore need electronics that significantly reduce the energy consumption of microprocessors and of information and communication technologies in general. In addition to improving the energy efficiency of individual components, we must achieve significant energy savings for distributed and networked ICT systems in order to meet the agreed climate change goals. This is especially true for AI systems. They can be much more efficient with customised, novel AI chips than with AI software running on conventional processors. We must also achieve a high level of resource efficiency by reducing the use of critical raw materials and implementing efficient recycling processes. This sustainability-based approach to developing ICT solutions, which focuses on resource and energy efficiency, not only protects the climate but also supports the economy: being an innovation leader in electronics for energy-saving ICT systems will give companies from Germany a competitive edge. At the same time, research and its funding will create the conditions for industry to meet the requirements of future regulatory steps – another competitive advantage.

The electronics sector continues to have a high level of innovative dynamism and short product life cycles. As a result, it remains research-intensive: semiconductor manufacturers typically invest around 15 % of their turnover in research and development activities. And entirely new technologies need new approaches from fundamental research. This is why electronics funding focuses on supporting research and innovation. In addition, high capital costs are the rule in electronics manufacturing. For the transfer from research to production in Germany and Europe, it is therefore essential that research and business development are well aligned.

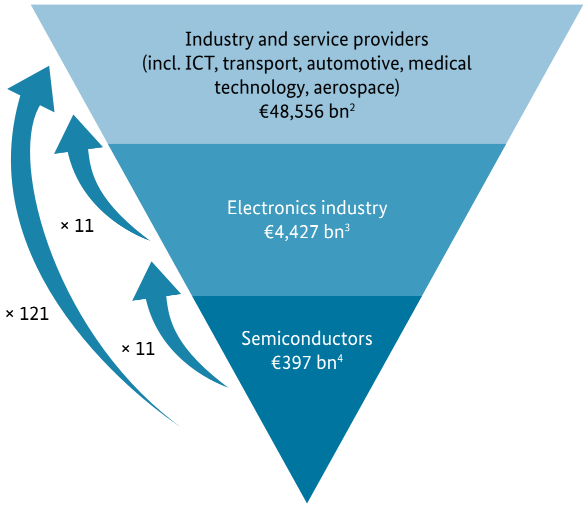


Figure 1 Electronics is the key technology in a digitalised society such as Germany. Semiconductors form the basis for value chains with high multipliers. List of sources: see footnotes[234]

The two aspects “Trustworthy electronics” and “Sustainable, climate-friendly electronics” are the pillars of the Federal Government’s present Framework Programme for Research and Innovation “Microelectronics. Trustworthy and sustainable. For Germany and Europe”, running from 2021 until 2024. The primary objective is to strengthen the technological sovereignty of Germany and Europe. National research funding will continue to be coordinated with European transnational funding, because the innovation and value chains are, and will remain, transnational. The aim is also to further strengthen industry’s willingness to invest in microelectronics production in Germany, in particular by funding joint projects between the scientific community and industry along the value chain from component manufacturer to system provider.

Pilot production lines, which ensure the rapid transfer of research results into production, play a key role in this. The success of this approach is demonstrated by the pilot line projects of the European co-financed initiative ECSEL (Electronic Components and Systems for European Leadership), with a follow-up initiative “Key Digital Technologies” (KDT) beginning in 2021 with-

1 theshiftproject.org/wp-content/uploads/2019/03/Lean-ICT-Report_The-Shift-Project_2019.pdf

2 decision.eu/wp-content/uploads/2020/02/ECS-study-presentation-of-Key-findings.pdf

3 zvei.org/fileadmin/user_upload/Presse_und_Medien/Publikationen/Regelmaessige_Publikationen/Daten_Zahlen_und_Fakten/Die_globale_Elektroindustrie_Daten_Zahlen_Fakten/Faktenblatt-International-August-2020_NEU.pdf

4 wsts.org/esraCMS/extension/media/f/WST/4298/WSTS_nr-2019_11.pdf – Average dollar exchange rate in 2018 ca €1.00 = $1.18 (de.statista.com)

in the EU Framework Programme for Research and Innovation Horizon Europe. In addition, the Important Project of Common European Interest (IPCEI) on Microelectronics (launched in 2017) was able to provide significantly improved support for the implementation of microelectronic innovations in production. As a result, companies have invested in new production capacities for new microelectronic products. For the first time in this millennium, a completely new microelectronics factory is being built in Germany. At the other edge of the innovation network, research institutions and universities ensure that new ideas keep flowing.

For many issues outlined, such as the development of AI chips, the greatest potential lies in finding completely new approaches. Particular attention will therefore be paid to accelerating innovation in order to translate creative ideas and novel approaches into concrete technologies and applications faster. This will be achieved by providing targeted support for cooperation and structures that bring together basic researchers with potential users at an early stage. Small and medium-sized enterprises (SMEs) and start-ups can also quickly turn new ideas into new products, which is why support is targeted particularly at them: regarding the electronics funding provided by the Federal Ministry of Education and Research (BMBF), SMEs account for around 35 % of commercial funding, while the SME share of R&D expenditure in industry as a whole is well below 20 %.[5]

The present programme builds on the Framework Programme for Research and Innovation 2016–2020 "Microelectronics from Germany – Driver of innovation for the digital economy", the first programme of the Federal Government dedicated to electronics research. To accelerate innovation, the BMBF is pursuing new approaches in implementation, for example with the funding line "Research for new microelectronics (ForMikro)" and the pilot innovation competition "Energy-efficient AI system". The previous programme also launched the investment projects Research Fab Microelectronics Germany, Research Laboratories Microelectronics Germany (funded by the BMBF) and the IPCEI on Microelectronics (funded by the Federal Ministry for Economic Affairs and Energy, BMWi). The Research Fab Microelectronics Germany pools the technological capabilities of 13 leading institutes for applied electronics research in a joint technology pool with a central contact point for partners and customers from the scientific community and industry, and the Research Laboratories strengthen universities in their pivotal role in the microelectronics innovation system. The positive results of microelectronics funding to date and the geopolitical situation with regard to this key technology also form the basis for the Federal Government's considerations to initiate an IPCEI on microelectronics and communication technologies at European level.

The priorities for the focus of the current programme were identified in the exchange between the Federal Government and the research community. In dialogue with industry and the scientific community, the lead initiative "Trustworthy Electronics" was devised, which is also part of the BMBF's digital strategy. In addition, a series of expert meetings identified priority aspects of energy efficiency and sustainability. These insights, together with the results of an environment analysis and a review of the previous framework programme, form the basis of the current programme. The main

5 Die Rolle von KMU für Forschung und Innovation in Deutschland (The Role of SMEs in Research and Innovation in Germany – only in German), a study commissioned by the Commission of Experts for Research and Innovation Studies on the German innovation system No. 10/2016, e-fi.de/fileadmin/Innovationsstudien_2016/StuDIS_10_2016.pdf

areas of focus are described in the chapters on "technologies" and "fields of application". Over the next four years, this content will be continuously reviewed and developed in exchange with the research community. In 2023, a decision will be taken on whether to extend the programme for two years or to relaunch it with a new focus.

The programme contributes to implementing the High-Tech Strategy 2025, in particular through the contributions of electronics to the missions "Safe, networked and clean mobility", "Putting artificial intelligence into practical application" and "Achieving substantial greenhouse gas neutrality in industry", the AI strategy, the implementation strategy "Shaping Digitalization", and the Federal Government's Climate Action Programme 2030. The "Sustainable, climate-friendly electronics" aspect includes the initiative "Green ICT – Grüne IKT" of the BMBF action plan "Natural. Digital. Sustainable." The programme interacts with numerous other current or planned research programmes of the Federal Government and its ministries, in particular regarding communication technologies, IT security, Industry 4.0, medical technology, photonics, and automated and connected driving. This is because digitalisation, and with it microelectronics, is penetrating more and more areas, and because there is an increasing merging of technological worlds that were once separate (e. g. hardware and software or electronics and photonics).

2 Missions and objectives for research and innovation in microelectronics

The present programme is geared towards:

- Technological sovereignty of Germany as a part of the European Research Area and the European Single Market, without any unilateral dependencies on other world regions.

- Electronics from Germany and Europe attaining a new quality and being verifiably trustworthy, thereby becoming the first choice for safety-critical applications such as autonomous driving, smart medical technology or the self-controlling factory of Industry 4.0. Players in Germany and Europe being able to understand the trustworthiness of electronics from all regions of the world by virtue of their own knowledge. This will also help to reduce trade conflicts.

- Electronics from Germany and Europe making a significant contribution to climate protection: through electronics that consume less energy themselves – for example in energy-efficient AI processors. Or through electronics that intelligently control other devices and thus curb their appetite for electricity – as is the case when using motion sensors instead of light switches. This provides an important contribution to achieving the German Government's climate change goals.

- Electronics providing technical solutions to other societal challenges, such as the looming demographic labour shortage or maintaining good health in all phases of life. Powerful, trustworthy, and sustainable electronics, which open up new solutions for smart assistants, the Internet of Things, AI applications or modern, climate-friendly data centres.

To accomplish this, the Federal Government is taking the following steps:

- We support the development and implementation of new basic technologies in Germany and Europe.

- We continue to strengthen cooperation and networking between the scientific community and industry for the transfer of know-how and research findings; also in order to incorporate the latest findings into regulation and standardisation. After all, in digitalisation, product innovations rely not only on software, but increasingly and in many sectors on electronics hardware.

- We promote the transfer from fundamental to applied research as a catalyst for leap innovations in Germany and Europe. The direct research funding of this programme complements closely and collaboratively the funding of the Federal Agency for Disruptive Innovation SPRIND.

- We also promote promising new developments in the area of cyber security. To this end, the Federal Agency for Innovation in Cyber Security (GmbH) commissions and finances risk-taking, ambitious research and innovation projects and coordinates the entire research process from the idea to the prototype in order to quickly achieve results that meet the Federal Government's needs.

- We support young researchers, start-ups, and small and medium-sized enterprises (SMEs) for an agile innovation system.

- We promote an effective dialogue between the relevant stakeholders in order to identify and address new research and innovation issues in timely fashion.

- We link up our research policy at the national and European levels, because both the scientific community and industry have a transnational outlook; closed, value chains exist within Europe or even beyond, but rarely within the borders of one nation. National measures are therefore strategically aligned with European initiatives such as the Digital Single Market, the European Green Deal and, in particular, the Research Framework Programme Horizon Europe as well as the investment programme Digital Europe.

If we want to continue shaping the digital transformation ourselves in future, we must strengthen Germany's position as a location for the electronics industry. This means not only continuing to improve our strengths, but also significantly promoting other important technology areas and thus acquiring and developing new competencies. This programme will make a substantial contribution towards this. The BMBF alone is providing around 400 million euros for research and development projects over the four-year programme period. The BMWi is considering providing further substantial funding for the above-mentioned IPCEI on microelectronics and communication technologies.

The BMBF's microelectronics research funding is based on the following operational objectives:

- At the level of the entire programme: we are strengthening value chains as innovation incubators. We ensure the networking of research and innovation stakeholders in Germany, especially small and medium-sized enterprises, and the transfer from knowledge-oriented to application-oriented research, which also takes place when people move from academia to industry. We are pressing ahead with developing capacity and competencies in the field of microelectronics research. Indicators for this are not only the number of PhDs, publications, patents, and products, but also, for example, measures for covering value chains, the breadth of technological competencies, the number of new institutional contacts within and between associations or the number of new collaborations.

- In addition, for technological sovereignty: we are strengthening semiconductor production in Germany and Europe. We are establishing a complete innovation ecosystem for accelerated, platform-based design of specialised processors based on the RISC-V architecture for a wide range of applications. Indicators for this are, for example, the development over time of sectoral key figures on innovation and production as well as the degree of coverage of value chains or the completeness of the innovation ecosystem supplied by German and European stakeholders.

- Moreover, for sustainable, climate-friendly electronics: we provide exemplary solutions demonstrating Germany's commitment to a pioneering role in the development of sustainable technologies. This includes the further development of methods and models to quantify the resulting energy and CO_2 savings. Indicators are, for example, the number of corresponding product innovations and the concrete savings potential.

In order to be able to respond to the respective state of the art and research in each of the technology and application fields described below, specific operational objectives will be identified for each funding measure in accordance with the respective status quo ante and research needs.

3 Creating the technological conditions for a sustainable digital sovereignty

Microelectronics is a prime example of advanced technology. Mastering the basic technologies outlined below, being able to advance them or even create new ones is a prerequisite for deploying electronics in a self-determined and beneficial manner.

3.1 Electronic Design Automation (EDA)

Every microelectronic system starts with its design.

To get from the initial idea to the finished product, every electronic circuit or system first has to pass through a complex design process that considers all internal interactions. The design process is automated as much as possible (EDA, electronic design automation) in order to manage this complexity. This process plays a key role when it comes to the performance, reliability, and trustworthiness of any future system. Development times and efforts are significantly reduced by detecting errors as early as the design stage and by performing virtual optimisations instead of real hardware tests.

Many companies use the EDA tools of major suppliers when designing their microelectronic components. However, these are often not tailored to the needs of Germany's multifaceted user industry regarding analogue electronics, for example. What is needed is the in-house design competence that not only enables innovation, but also the competent management of all links in the value chain. Consequently, EDA as an interdisciplinary competence constitutes a key element for Germany's and Europe's technological sovereignty.

To facilitate the use of new technologies and to be able to meet the requirements of new applications, it is necessary to continuously develop and advance EDA tools. Future design technologies will help to speed up innovation processes, reduce the time and effort required, and shorten the time-to-market. Despite increasing complexity, many parameters can be optimised by simulations carried out during the design stage. This eliminates the need for the conventional lengthy test and evaluation process that involves the building and subsequent testing of several hardware prototypes.

Current developments are characterised by an increasing complexity that requires automating designs not only for every single chip but also at the system level: the number of circuits increases, systems become more heterogeneous, and different technologies are combined. The higher integration density and the accompanying physical interactions lead to new effects that must be mapped out in models – in particular in terms of electromagnetic compatibility (EMC). In addition, innovative applications focus more and more on energy efficiency, reliability, and functional safety, resulting in ever more complex modelling.

Future fields of action include, for example:

- **Development platforms and ecosystems**: electronic systems for specific applications have to be optimised to the usage – be it in terms of energy efficiency, costs or specific operating properties. However, low-volume developments are time-consuming and therefore often not profitable. Especially small companies also often lack the expertise required. Although, new approaches and technological developments (e.g. based on RISC-V) are currently being pursued, the tool support is still insufficient. Versatile development platforms are needed that enable the efficient creation of custom hardware by means of modular IP (intellectual property – here in relation to chip design) and adapted tools. This demands the availability of scalable and modular-based hardware IP, software and development tools (design, verification, modelling, compiler, debugger). In this context, open source approaches such as RISC-V are particularly interesting for the German and European semiconductor industry and research community.

- **Hardware/software co-design**: specific functionalities can be implemented through both hardware and software. Exploring the most efficient distribution and interconnection is of fundamental importance here in order to be able to optimise development costs, maintainability, updatability and performance in terms of speed and energy efficiency. Comprehensive models through to virtual prototypes enable simultaneous development of hardware and software across value chains. An adapted hardware architecture can result in considerable increases in efficiency, particularly in the case of highly specialised systems (e.g. neural networks and neuromorphic architectures).

- **AI for EDA**: artificial intelligence can help to master the complexity of the design, optimise test procedures, and thus accelerate the entire design process. Faster designs drive innovations and are critical for economic success.

- **Design for test**: in complex, highly integrated chips and systems, many parameters are no longer accessible from the outside. This must be taken into consideration to a greater extent to ensure adequate testability during the design process.

- **Analogue design**: highly integrated chips or systems often contain a high percentage of analogue electronics such as interfaces to sensor systems, communication units, and power supply. When designing a microchip, up to 90 per cent of the time is spent on the analogue section, although it normally only contains 10 per cent of the components. Numerous physical effects and interactions occur during the design of analogue circuits, making it extremely intricate and requiring comprehensive expert knowledge and experience. Consequently, the objective should be to formalise knowledge and design automation by means of suitable tools.

RISC-V

RISC-V is an open instruction set architecture, i.e. an abstract description of the implementation of a data processor in terms of executable machine instructions that provide the basis for the quick development of new processors. "Open" means: the architecture is not patented or protected by copyright, but is available under an open source licence and can be used freely. This enables small and medium-sized enterprises in particular to design, manufacture and market bespoke and high-performance microprocessors without high licensing costs. It gives Germany and Europe the opportunity to develop their own processors and make them available to industry.

3.2 Specialised processors for edge computing, artificial intelligence, and high-performance applications

High-performance specialised processors drive innovations.

High-performance universal processors for servers, PCs, and smartphones are currently neither designed nor built in Germany; by contrast, specialised processors are one of the strengths of the German electronics industry. They play a major role when it comes to innovation. Thanks to properties such as energy efficiency, real-time capability, robustness, and reliability, they are better equipped to meet the distinct requirements of applications that are particularly relevant for the German industry. They also enable a higher degree of application-specific performance and security and thus make a decisive contribution to meeting cyber security requirements.

However, new fields of application and rising performance requirements in established applications are increasingly pushing solutions for specialised processors available in Germany to their limits. This is the case, for example, in edge computing, the shift of computation-intensive applications from the cloud closer to the end devices. Artificial intelligence applications also place particularly high demands on processor performance since the processed data volumes and operations are much larger.

For future specialised processors electronics and algorithms will be coordinated to enable applications to be accelerated significantly. Furthermore, the combination between sensor systems, artificial intelligence and electronics will substantially increase energy efficiency. This will open up the opportunity for Germany to make the leap into new performance classes and fields of application – with processors made in Europe providing a trustworthy basis for digitalisation. To this end, the European Processor Initiative (EPI)[6] can make knowledge available to the industry, e.g. for automated and connected driving applications.

Currently, there are many new technological developments that open up possibilities for Germany and Europe. Fields of action include:

- **Ecosystems based on a modular approach:** specialised processors are required for a wide range of applications, but usually only in small quantities. Developing new processors for every application is not economically viable. Flexible and modular components are needed that can be integrated easily into one system. Scalable modular systems like these foster solutions from energy-efficient microcontrollers to AI processors. These modular systems are created using ecosystems that offer the relevant hardware and software. They provide a trustworthy basis for SMEs and start-ups to quickly implement their own developments. Freely available architectures like RISC-V are a good starting point for German industry to efficiently tap into new areas of use and fields of applications.

- **Processors with optical and electro-optical components**: the combination of electronic and photonic components offers great potential for energy efficiency and speed in suitable applications, for example in optical data processing.

- **Further trends**: in the context of new specialised processors, emerging architectures and storage technologies, such as non-volatile embedded memories, memristors for neuromorphic chips or what is known as approximate computing are cutting-edge approaches to saving energy. Analogue computing also holds a promising potential for certain applications. Much needs to be done, however, regarding the transfer of the fundamental research (cf. Chapter 3.8).

Edge Computing

Edge computing or edge cloud solutions refers to electronic systems that collect and pre-process data at the edge of the network, e.g. at the end device and not in a cloud environment. Since it is not necessary to transmit large volumes of raw data sets to the cloud, data streams can be processed in a more resource-efficient manner. Further processing steps then take place in the cloud. This market could grow so fast that edge AI chips generate higher turnover than AI processors for cloud computing as early as 2025.

6 european-processor-initiative.eu

3.3 Innovative, intelligent, and connected sensor systems

Sensors are the sensory organs of machines, equipment, and intelligent systems.

Trust is good, sensor technology is better: trustworthy electronic systems require sensors that supply trustworthy data.

Sensors are already widely used, and their importance is set to increase as digitalisation and connectivity advance. MEMS sensors, microelectromechanical systems, not only share the same base material, namely silicon, and the associated processing techniques with electronics, but are also growing increasingly closer together with the corresponding electronic systems. As a result, sensors are less and less "extra devices", but increasingly part of the electronics. In almost every industry, the functional safety and efficient operation of complex and intelligent systems is based on the collection, processing, and transmission of measured values. Be it in automated and connected driving, industrial production or robotics, they constitute the interface to the real world and ensure safe and secure cooperation between human and machine.

Sensors are also used when it comes to monitoring and controlling of processes with regard to sustainability and climate protection. They enable resource-efficient process control regarding energy, water and raw material consumption, and ensure efficient control of flows such as materials, energy, mobility, logistics or infrastructure. Sensor systems can monitor water quality, measure the CO_2 level near CO_2 sequestration sites, and detect pollutants as well as defects that cause environmental hazards.

Modern mid-range cars are fitted with around 100 sensors. They record physical quantities such as temperatures, speed, angles, pressure etc., and convert these non-electrical quantities into electrical signals. They serve as sensory organs of the electronic control units.[7]

Regardless of the application, sensors must always meet the highest standards in terms of reliability and effectively resist interference. High detection quality with low noise levels is desirable for analysis, especially with AI methods.

In view of the demand for specialised solutions and given its wide field of application, sensor technology is attractive for SMEs. As with special processors, modular systems and development platforms can act as drivers for innovation.

Fields of action result, for example, from new sensor principles and system approaches:

- **New sensor principles**: sensor systems that are based on new measuring principles such as quantum effects, or build on new materials or integration technologies can tap into new applications. Improving the intelligence and decentralisation of sensor systems by means of AI methods is another important field of research that opens up new possibilities (cf. Chapter 3.2)

- **Organic electronics**: while sensors based on organic electronics hold great potential, they still have to master huge technological challenges.

7 Sensoren im Auto (Sensors in cars – only in German) springerprofessional.de/bordnetze/energiemanagement-im-elektrofahrzeug/das-moderne-automobil-fordert-die-sensorbranche/16152976

- **Lab-on-a-chip**: lab-on-a-chip solutions are of great importance for point-of-care-diagnostics in medicine, environmental monitoring, and in the food industry since they can significantly reduce the time-to-result compared to traditional lab analyses.

- **Chemical sensors and biosensors**: in numerous industries (chemical, semiconductor, food), medicine, and environmental analysis, chemical sensors help to improve process control and reliability. To date, chemical sensors and biosensors are only found in special applications. Supported by research and development, the aim is to develop low-cost-high-volume applications and new application areas, e.g. for the pharmaceutical industry and medicine (cf. Chapter 4.4).

Further trends can be determined from areas of use such as:

- **Intelligent sensor systems**: energy-efficient, local data processing and evaluation as well as sensor data fusion are key elements of intelligent sensor systems for Industry 4.0 and other industries (cf. Chapter 3.2).

- **Self-diagnosis and self-calibration**: sensors must always meet the specific requirements of individual applications. Self-diagnosis and self-calibration increase trustworthiness without any additional effort.

- **Energy-autonomous sensors and system solutions** enable new applications and contribute to cost efficiency.

Energy-autonomous sensors

By converting thermal, mechanical or optical energy into electricity, it is possible to “harvest” energy available from the immediate environment and use it to operate the electronic system and the integrated sensor technology as well as any communication unit. In this way, previously inaccessible locations can be fitted with sensors without using cables or high-maintenance batteries.

3.4 High frequency electronics for communication and sensor technology

High frequency electronics is at the heart of modern communication technologies.

High frequency electronics is a cornerstone of digitalisation and used, for example, for building 5G/6G infrastructure, for vehicle distance radars or service robots. As a safety-critical component, high frequency electronics must meet the highest standards in terms of reliability. This is also true when using high frequency electronics in sensor systems – the eyes and ears of the connected world. As a centre of innovation and in order to ensure its technological sovereignty, Germany has great interest in securing the availability of high frequency electronics by further developing this technology itself.

Developments tend towards ever-higher frequencies. In sensor technology, they help improve resolution. In communication technology, high frequency electronics enable the simultaneous transmission of large data volumes, but also limit the range at the same time. Consequently, more transmitting stations are required. In order to avoid higher power consumption, the transmitting stations must become significantly more efficient. This can be achieved by improving the energy efficiency of high frequency technology, but also by combining electronic and optical data transmission across long distances.

In general, the transition towards ever-higher frequencies calls for continuous research in high frequency technology and also in faster electronics. There is also scope for research on optoelectronic interfaces (silicon photonics); being able to manufacture highly integrated circuits with a feature size of less than 10 nm is relevant in this context since no European company currently masters this skill.

Fields of action in high frequency electronics include:

- **Radar systems**: highly integrated and high-frequency radar systems can significantly improve system properties and cost efficiency. One of the major challenges will be the system integration of future radar systems.

EMC

Electromagnetic compatibility (EMC) in terms of high-frequency electronics refers to the ability to design a technical device or single circuit so that other circuits in the same device and other devices are not affected by unwanted electrical or electromagnetic effects. Unwanted interference between electronic systems is not only a technological and legal issue, but also a question of safety and security.

- **Antennas**: higher integration densities and frequencies require new and complex antenna designs and concepts including the relevant antenna control as well as hardware implementation of new modulation methods.
- **EMC (electromagnetic compatibility)**: the trend towards higher frequencies exacerbates the challenges in EMC and calls for research in this field.
- **Combination of high frequency electronics and optics for communication**: early and energy-efficient conversion between electronic and optical (photonics) signals is a major field of research and a cornerstone of sustainability. Design tools are also needed to facilitate the integration of optoelectronics.
- New **substrates and materials** for high-frequency electronics are needed to exploit the theoretical potential of higher frequencies in practice.

3.5 Intelligent and energy-efficient power electronics

Power electronics is and remains a key interdisciplinary technology of electronics.

To ensure electrical energy is available where it is needed, it has to be distributed, converted and controlled. This is where power electronics comes into play. It will continue to grow in importance since the share of electrical energy in primary energy consumption will increase substantially with digitalisation on the rise and Germany's transition towards renewable energy, also known as the Energiewende, and more and more applications and devices being powered by electricity.

Germany plays a pivotal role in power electronics. However, as markets for power electronics expand and grow, they also attract new international players, and it is expected that cost pressure will increase due to higher unit volumes. For Germany to maintain its competitiveness in power electronics, it is primarily the costs above all that have to be lowered. At the same time, the requirements regarding weight, size, reliability, and efficiency are more likely to increase than diminish in future.

In addition, modern power electronics are expected to become smarter and be able to control industrial electric drives on an as-needed basis instead of running them unnecessarily at full load. This helps to save energy in more and more applications and constitutes a vital step towards improved climate protection.

As more and more applications are electrically powered, demand for electricity could potentially double by the year 2050. [8]

Advancing power electronics opens up the following fields of action:

- **Cost reduction**: new concepts for packaging technology and for system integration are promising research and development approaches that are geared at higher unit volume production. Platforms and material efficiency are also gaining importance in power electronics since they help leverage scaling effects and reduce costs. This, in turn, enables a wider use of the systems.
- **Efficiency**: wide-bandgap semiconductors also hold great potential. They can be operated at high switching frequencies and thus achieve higher efficiency levels. In addition to the already well researched materials silicon carbide and gallium nitride, new

8 www.acatech.de/publikation/sektorkopplung-optionen-fuer-die-naechste-phase-der-energiewende

semiconductor materials such as aluminium nitride and gallium oxide are attributed high efficiency potential in power electronics.

- **Sustainability**: the more durable and robust the design of power electronics, the greater its sustainability. By avoiding critical raw materials and employing the circular economy concept, it is also possible to generate significant sustainability effects.
- **Intelligent power electronics systems**: research topics for smart power electronics include new topologies for systems with higher efficiencies also when operated at zero load or partial load, integrated sensors for self-monitoring, active control and integrated communication technology for linking up with other system levels or systems.
- **Ultra-low power electronics**: more and more IoT micro devices use ultra-low power electronics. In terms of unit volumes alone, they therefore play an increasingly important role in energy efficiency. Zero power standby solutions and improving efficiency towards energy self-sufficiency are two fields of research.
- **Electromagnetic compatibility and system integration technologies**: in power electronics, electromagnetic compatibility in relation to the system design must be considered at all levels. With increasing system complexity, integration density, and switching frequency, the challenges continue to increase here, too.

Wide-bandgap semiconductors

Wide-bandgap semiconductors (WBG) are semiconductors that are more efficient than their silicon-based counterparts due to their wider bandgap. They are used in applications with special requirements such as low-noise or high-frequency amplifiers. In addition to low switching losses, WBG semiconductor-based devices can be operated at higher voltages, temperatures, and frequencies, and offer more reliability. The wider bandgap enables their use in optical emitters in the short-wavelength range (visible light), e.g. in blue or ultraviolet light emitting diodes (LEDs).

3.6 Interdisciplinary technologies and topics

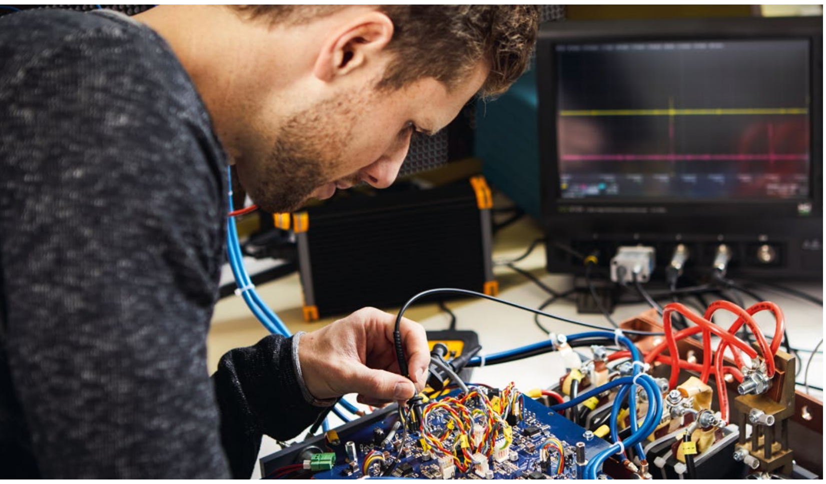
Due to the interdisciplinary character of some aspects, they are of fundamental importance for several fields of technology. In research funding, they are usually considered together with the respective application, but deserve to be treated separately.

3.6.1 System integration technologies

Innovative integration makes systems more efficient, reliable, and cost-effective.

An important trend in electronics is the integration of an increasing number of functions and components into one system: instead of combining them on a circuit board, they are incorporated into a compact module, into a package or directly into a single chip. The reasons for this are manifold: due to restrictions on size or weight, the application may require space-saving system integration. In addition, system integration can improve reliability, because every subsequent assembly step presents a potential source of error. This technology trend is referred to as More-than-Moore to differentiate it from Moore's Law (cf. Chapter 3.8), which is an empirical observation on the increase in integration density. The integration of optical and mechanical functions into electronic systems is one of the key strengths of the German and European semiconductor industry: terms such as microsystems technology, microelectromechanical systems (MEMS), and micro-opto-electro-mechanical systems (MOEMS) are commonly used in this context. Current examples include multidimensional accelerometer sensors, LiDAR for autonomous driving and micro-spectrometer – all as on-chip systems.

Higher volumes in combination with a suitable system integration design can help to reduce production costs. This could even reach a stage where the integrated electronic system is manufactured directly on the wafer – from the single function or component to its connection and packaging. Smartphones are a typical example of an extremely high integration density and complexity (albeit manufactured outside Europe). Their high production volumes economically justify the technological development costs and efforts involved. To enable packing more functions into the device without increasing its size, the electronics must reach higher



and higher levels of integration. This can be achieved with a wide range of technologies (see below).

Numerous challenges arise from the increasing complexity of system integration and this places enormous demands on the conceptual and technological architecture. For instance, the number of materials used in the system increases and this must be taken into account for the technological processes. Different functions can lead to diverging technological requirements. In this context, it is necessary to take a look at the general conditions such as the need for optical windows or a hermetic design, thermal and electromagnetic dependencies or the operating conditions for the finished system. In packaging technology, i.e. the back-end-of-line, system integration increasingly requires automated processes and advanced systems technology. Measuring and testing technology is also much more complex for a system than for components with individual functions. To make matters worse, the trend towards outsourcing production steps, especially in assembly and packaging, makes the finished product more vulnerable. By contrast, new approaches such as split manufacturing can make a targeted contribution to improving the trustworthiness of electronic systems.

This leads to numerous fields of action for research and development:

- **Packaging technologies for new complex systems**: this includes the design of multichip packages and SiPs (system-in-package), 3D packaging, stacking techniques (flip-chip), interposer technologies (e.g. vias), embedding, but also the development of alternatives to wire bonds and solder contacts. Thin packages that use no separate circuit board ("substrate-less") offer low thermal resistance and good high-frequency properties due to short and planar electrical connections. Fan-out-wafer-level-packaging (FOWLP) has a high miniaturisation potential both in terms of package volume and package thickness. Fan-out-panel-level-packaging (FOPLP) is another promising approach. Additional topics requiring research include, thermal and stress management, robustness, and recyclability.

- **Manufacturing processes**: focus areas include assembly and packaging automation (back-end-of-line), integration of additive manufacturing processes such as 3D printing of components and conductors, stereolithography for 3D packaging and embedding, the development of customised manufacturing equipment and suitable measuring and testing technologies as well as the use of resource-saving process steps.

- **Packaging technology and manufacturing processes for trustworthy electronics**: new system integration methods can make a decisive contribution to leveraging the trustworthiness of electronics. Modular designs and distributed functionality approaches, e.g. by wafer-to-wafer-bonding, chiplet designs and split manufacturing play a key role in this context.

- **Design and simulation**: when developing hardware and software simultaneously, the system architecture and functionality are jointly considered during the

Hardware and software co-design

Hardware and software co-design can considerably accelerate the development of microprocessor-controlled devices because it involves the simultaneous development of electronic components, board, and application software. System development remains flexible for a longer time, which is another advantage since the allocation of functions to hardware and software can still be adjusted as requirements change.

design process. Due to the increasing complexity, requirements of downstream manufacturing processes are also taken into account at this stage, e. g. design for testability, design for reliability or design for trust. Further research topics are thermal, mechanical or electromagnetic interactions in complex systems.

3.6.2 Test, verification and validation

Testing builds confidence.

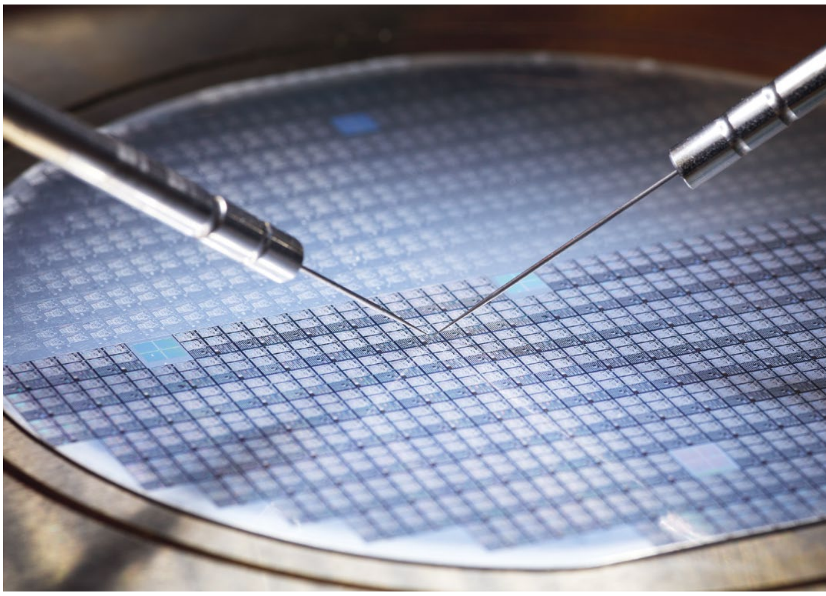
The requirements for the durability of many electronic components and systems are continuously increasing. The demand for reliable and robust electronics is rising especially with regard to critical applications. By introducing autonomous driving technology in driving services, for example, car electronics will no longer run for just a few hours a day but will be operated constantly with few breaks.

At the same time, the architecture of electronic systems is becoming more and more complex, combining multiple technologies in a confined space. This gives rise to new potential sources of error that can result in defects. However, system failures are not always the result of the unexpected behaviour of complex technologies. Counterfeit and pirated products from component suppliers are another risk, causing billions worth of damage to the economy every year while also posing a considerable safety and security risk for users.

As a result, the role of testing and test method effectiveness becomes increasingly important for trustworthy systems. This applies to the entire chain – from design and production to verification and validation. However, research and development effort in the field of testing, verification, and validation is considerable.

All in all, this leads to different fields of action such as:

- **Design for test**: electronic systems must be designed to facilitate efficient testing at all stages of product development – from simulation and prototyping to the finished product. This saves time and expense as testing and verification meanwhile account for a major part of electronics development work due to the complexity of the systems, stringent requirements, and high integration density. Testing is very complex and never comprehensive, especially in systems that also contain analogue elements such as communication interfaces. Emerging technological developments require the constant adjustment of test coverage specification and test design in combination with simulation models.



- **Test methods and equipment**: they must keep up with technological progress. Research and development of new microelectronics technologies must always go hand in hand with research and development in testing and validation. In addition to identifying unintentional errors, test methods also focus on detecting intentional manipulations.

- **Global network of various component test benches**: the aim is to validate systems and provide standardised component data for simulation models. A secure data connection provides the basis for companies and researchers to analyse component interactions without disclosing confidential information on their own components. New methods such as modular security approval also benefit from this. Whereby single components are individually approved and then released for operation of all system combinations. This significantly reduces the test bench utilisation time.

- **Measuring methods and equipment**: component functionality and efficiency can be verified by means of suitable measurements and measuring technology helps to identify counterfeits. To this end, it is necessary to develop suitable measuring methods and equipment. Due to the increasingly high integration level, it should ideally be possible to perform measurements inside the components in order to be able to capture and analyse the relevant condition data.

- **Harmonising component analyses by standardisation**: standardisation can advance the processes for trustworthy and reliable electronic components and systems, and support homogeneous and structured procedures for the validation and security approval of individual components and complete systems.

3.6.3 Adapting new materials

Progress in microelectronics development is often based on innovations in the field of materials.

The ongoing trend towards miniaturisation of structures, components, and systems places great demands on the properties of the materials used. In addition to supporting the functionality and efficiency of the electronic components, the materials used must also support overriding requirements such as robustness and reliability, energy efficiency, and sustainability.

This underpins the necessity to research and use new materials for microelectronics. But also newly identified properties of existing materials hold potential for new and further developments in microelectronics, power electronics, and sensor technology.

Memristive materials

Neuromorphic electronic systems are built with memristive materials. The term "memristive" is a combination of the words memory and resistor. The intelligent materials emulate the learning and memory processes of biological systems with non-biological technology.

The application of new materials poses many challenges: combining different materials in heterogeneous systems also increases the complexity of system integration technologies. Moreover, they also require new manufacturing processes and systems. To ensure that no new dependencies arise for Germany as an innovative microelectronics location in terms of technological sovereignty, the new materials must not only be available, but it is also imperative to build up the necessary competencies and skills in order to master the technologies essential for these materials. This requires interdisciplinary collaboration between the materials and electronics research communities. To this end, projects focusing on the development of new and innovative materials are primarily funded by the BMBF with its programme "From Material to Innovation", in particular with regard to the sustainable use of materials in the entire process chain.

Current research and development topics include:

- **New materials and material systems for microelectronics**: in addition to new materials, their combination with established CMOS technologies offers great potential; one example is the successful use of gallium nitride on silicon. New and optimised materials are also required for high-frequency electronics with constantly increasing frequencies and performance requirements. In terms of neuromorphic computers, advancing memristive materials is another field that needs investigating.

- **New materials for power electronics**: wide-bandgap materials in particular, such as aluminium nitride and gallium oxide, promise enormous innovation potential for power electronics. In addition, new system and integration approaches require new substrate and sinter materials.

- **New materials for sensor technology**: in addition to one and two-dimensional materials, research approaches focus on materials whose use enables improved and new sensor properties (e.g. organic materials and materials with special physical properties).

- **Sustainability**: one option to support sustainability is to select materials according to criteria such as efficiency, production, durability or recyclability; self-healing material systems, substituting critical materials and avoiding rare earth elements represents another option along with the use of compostable and biodegradable materials, and materials based on renewable raw materials.

3.7 Selected systems for microelectronics production

Electronics production on systems made in Germany.

Germany's industry has been traditionally strong in the field of mechanical engineering, measuring technology, and optics, which opens up many opportunities for strengthening and expanding semiconductor production in Europe and generating significant turnover on international markets. This calls for a closer collaboration between research institutions and the industry in Germany and Europe.

Non-European suppliers increasingly dominate the market for high-output systems. However, the production of trustworthy electronics, in particular for safety and security-relevant applications, requires special low volume equipment. Germany has a strong expertise in this field as well as in plant engineering for special applications such as coating processes (e.g. MOCVD, sputtering), plasma etching or automation. Here, the close cooperation of industry and research institutions in Germany pays off.

German companies also take a leading global role when it comes to other types of systems, thanks to their collaboration with European partners. Zeiss (Germany) and ASML (Netherlands) have been cooperating closely for decades; together, the two companies are world market leaders in the field of exposure units for semiconductor imaging (lithography steppers). Sup-

Additive manufacturing process

3D printing, also known as additive manufacturing or rapid prototyping, is a manufacturing process that uses different materials and applies them layer by layer to build a three-dimensional object. Additive manufacturing is used in prototyping, by industry, and by the research community for creating models, samples, prototypes, tools or spare parts to eliminate the need for inventories.

ported by many years of funding from both the BMBF and the EU, they have been instrumental in driving the development towards ever-smaller semiconductor feature sizes and are now the world's sole providers of novel EUV steppers for the smallest feasible feature sizes. Within the IPCEI on Microelectronics, it was possible to support the research and development for the first time, as well as the relevant equipment, which was needed to set up mass production of this technologically sophisticated innovation.

In the wake of globalisation, the focus of labour-intensive production steps in the electronics industry has also shifted to regions with traditionally low labour costs. An increasingly automated workflow can help strengthen production in Europe and thus uphold its technological sovereignty as a production location. In fact, German semiconductor manufacturers are among the pioneers of Industry 4.0. In particular, the back-end of semiconductor production, e.g. the packaging technology, holds further potential to drive automation.

This opens up various research options for microelectronics production, such as:

- **Automation solutions for semiconductor and electronics production**: new electronic systems require new automation solutions. This has the benefit of utilising cost reduction potentials in the production while also improving process reliability and system properties. In addition, research and development activities on special systems are expected to strengthen Germany's and Europe's position in the global race for technological sovereignty.
- **Complex machines for additive manufacturing processes**: these are used to integrate electronic and sensor functions into substrate materials and can be adapted to meet special requirements in packaging technology. Germany's strong expertise in mechanical engineering opens up the possibility to become a global market leader for specialised machines for additive manufacturing.
- **Measuring and testing technology**: electronic development and quality control in production require technically sophisticated measuring technology. German companies are world leaders in this field. However, new materials and technologies such as neuromorphic chips call for new measuring technologies. It must be possible to integrate them directly and permanently into a production line in future in order to monitor production processes. A great deal of development work is still needed on this front. Developments in measuring technology in Germany are mainly driven by SMEs and start-ups, which enables them to capture niche markets. The close collaboration between the research community and the industry provides a good starting point for spearheading this field on an international scale.

3.8 Advanced silicon and beyond

In search of new technologies.

In line with Moore's Law, improving the performance and energy efficiency of semiconductor components has been associated for a long time with ever increasing miniaturisation. However, this reduction of features is now beginning to reach its physical limits, making it increasingly more difficult to continue on this path of development ("More Moore"). At the same time, a profitable production is becoming less viable.

This is why research in "beyond silicon" concepts has been intensified: new technologies and materials with disruptive potential. Firstly, significant progress in the energy efficiency of electronic systems can be expected here. Secondly, this opens up the opportunity to be involved in new fundamental technologies right from the start and to maintain competence leadership and sovereignty.

Fields of action include:

- **New structures and components**: the constant increase in efficiency of integrated circuits combined with a continued structure reduction regularly requires new concepts, both at transistor level and at memory and chip architecture level. New research approaches can help to optimise microelectronic systems for specific applications or support the integration of additional functions in a chip, e.g. by incorporating optical and micromechanical components. Conducting research on novel components such as memresistors (cf. Chapter 3.2) is another important aspect.

- **New approaches to computing power**: areas of research include disruptive concepts of the "beyond von Neumann" trends such as "in memory computing", "neuromorphic chips" and "artificial synapses". Neuromorphic chips have the advantage of high computing capacity and low power consumption.

Neuromorphic chips

A neuromorphic chip is a special microchip that is modelled on natural nerve cells in the brain (neurons) and their interconnections. Neuromorphic chips have the potential to be significantly faster and more energy efficient than conventional universal processors for AI applications – just as the human brain is much more energy efficient than previous computers. This relatively young field of research has already produced prototypes such as artificial retina implants or special processors for natural motion sequences in robots.

4 Microelectronics underpin cutting-edge applications

Microelectronics continues to be the driver of innovation for a wealth of applications, especially in the field of digitalisation. In turn, applications are driving the demand for trustworthy and sustainable electronics.

4.1 Artificial intelligence

Artificial intelligence that is designed to serve humankind and runs on trustworthy microelectronics conforms to our European standards and values.

From the automotive industry to pharmaceuticals right through to Industry 4.0: more and more industries are now using methods based on artificial intelligence (AI). The reason for this is that self-learning systems that rely on artificial intelligence and big data facilitate diverse innovations and business models based on exponentially growing data volumes and computing power. Among other things, artificial intelligence can help control processes and systems more efficiently in the interests of sustainability and thus support energy conservation in Industry 4.0, for example. At the same time, more energy-efficient chips provide for more sustainable AI and open up new areas of application – such as medical devices, which can be worn on the body, or personalised AI, trained in the end device.

However, although it offers enormous economic and social opportunities, AI is not without risks. This makes it all the more important to be proficient in the underlying technologies in Europe to enable us to act confidently, benefit from opportunities and manage potential risks.

This applies in particular to electronics, enabling technology, and the "electronic brain" of AI. Thus anyone wishing to integrate artificial intelligence into their products should also have electronics expertise at overall economy level to avoid being dependent on manufacturers outside Europe. To ensure that Europe as an economic location secures its technological sovereignty, it needs not only its own AI ecosystem, but also its own electronics expertise: ideally with its own production, but at the very least with the knowledge base to design and verify the required chip functions. This is the starting point for developing trustworthy AI, which is in line with the needs and values of European society.

Germany is ideally positioned to establish itself as one of the leading electronics suppliers for European AI. AI processor technology is experiencing very dynamic growth and provides good opportunities for application-specific AI methods with corresponding hardware, e.g. via open source approaches or modular systems.

Training an artificial intelligence system with large data volumes requires vast computing power and thus energy, and the demand for this is growing exponentially. For this reason, energy efficiency will have to be substantially improved before many applications can fully exploit the enormous potential of AI. Energy-efficient processors made in Germany and Europe can play an important role in this respect. Special processors enable the use of edge AI and embedded AI, thereby making a significant contribution to resource conservation and data protection: up until now, AI algorithms have mostly been trained in large data centres. Significant amounts of energy can be saved by processing these algorithms locally on user devices instead of in the cloud. If data is processed directly in the user device without first being sent to the cloud, it also makes it easier to uphold European privacy values by technical means.

However, the development of special processors for AI applications is extremely complex, because sensors (data), algorithms and electronics have to be dovetailed with such precision. The requisite design and manufacturing skills must therefore be developed in Germany and Europe. In this context, it makes sense to be open to new hardware technologies, since alongside conventional semiconductor processors, processors with optical or electro-optical components, for example, offer great potential for boosting energy efficiency and speed.

4.2 High-performance computing

High-performance computing enables scientific excellence.

Computer-aided simulations are often used to solve complex issues in research and development. This requires enormously powerful supercomputers capable of calculating complex models. This type of computing, also known as high-performance computing (HPC), is helping to address pressing 21st-century issues – from climate change, the transition to renewable energy and health to mobility, security, and communication. Thus, high-performance computing contributes to strengthening Germany's leading position in key technologies and its competitiveness as a scientific and industrial location. The efficiency of supercomputers can be increased significantly through the use of new microelectronics; for example, components which expand computing capacities and ensure reliable server and cloud architectures.

> If you were to equate the computing speed of a laptop with the speed of a snail, then the computing speed of an exascale supercomputer would exceed the speed of a space rocket.[9]

The German Federal Ministry of Education and Research (BMBF) promotes supercomputing as the basis for scientific excellence and pioneering industrial applications by supporting computing capacities both at national level at the Gauss Centre for Supercomputing (GCS) and at European level through its involvement in the EU partnership EuroHPC. The hardware required to do this is being developed partly through the European Processor Initiative (EPI). This initiative, which involves researchers from Germany, aims to develop powerful, efficient processors for supercomputers, data centres, and autonomous vehicles. As part of the EPI, homegrown processors are currently being developed based on the open RISC-V instruction set architecture and licenses from the CPU manufacturer ARM (cf. Chapter 3.2). EPI is part of the European strategy for developing infrastructure for high-performance computing in Europe.

4.3 Communication technology

Communications networks are the lifelines of the digital world.

Communications and data networks are composed of numerous different microelectronic components – from high-frequency technology and optoelectronics to power electronics and special processors. As these become ever more powerful, new applications and business models for communications technology are continuously emerging.

However, anyone wishing to make the most of these opportunities and establish themselves as a confident player in the digital world must have access to trust-

9 exanode.eu/exascale-computing

worthy data networks with corresponding hardware for data transmission and encryption. Microelectronics thus has an important role to play in shaping the technological sovereignty of Europe as a location – both in terms of the sustainability of communication technology and of climate protection:

Digitalisation in the form of “smart grids” can help save significant amounts of energy. Nevertheless, climate-friendly digitalisation can only succeed with energy-saving communications electronics, since each individual bit consumes energy as it passes through the data networks. Given the exponentially growing volumes of data in the Internet, there is an urgent need to reduce this energy consumption massively in all areas. Advances in microelectronics are essential in the interests of both the trustworthiness and sustainability of communications networks. The relevant aspects of communication technology systems are dealt with in a separate research programme and also in other departmental research activities.

As an enabling technology for communications networks, microelectronics must therefore meet very strict specifications. System accessibility, availability, robustness, and resilience – and often real-time capabilities as well – must be reliably ensured, especially for industrial applications or the mobility sector.

Some innovative application concepts would be impossible without microelectronics. Edge computing, for example, aims to minimise the amount of raw data that needs to be transferred. To this end, the electronics industry supplies the components for the requisite intelligent network design and data pre-processing at the point of measurement – in the edge device or in edge cloud/fog computing approaches within the network.

Wireless transmission also calls for innovations from the microelectronics industry. With the launch of 5G and in future 6G, even more devices will be connected with each other in the Internet of Things, in industrial and transport applications. Research is being carried out on the design of electronics for new 5G systems to enable data centres, edge cloud systems, narrowband radio technology, and large-scale data transmission to be connected with one another and thus ensure the smooth functioning of these systems. In future, localisation functions will supplement or even replace separate sensor systems. The aim in all cases is to ensure highly efficient data transmission. There is also scope for development when it comes to equipment for 5G/6G networks. This includes electronics for new, higher frequency bands, new process technologies for individual high-frequency electronics, and energy-efficient hardware for software-defined radio technologies (e. g. OpenRAN). Another major focus is the efficient combination of different standards and technologies (e. g. WLAN and LIFI).

Glass fibres are the backbone of modern wireless networks, but these, too, need microelectronics. Highly integrated photonic components enable early, energy-efficient conversion between electronics and optics, allowing energy consumption to be further reduced. Exploiting the synergies between electronics and optics offers further potential for improvement; for example, by developing platforms for integrating electronics and optics.

4.4 Smart health

Reliability and trustworthiness are paramount when it comes to health.

Digitalisation has long been a part of medicine, too. Electronics is an enabling technology for smart, connected health applications, and it largely determines the degree of innovation of a new medical device. To this end, the electronics must satisfy very specific requirements – for example, minimum power consumption, minimum component size, a high level of robustness or the biocompatibility of the entire system, depending on the application.

But one requirement applies to all medical applications: the electronics must be completely reliable. Patient data must also be handled safely and confidentially, since sensitive health information is subject to special data protection laws. These laws reflect the European understanding of fundamental values, which encompass human dignity, informational self-determination, freedom, the rule of law and solidarity, and they must all be upheld. The European Health Data Space creates structures to safeguard data across European borders and to enable data to be accessed and shared in compliance with data protection law. Electronics has a role to play in all of this. Furthermore, to ensure that appropriate medical equipment can be provided rapidly in crisis situations such as pandemics, the necessary electronic components must also be available in sufficient quantity at short notice.

We need dependable value chains in order to meet these stringent requirements for the reliability, trustworthiness, and availability of electronic components. Especially in critical segments such as the health sector, Europe must ensure its technological sovereignty in order to minimise the sole dependence on manufacturers outside Europe and to ensure that the best possible medical care is available to its citizens at all times.

On the technical side, there are several promising approaches for improving the immediate availability of essential electronics. For example, by ensuring that components and entire functional units have a high degree of modularity and exchangeability, it is possible to respond flexibly to changing requirements. Furthermore, platform solutions and standardised interfaces can shorten the time to market for new developments.

New microelectronic components will significantly extend the range of applications for medical electronics. When it comes to medical diagnostics, data pre-processing, drug development, and our understanding of rare diseases, artificial intelligence can save a great deal of time and resources. Electronic systems for telemedical e-health applications can improve and speed up the provision of health care in medically under-resourced rural areas. New biosensors in lab-on-a-chip applications can complement or even replace laboratory diagnostics at the point of care. Edge computing approaches have an increasingly important role to play in these applications (cf. Chapters 3.2 and 4.1).

Microelectronics can assist with energy management in implantable medical devices to ensure a long-term energy supply; for active, smart, and connected implants, which enhance the quality of life for patients, for instance. Components with sensor and actuator functions combined with new forms of power supply will enable gentler theranostic treatments in the future. Energy-saving electronic systems and specialised AI solutions will increasingly form the basis for improved prosthetics and orthotics tailored to individual patients.

Highly specialised electronic systems for neuroprosthetics in turn are helping to reduce the effects of incurable neurological diseases such as Parkinson's disease, epilepsy or locked-in syndrome. Neuroprosthetics can in future restore at least partially the functioning of damaged or severed nerves in patients suffering from paraplegia or with damage to the extremities caused by an accident. Micro-implants can also replace medication, for example in the treatment of chronic pain and severe depression.

Solutions based on modern electronics can alleviate routine tasks for medical and healthcare workers. This includes a wide range of options, from simple RFID tags to robots for assisting with operations and supporting nurses, and ultimately to ultra-high-performance in-patient diagnostics.

In bioprocess engineering and pharmaceutical production, microelectronics can be used to continuously monitor production processes, minimise production downtimes, and maximise product quality (cf. Chapter 3.3).

4.5 Autonomous driving

Electronics and sensor systems make people mobile.

The mobility sector is one of the strongest sectors in Germany in terms of research and innovation and plays a key role in maintaining jobs and prosperity. In the next few years, automated and connected driving and the need for sustainable mobility will dominate development. The electronics industry is currently still a reliable supplier of innovation for the German automotive industry. When it comes to autonomous driving in particular, however, it also creates a disruptive potential that challenges previous business models. There is a close connection here between innovation leadership and market dominance.

Electronics and sensor systems in driver-assistance systems are already reducing the risk of accidents and protecting lives today. In future, self-driving vehicles will further improve road safety.

They will optimise traffic flows on motorways and in cities, and improve energy efficiency in both vehicles and the transport system. Autonomous driving therefore also contributes to climate protection by reducing noise pollution, air pollution, and CO_2 emissions. Finally, autonomous driving makes it easier for everyone to use road transport. The way we travel will undergo a fundamental change.

This new form of mobility is based on powerful and highly innovative microelectronics, which essentially determine safety, functionality and sustainability. In order to secure Germany's position as a location for mobility in a world of advancing digitalisation, technological sovereignty in key microelectronic components is becoming increasingly important.

First and foremost, all autonomous vehicles need powerful sensor systems with a high level of detection accuracy that work in real time under all environmental conditions (cf. Chapters 3.3 and 3.4). As the number of sensors increases, so does the amount of data that needs to be processed by increasingly powerful computing systems – especially in battery-powered vehicles with limited energy budgets (cf. Chapters 3.2 and 3.4). For a complete view of a vehicle's surroundings, the data must first be merged and then categorised according to recognised objects. Making real-time driving decisions from this data requires a very high level of computing power. Very promising in this context is the use of artificial intelligence, which combines important information about a vehicle's surroundings by connecting autonomous vehicles, infrastructure such as smart traffic lights or roadside edge computers, highly precise maps, and data from the cloud.

Only when all components and the entire system function safely and reliably under all conditions can the technology be trusted to make the right decisions and be responsible for the safety of the occupants. In an emergency, if this is no longer guaranteed, it must be possible to return the vehicle to a safe condition (e.g. stationary) at any time.

The trustworthiness of the electronic components used and the overall system has absolute priority when it comes to autonomous driving. There must be zero risk of accidental interference or intentional manipulation – from the individual chip to data processing, and the software in the control system and infrastructure. To achieve this, technologies and concepts must be developed which both detect and prevent possible tampering or other external influences. Trustworthy electronics are among the essential elements.

The energy efficiency of individual systems must be significantly improved in order to reduce the vehicles' power consumption. Some energy-intensive functions can also be removed from the vehicle and undertaken externally elsewhere. The collection of information on the surroundings and the processing of the data, for example, can take place in the infrastructure or alternatively in the cloud using edge computing. It is important that latency, i.e. the reaction time of the vehicle, is kept low and the data transmission rates high.

The pace of development and the pressure from international competitors are high. The demand for increasingly high-performance components is accompanied by ever shorter innovation cycles in automotive electronics, which is at variance with a normal vehicle service life of 10 to 15 years. Refurbishment – a term used in electronics production, which means the overhaul and repair of equipment for the purpose of reuse – will in future also play a role in the electronic equipment of autonomous vehicles. This requires flexible modular concepts and standardised interfaces.

4.6 Industry 4.0

Industry 4.0 is only possible with the most advanced microelectronics, AI processors, and sensor systems.

Industry 4.0 stands for intelligent, flexible, and networked production and therefore can be regarded as no less than the fourth industrial revolution. Industry 4.0 is unique in that it not only changes the production processes themselves, but also their interplay with their economic, societal, and social environment. The BMBF has prioritised the topic Industry 4.0 as a future project of the BMBF because of its tremendous importance for German industry.

In Industry 4.0, data from the production process is collected automatically and then used in a wide variety of contexts. This makes production and logistics more efficient, flexible, and individual. Decentralised forecasts and decisions enable production systems to act increasingly autonomously. The predictive maintenance of production facilities and improved monitoring of industrial processes is another key theme of Industry 4.0. And when production systems and processes are networked across company boundaries, this also enables the effective analysis and management of the interaction with cooperation partners in the value chain, with sales, marketing, and customers. Frequently, this also yields insights for research and development. Conversely, customers and partners can influence production faster, more directly, and more efficiently by digital means.

Industry 4.0 opens up completely new business model and cooperation opportunities in cross-company production and marketing networks via comprehensive digitalisation and the automation of production processes and operational procedures. For Germany – traditionally a strong leader in manufacturing engineering, automation, sensor technology, and system solutions – this development is significant in several respects. The German mechanical and plant engineering industry has a large global market share over and above national demand. Similarly, Agriculture 4.0 could contribute to efficient and ecological agriculture and make German agricultural technology an export hit.

Survey findings: 94 per cent of German industrial companies see Industry 4.0 as the prerequisite for maintaining the competitiveness of German industry. More than one in two say that Industry 4.0 is giving their own business a general boost. Almost three quarters of German industrial companies are planning not only to change processes as part of Industry 4.0, but also to modernise their own business models.[10]

Microelectronics and sensor systems are the key technologies for Industry 4.0. In addition to the actual gathering of information, they enable data processing in the sensor, in the machine, in edge computing or in the cloud, as well as internal and external communication via data transmission. In many cases, application-specific solutions are required, for which the German microelectronics industry is very well positioned.

10 BITKOM Industrie 4.0 – so digital sind Deutschlands Fabriken (BITKOM Industry 4.0 – how digital are Germany's factories, in German), bitkom.org/Presse/Presseinformation/Industrie-40-so-digital-sind-Deutschlands-Fabriken (2020)

If Germany is to remain competitive in the future as a global production location and a leading supplier, it is essential that microelectronics technology is consistently developed further so that rapid innovative advances can be achieved in the field of Industry 4.0 technology.

There are already numerous approaches to this: for example, energy-efficient or even energy-autonomous sensor systems can significantly improve sustainability and the economic operation of the equipment, and also simplify the infrastructure – because cabling becomes superfluous in many places (cf. Chapters 3.3, 3.5 and 3.6). The microelectronics industry also supplies the components with which production can be fully digitalised, product development cycles shortened, and product life cycle management established. And sensor systems ensure safe and efficient cooperation between human and machine.

Powerful and coordinated hardware and software components enable energy-efficient data collection and processing. To this end, research is also being conducted on electronic systems that already enable the implementation of identification and safety functionalities at hardware level, as well as on new hardware concepts, circuits, and systems that are optimised for artificial intelligence (AI) or machine learning methods.

Microelectronics technology also supports decentralised data processing as well as data reduction and data pre-processing for real-time process control, as well as self-diagnosis, configuration, optimisation, and repair. New solutions for sensor data fusion, measuring methods, and sensor concepts as well as secure interfaces from the sensor to the cloud and back are being developed. Further interdisciplinary topics relating to microelectronics for Industry 4.0 are real-time capability, reliability, electromagnetic compatibility, robustness, resilience, interconnectivity, quality and cost-effectiveness for use in industrial environments.

In order to quickly produce new innovative microelectronic components for Industry 4.0, system design must be further accelerated by using and developing new EDA tools. New possibilities are also required for the simulation and virtualisation of processes and objects in terms of a digital twin, and adaptation to standardised, widespread industrial digital communication protocols, including hardware-software co-design.

4.7 Smart energy conversion

The Energiewende – Germany's transition to renewable energy – requires us to completely rethink energy conversion.

Energy undergoes various transformation processes on its way from primary to usable energy. For example, before solar energy can be used to operate an electrical device, it has to be converted into electricity over several stages and often transported over long distances. In the past, the generation, conversion, and transport of electricity were organised on the principle that well-managed generation follows not fully predictable consumption.

This has changed markedly in recent years. Our energy system is no longer dominated by a few large electricity producers who can adapt their supply to demand. Today, almost half our electricity is already provided by renewable energy sources such as wind and sun, and thus by an increasing number of small electricity producers with highly fluctuating output. Electricity consumption, which has always fluctuated throughout the day, is also changing with the increasing electrification and digitalisation of end applications. The inte-

gration of energy storage systems, the digitalisation of the Energiewende, e.g. with “smart” electricity meters, and the increasing coupling of the energy sector with the demand sectors can help here, but at the same time they also increase the complexity of the overall system.

Significantly more flexible energy conversion, energy distribution, and “energy consumption” are needed than before, which are at the same time more intelligently coordinated and also more “communicative”, in order to keep electricity generation and consumption in balance – even under volatile conditions in the European electricity market – to promote the use of renewable energies and thus contribute to climate protection. This will allow renewable energies to be used more effectively and efficiently, thus not only maintaining supply security, but even improving it.

There are challenges at all levels. This applies to end devices whose power consumption must be as low and whose supply must be as efficient as possible –under all load conditions, and for devices with flexible operating times which are ideally controllable from the grid side. There is also a need for more flexible systems, including bi-directional ones, for power grids. These are needed, for example, for isolated grids, for charging systems for electric vehicles, between different grid levels, but also for sector coupling or large storage facilities. After all, the power grids of the future will have to exchange not only energy but also data to enable smart conversion, storage, and transport of energy.

Microelectronics technology plays an important role in this. It provides highly efficient and flexible power electronics for conversion; cost-effective, economical or even energy-autonomous sensor systems for determining key figures in the grids; and communication electronics for data exchange. This technological basis also allows artificial intelligence approaches to be used to evaluate data, to regulate complex grids faster and more precisely than today, and to use smart power electronics for producers and consumers to stabilise grids (cf. Chapters 3.2, 3.3, 3.5, 3.6).

There is still development work to be done in many areas, e.g. the status of the medium and low-voltage grids in particular is still difficult to determine. High investment costs for measurement and communication technology, a lack of installation space in the facilities, and the high requirements for secure data transmission are obstacles – problems to which microelectronics technology makes a decisive contribution.

In 2018, 24.6 TWh were lost in the power grids nationwide,

4 %

of the total energy output (621 TWh), and almost twice as much as the total annual electricity consumption in Berlin (13.5 TWh).[b]

Information and communication technologies accounted for

3.7 %

of global greenhouse gas emissions in 2018.[a]

70 %

of the effort for complex microelectronics is spent on verification and testing.[c]

Around

90 %

of traffic accidents in Germany are attributable to human error.[d]

The industrial sector accounts for approximately a quarter of the gross value added in Germany. This puts Germany well above the European average of

19%[e].

a theshiftproject.org/en/article/lean-ict-our-new-report

b bundesnetzagentur.de/SharedDocs/Mediathek/Berichte/2019/Monitoringbericht_Energie2019.pdf (only in German)

c blogs.sw.siemens.com/verificationhorizons/2016/08/22/part-2-the-2016-wilson-research-group-functional-verification-study

d destatis.de/DE/Themen/Gesellschaft-Umwelt/Verkehrsunfaelle/Publikationen/Downloads-Verkehrsunfaelle/verkehrsunfaelle-jahr-2080700197004.pdf (only in German)

e destatis.de/Europa/DE/Thema/Industrie-Handel-Dienstleistungen/Industrie.html (only in German)

5 Cooperations, instruments, structures

It is clear from the previous chapters that modern microelectronic systems are based on many different basic technologies and must be adapted to many different applications. The social and economic opportunities of microelectronics can therefore only be fully exploited through cooperations, which the Federal Government's funding is designed to encourage, and which will become permanently effective in the right structures. The measures and instruments of this programme fall into the following three categories.

5.1 Strengthening networks

Microelectronics is a very research-intensive technology and thus fundamentally depends on close cooperation between research and industry. Moreover, microelectronics applications are based on complex collaborative supply chains, which depend on numerous players with a wide range of know-how, from materials science to the component and module level and to the system with all its software components. Combining the technological competence of the microelectronics industry with the systems competence of German and European user industries is therefore essential for developing and preserving skills.

In order to secure Germany's technological sovereignty, and in particular to develop trustworthy electronics, the Federal Government is striving to further intensify cooperation at various levels:

- **Cooperation between the scientific community and industry**: the core element of the BMBF's microelectronics funding remains pre-competitive cooperative research by the scientific community and industry within traditional joint projects and beyond. Cooperation between non-university research institutions will also be strengthened. The Research Fab Microelectronics Germany (FMD) bundles a range of research expertise on microelectronics and creates a central interface that facilitates access to cutting-edge technology for industry, especially SMEs. From the outset, FMD comprises institutes that cooperate closely with industry: Fraunhofer institutes on the one hand, and the applied research institutes of the Leibniz Association on the other. Similarly, universities and research institutions should increasingly cooperate with start-up initiatives in order to consciously create an open atmosphere for new collaborations between the scientific community and industry.

  Joint projects also play a key role in the training of young academics and for the transfer of know-how between the scientific community and industry: universities and research institutions have broad opportunities to educate and train master's students, doctoral students, and post-doctoral scholars in application-oriented projects via funds granted to joint projects. Through collaboration, direct contacts are established with industry, which is in need of skilled workers. This programme thus helps counteracting a shortage of skilled workers.

- **European and multilateral cooperation**: the coordination of national microelectronics research funding with European programmes creates a leverage effect through long-term cooperations in Germany and Europe. In addition to the direct results from funded projects, SMEs in particular benefit from the intensive contact with European partners from the scientific community and industry. Fruitful cooperations often develop over and above the projects.

  The Electronic Components and Systems for European Leadership (ECSEL) Joint Undertaking and its planned successor on key digital technologies (Key Digital technologies, KDT) are at the heart of European cooperation in the EU Research Framework Programme Horizon Europe and its predecessor Horizon 2020, while EuroHPC promotes the expansion of cooperations on high-performance computing (HPC) and the European Processor Initiative (EPI, see above). In addition, international cooperations contribute to developing knowledge and skills in Germany. This includes bilateral cooperations such as the German-Japanese research cooperation on autonomous driving, but also multilateral measures such as funding in the intergovernmental initiative EUREKA (in the years 2016–2020 in the electronics cluster PENTA).

  IPCEIs are a special form of cooperation. Here, European countries cooperate with the aim of enabling not only the development of new technologies, but also their implementation in production to strengthen the EU economy and its competitiveness. Together with Italy, France and the United Kingdom, the Federal Government launched the first IPCEI in 2017 in accordance with the European Commission's criteria defined in 2014.

- **Cooperation between the Federal Government and the Federal States (Länder)**: in the European electronics initiative ECSEL, the Federal Government has achieved a particularly high level of synergy through joint funding with the Free States of Saxony and Thuringia. This opens up additional opportunities for research players in both Free States to participate in the European co-financed projects. The Federal States meet the conditions for participation in the ECSEL follow-up initiative KDT. Within the IPCEI on Microelectronics, the Federal Government is funding a sub-project in cooperation with the Free State of Saxony.

- **Associations, networks, and clusters**: associations, networks, and clusters are important for Germany as a centre of innovation. The industry associations ZVEI – German Electrical and Electronic Manufacturers' Association and the AMA Association for Sensors and Measurement, the engineers' association VDE Association for Electrical, Electronic and Information Technologies, the Plattform Industrie 4.0, the networks Silicon Saxony, Silicon Germany, and Silicon Europe at their respective levels, the edacentrum as a network for electronics, design and applications – they all ensure cooperation and new ideas through networking, they provide forums and impulses for the research policy debate, they ensure the necessary exchange between the scientific community, industry, and politics. Clusters bring together all the relevant players of a thematic field and/or a region within a common strategy. Most notably, these include the ECPE European Center for Power Electronics for the power electronics sector and the leading-edge clusters It's OWL, microtech südwest, and Cool Silicon. Continuing its support for leading-edge clusters, the BMBF has launched the new future cluster initiative (Clusters4Future). It focuses on current, young research topics that are on the threshold of application. The aim is to establish the next generation of regional innovation networks, for example also for innovative topics in the field of microelectronics.

5.2 Individualised instruments

Which instrument can best strengthen Germany's innovative potential in the field of microelectronics and how fresh and targeted impetus can be given depends to a great extent on the individual case. Does it concern a strength of the German industry or is it important to reduce dependencies in a particular area? Are there a lot of established players or is it an innovation that opens up new markets? Can Germany build on its leading position in research in this field? Is the focus on strengthening the transfer to industrial research or the transition to production? The answers to these questions might be very different depending on the application and technology.

This programme relies on instruments tailored to provide the appropriate support:

- **Thematic calls for proposals to promote and strengthen technologies and applications**: this flexible instrument is usually used to launch a group of joint research projects, which together form a research focus. In preparation, new topics in microelectronics, which are at an early or basic stage, are identified, for instance, in expert discussions. The objective of the research focus is to accelerate the evaluation and application of new, even risky approaches. This gives the participating players from the scientific community and industry a head start. At the same time, joint projects provide networking opportunities between the scientific community and industry as well as the next generation of academically trained young professionals (see above "Cooperation between the scientific and industry").

- **Multi-stage joint projects**: in the transition from fundamental research to application-oriented research, promising ideas often arise from knowledge-oriented research but are still considered too risky for collaborative research co-financed by the private sector. There is thus a risk that innovative potential is not pursued further. Multi-stage programmes in which academic and industrial partners cooperate over several phases in sometimes changing constellations is a possible solution. In a first phase, the active part is played by the academic partners who are flanked by industry. As the project progresses, the focus shifts to industrial research. Decisions on the success of the project and the prospects of success of an industry-driven follow-up project with a broad commercial perspective are taken at clearly defined points in order to combine a high scientific and technological risk with an acceptable financial risk for the general public. "Research for New Microelectronics (ForMikro)" and "Sustainable Special Processors and Development Platforms (ZuSE)" are two funding lines that already adopt elements of such approaches in microelectronics funding.

- **Innovation competitions** are used as idea catalysts where a field needs to be developed before funding broad-based joint research projects. It is not always immediately recognisable whether and how the results of cutting-edge research can be used for new technology and applications. Innovation competitions address this problem. Early-stage research topics in which networks are just arising can be advanced rapidly through innovation competitions. Microelectronics optimised for the implementation of artificial intelligence is an example of this. Short-term, highly focused grants are awarded. Several groups compete against each other to find a solution for a given problem. Whoever best meets certain quantified target parameters (e.g. energy efficiency) emerges as the winner. The pilot innovation competition "Energy-efficient AI system" is a first example of how a compact competition on a highly relevant topic catalyses ideas, motivates creative minds, and generates visibility for cutting-edge research among the public, but above all in German industry. Innovation competitions have a great potential as a quick tool for comparing different approaches, creating visibility for top results, and connecting emerging communities in Germany.

- **School and student competitions**: electronics technology is subject to a rapid pace of innovation, which can only be maintained by creative minds and committed young scientists. In order to address a shortage of skilled workers in the field of electronics in the medium term, opportunities are being created

to improve the electronics knowledge of students and pupils and for them to present their own development results in a competitive form nationally and internationally. For example, the electronics competitions INVENT a CHIP and LABS for CHIPS are organised jointly with the VDE. The VDE student competition COSIMA is supported by BMBF, too.

- **Funding of innovative SMEs**: The funding line KMU-innovativ (KMUi) is designed to effectively support especially small and medium-sized enterprises in innovation processes. KMU-innovativ also supports the first participation of SMEs with less experience in funding and research, breaks down barriers, and strengthens the motivation for demanding, high-risk but focused research and development projects. Submissions to KMUi are possible on a continuous basis, with two fixed evaluation dates per year. This funding is open to the whole range of topics covered by the programme.

- **European multilateral joint projects**: the combination of EU and national funding as part of a multi-annual strategy in ECSEL and its planned successor KDT provides a long-term framework for innovation and funding and ensures programme coherence between the EU, its member states, and participating industries. This is the basis for a rapid transfer of research results into new production via pilot line projects and thus for a new willingness of European electronics manufacturers to invest. ECSEL and KDT cover the entire range of topics of this programme. Complementary to this, further impetus can be given through the EUREKA multilateral initiatives on specific themes.

- **IPCEI**: as a rule, EU countries may only support innovations outside regional funding areas through research and development projects. However, if there is an overriding pan-European interest, such projects can be jointly funded as IPCEI by several EU Member States until first industrial deployment.

5.3 Structures for research and innovation

With its higher education and non-university research institutions, Germany has outstanding structures for research and innovation worldwide. The Research Fab Microelectronics Germany (FMD) covers the broadest range of application-oriented microelectronics activi-

ties with its thirteen institutes: the eleven full members of the Fraunhofer Group for Microelectronics, part of the Fraunhofer-Gesellschaft (FhG), along with the Leibniz Institute IHP Innovation for High Performance Microelectronics and the Ferdinand Braun Institute, Leibniz-Institut fuer Hoechstfrequenzelektronik (FBH). The five further institutes of the FhG that are guest members of the Group for Microelectronics also work on related topics; from the Leibniz Association, the Paul Drude Institute for Solid-State Electronics, which is comparatively more fundamental research-oriented, should also be mentioned. The Helmholtz Association performs research on the fundamentals of future electronics in the Future Information Technology programme, particularly at the Forschungszentrum Jülich. The Max Planck Society is also dedicated to such fundamentals, for example in organic electronics or quantum electronics. Finally, via the Deutsche Forschungsgemeinschaft (DFG), German Research Foundation, the German Federal Government and the *Länder* governments support research at higher education institutions, including several collaborative research centres on electronics topics of the future. It is worth noting that in practice, innovation rarely proceeds as linearly as the division into fundamental and application-oriented research organisations might suggest.

Traditionally, microelectronics research in Germany is decentralised: with strong smaller institutes, each specialised and often firmly integrated in the respective regional innovation ecosystems. Since microelectronics technology is especially research- and equipment-intensive, the costs of purchasing and operating the necessary equipment are high. It is therefore advantageous for German electronics research to be more collaborative and complementary. The first steps have already been taken: the thirteen institutes mentioned above combine their expertise in the Research Fab Microelectronics Germany (FMD), work closely together across institutes and share their equipment pool. This affords research partners and customers from the scientific community and industry easy access to the entire microelectronics value chain from a single source. The FMD offers small and medium-sized companies in particular comprehensive use of advanced technology, thus strengthening rapid and efficient technology transfer for the whole range of technologies represented: multifunctional, energy-saving sensors, MEMS actuators, power electronics, high-frequency electronics, optoelectronic systems, and high integration. The German government provided 350 million euros in funding for the start-up phase of the FMD from 2017 to 2021.

Alongside non-university research institutes, higher education institutions in Germany are a central innovation factor in research- and equipment-intensive microelectronics. They tap into new knowledge and educate the next generation of young researchers. The twelve institutions that participate in the programme Research Laboratories Microelectronics Germany (ForLab) are therefore already receiving investment funding of further 50 million euros for modernised equipment. This funding makes it possible to strengthen research at top international level, open up new fields of research for the microelectronics of the future and train young researchers with cutting-edge equipment. In addition, networking with one another and with external partners from the scientific community and industry is encouraged – for more scientific exchange and cooperation.

In order to advance the topics and initiatives of this programme for the benefit of the economy and of society, the Federal Government continues to promote efficient structures, modern research equipment, and new forms of cooperation in microelectronics. First-class research needs first-class equipment in order to strengthen Germany as a country where microelectronics is developed and manufactured and to keep it competitive.

The Federal Government intends to intensify further cooperation between industry and knowledge-oriented microelectronics research, also with Helmholtz centres and with institutes of the Max Planck Society. The aim is to intensify the dialogue between the scientific community and industry in order to accelerate the transfer of strategically relevant findings on the basic principles of future microelectronics into innovative applications. Project and institutional support could thus develop their complementarity even better.

5.4 A living programme through strategic foresight and evaluation

Due to the fast pace of innovation and development in microelectronics and its constant spreading into ever new fields of application, it is necessary to design and implement the Framework Programme as a living programme. This requires that the measures are developed on an ongoing basis.

An evaluation of the research funding is carried out continuously and in parallel with the programme, which also takes into account the fact that some or even much of the impact of pre-competitive research only develops indirectly and in the medium term. This “real-time” monitoring enables a prompt evaluation and feedback into research policy; it is based on funding data and on information collected via project reports. The monitoring results are used to generate a rolling strategic foresight and to define new priorities or completely new topics in order to derive suitable measures. Firstly, this enables an evidence-based adjustment and, secondly, it lays the foundation for the subsequent ex-post evaluation of the programme as a whole.

With the present programme for research and innovation in the strategically important technologies and applications of microelectronics, Germany is well positioned to strengthen our strategic sovereignty in European partnership and to increase our prosperity in the coming years.

Imprint

Published by:
Bundesministerium für Bildung und Forschung/
Federal Ministry of Education and Research (BMBF)
Division for Electronics and Autonomous Driving;
Supercomputing
53170 Bonn, Germany

Orders
In writing to
Publikationsversand der Bundesregierung
P.O. Box 48 10 09
18132 Rostock
Email: publikationen@bundesregierung.de
Internet: bmbf.de
or by
Tel.: +49 30 18 272 272 1
Fax: +49 30 18 10 272 272 1

November 2020

Layout
VDI/VDE-IT Berlin

Printed by
BMBF

Photo credits
cover: naka/AdobeStock
p. 2: BMBF/Laurence Chaperon
p. 3: Gorodenkoff/AdobeStock
p. 4: Valeriy/AdobeStock
p. 6: TU Ilmenau
p. 8: Westend61/Getty Images
p. 10: Valeriy/AdobeStock
p. 13: Rohde & Schwarz
p. 17: Universität Paderborn
p. 18: Aleksandr Matveev/Adobe Stock
p. 19: Fraunhofer EMFT/Bernd Müller
p. 20: Fraunhofer IPMS
p. 22: Monty Rakusen/ Cultura via Getty Images
p. 23: NicoElNino/AdobeStock
p. 26: lukszczepanski/AdobeStock
p. 27: Anski21/Shutterstock.com
p. 29: Gorodenkoff/AdobeStock
p. 30: iStock/MartinPrescott
p. 32: alotofpeople/AdobeStock
p. 33: BLEND3 Frank Grätz
p. 35: arthurhidden/AdobeStock
p. 36: Fraunhofer Mikroelektronik/Steinert