Electronics R&D Roadmap 2.1

Top Sector HTSM

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December 2020

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1. Societal and economic relevance

1.1 Introduction and scope

The incredible flow of products from the Information, Communication and Consumer industries has changed our lives dramatically over the last 40 years. At the basis of these innovations is a continuous drive for smaller, better, cheaper and more power efficient electronic components and circuits with increased functionalities.

The cost-effective scaling of integrated circuits (ICs) and the resulting exponential growth of chip complexity is named after scientist and Intel veteran Gordon Moore. Moore's law has generated a large number of innovations in the field of integrated circuits technology.

Moore's law has sparked innovations in adjacent fields such as: displays, antenna, sensors, packaging techniques and energy sources. For a Dutch innovation roadmap, the developments are crucial in (1) the field of Moore's law, (2) the innovations in the neighboring fields often described as "More-than-Moore" including integrated sensor technologies and (3) the progress in various forms of packaging.

The progress in electronics development has created many high-tech innovative applications. Moreover, the Internet of Things developments will lead to tens of billions of connected devices. All of these innovations require improvements in analog and RF components, high-voltage devices, digital circuits, ultra-low power electronics, sensors and actuators, and skillful combinations of components into high-performance mixed-signal circuits.

Complementary to above economic perspective which creates more turn over, an excellent export position and more employment opportunities in our national ecosystem, societal challenges in the fields of energy and CO2 reduction, agriculture and food, health and care, climate and water, mobility and transport and a safe society require breakthroughs that only can be enabled by a new generation of electronic components and systems. Industry and knowledge institutes in the area of this Roadmap are well positioned to find a healthy balance with growth perspective to comply with both the economic and the societal challenges at the same time.

Electronics Roadmap – Scope

Electronics is pervasive in all aspects of society and daily life. The roadmap joins universities, international corporations, SME's and institutes around an innovation program that spreads from (chip) technology to component, to integrated circuits to electronic systems. Design, Characterization and test methodologies are included as well. The Electronics R&D Roadmap is enabling for many other HTSM Roadmaps and supports all Societal Themes.

1.2 Supporting the Dutch Innovation Themes for the period 2020-2023

In the Knowledge and Innovation Covenant (KIC: *Kennis- en Innovatieconvenant*[1]) for the years 2020-2023, Dutch companies, knowledge institutes and governments confirm their commitment to the important

[1] The *Kennis- en Innovatieconvenant* (KIC) 2020-2023 is published at: https://www.topsectoren.nl/innovatie/documenten/kamerstukken/2019/november/12-11-19/kic-2020-2023

innovation themes for the coming years. This builds on the cooperation in this 'golden triangle' in recent years. The focus of the collaboration is on four societal themes of the mission-driven knowledge and innovation policy: Energy transition and Sustainability; Agriculture, Water and Food; Health and Care; and Safety.

The inception of modern electronics enabled dramatic innovations (like 5G communications, mobility, handling big data, embedded AI etc..). Now that electronics has become ubiquitous and pervasive in all aspects of society, its profound contribution to society is often underestimated. The participants in the HTSM Roadmap Electronics jointly support their commitment to the Knowledge and Innovation Agendas (KIA: *Kennis en Innovatieagenda*[2]) of the four social themes and to the key technologies and see a lot of synergy with their own agendas. In this paragraph we will briefly highlight how the HTSM Roadmap Electronics contributes to the four 4 societal themes and to the further development of the key technologies.

1.2.1. Energy transition and Sustainability

The Energy transition and Sustainability KIA consists of six (5) missions themselves comprising 13 *Meerjarige Missiegedreven Innovatie Programma's* (MMIPs: multiyear mission driven innovation programs). Accomplishing the six missions through MMIPs in short boils down to: i) reducing the national emission of greenhouse gas by 45 percent by 2030 and by 95 percent by 2050 compared to 1990, ii) attaining an entirely carbon-free electricity system by 2050 as well as iii) a carbon free built environment together with iv) a carbon-neutral industry with reuse of raw materials and products, v) zero-emission mobility of people and goods and vi) a sustainable and completely circular economy (by 2050) with resource use halved by 2030.

The path to accomplishment of these missions will be significantly enabled by the early availability of innovations in electronics.

In particular, the sustainable and emission-free energy systems of the future (consisting of five phases – production, transmission, transformation, distribution and consumption and often designated as smart grids) are cyber-physical systems (CPSs) by nature as they integrate physical dynamics through sensing and actuation with computation, control and communication (networking). Hence, electronics is omnipresent: to convert power produced by renewables we need novel power electronics solutions accounting for stability challenges, to integrate physical dynamics with the rest of the systems we shall need novel sensor and actuator solutions, control software we shall run on novel (often low-power, low-voltage and AI-enabled) hardware platforms and communicate we shall using novel communication electronic circuitry (here of particular interest being 5G and beyond technologies as stringent requirements on latency and throughput need to be satisfied in the Internet of Energy (IoE) setting).

Should we talk about zero-emission mobility – before we can attain it – the two major challenges need to be addressed (according to the ARTEMIS Electronic Components & Systems (ECS) Strategic Research Agenda (SRA) 2020 [1]) developing clean, affordable and sustainable propulsion and ii) ensuring secure connected cooperative mobility and transportation. Electronic engineering has a lot to contribute to addressing these. This includes, among others, developing of improved versions of various sensor types (performance, navigation, inertial, radars, lidar, infrared, ultrasound, driver's condition monitoring), high-efficiency power components, V2D, V2G, V2I, V2N, V2P, V2V and V2X communication solutions as well as AI-enabled real-time computer platforms.

[2] The four KIAs are published at https://www.topsectoren.nl/innovatie

Last but not the least, innovation in electronics can contribute to the advent of a circular economy by increased awareness in the usage of materials, products and systems. Such awareness will lead to increased selectivity in the usage of material (like heavy metals) and reuse of raw materials that are now disposed as waste.

Together with the big data, cloud computing, and IoE (the subset of which is IoT) technologies which dematerialize and transfer capabilities from consumer hardware to the cloud, electronics can support the matching of the useful with the technical lifetime. By monitoring the usage and performance during a use cycle, the need for maintenance, possibilities for up-grades to better suit the user's needs as well as the re-use potential for another use cycle can be determined.

1.2.2. Agriculture, Water and Food

This KIA comprises six (6) missions concerning: i) circular agriculture, ii) net-carbon neutral agricultural and nature system by 2050, iii) climate-proof and water-resilient Netherlands by 2050, iv) healthy, safe and sustainable food production by 2030, v) sustainable and safe North Sea, oceans and inland waterways and vi) The Netherlands remaining the most-protected and viable delta in the world.

To link electronics to this KIA we apply the same CPS-based line of reasoning as we did for the Energy transition and Sustainability KIA. In particular, we can consider the future agro-food systems based on the sustainability concept as well as water management systems as complex CPSs where the three (3) key operational ingredients are: i) smart sensing and monitoring, ii) smart analysis and planning and iii) smart control. Each of the three are powered by electronics. Sensors (from simple soil moisture sensors to cameras attached to drones and all the way to weather radars and satellite radiation sensing systems) are built from or are themselves (heterogonous) electronic components and (heterogeneously integrated) electronic systems. These systems are often autonomous implying low-power and low-voltage electronic circuit designs. Sensory data is often wirelessly communicated to analysis and planning systems that often rely on big data technologies where innovations in electronics are needed for providing fast and energy efficient data center infrastructure. Lastly, control is exercised through actuators themselves being composed out of (heterogeneous) electronic components and (heterogeneously integrated) electronic systems.

1.2.3 Health and Care

The Health and Care KIA aims at accomplishing five (5) ambitious missions concerning: i) the increase of life expectancy of Dutch citizens and the decrease of health inequalities between socio-economic groups, ii) decrease of the burden of disease caused by unhealthy lifestyle, iii) increase of the extent and frequency of care provision to people in their own living environments and iv) increase in the percentage of people with chronic disease or lifelong disabilities that can play an active role in society and v) increase in the quality of life of people with dementia.

Electronics has long made and continues to make an undeniable and most valuable contribution in the field of healthcare. Today, facing a rapidly growing and aging population, innovation in electronics will be a key factor enabling the healthcare systems of the future to face the challenges pertaining to listed five missions. Of particular importance are the innovations enabling the delivery of efficient and affordable (and IoT-enabled) wearable, implantable, ingestible and injectable devices used for monitoring/diagnostics and treatment as well as monitoring, diagnostics an treatment solutions used in clinical settings including scalable big data platforms. The key technical challenges often involve improving (or often optimizing or trading-off) the precision, accuracy and resolutions of the measurements of electrical and no-electrical quantities, form factor (miniaturization of components and systems) considerations, power consumption considerations, heating reduction, biocompatibility, communication and bandwidth scaling, IP/sensor integration and supply voltage scaling [4].

1.2.4 Safety

The Security Knowledge and Innovation Agenda consists of eight Multi-year Mission-Driven Innovation Programs (MMIPs) that are linked to the missions of the Ministries of Defense, Justice and Security and Economic Affairs and Climate. These MMIPs are: Integral approach, digitally supported, of interventions, tools and data; Maritime high-tech for a safe sea; Safety in and from space; Cyber security; Networked action on land and from the air; Innovate faster together for an adaptive force; Data and intelligence; and The safety professional.

Relevant knowledge and innovation are needed in the areas of sensors and observation techniques for (covert) monitoring and detection in both the physical and digital domain and possibly in difficult conditions (at night and in bad weather). Due to the digital transformation of crime, a strong attention is demanded for the digital domain. Digital innovations are transforming the way we live and work and can contribute to a peaceful coexistence with solutions supported by society.

Clearly, great strides need to be made in terms of end-to-end data security to build user trust. This can only be realized by building this in from the beginning at component, circuit and system level.

Enhanced electronic components and circuits are key enablers for affordable and societally acceptable defense and security systems. Access to such technologies is of strategic importance. Future challenges include a high degree of integration, massive and secure data handling, increased functionality, interconnectivity, configurability and resilient electronics. Challenges for a secure society are in the areas of digital security, operational security and physical security.

Strengthening **Digital security** asks for secure communications of the next generation requiring embedded authorization and authentication techniques. Dutch industry delivers integrated security solutions with the latest cryptographic techniques for a broad application range from connected cars to data centers, from healthcare to industrial control.

Sensor and data integration together with a capability to transform (sensor) data into user required information are crucial for **Operational security** to modernize the strength of a future-proof, adaptive armed forces. This is particularly applicable in the maritime domain where new naval ships require advanced sensor technology. Dedicated Active Electronically Scanned Array antennas (AESA, also often referred to as phased-arrays) for radar systems, including custom RF, mixed-signal, digital assisted RF and digital electronics are an outstanding asset for the Dutch Navy, collaborating with Netherlands industry and research institutes to maintain and expand an excellent and renowned position worldwide in this area.

Physical security covers the safety and security of people and objects in a broad sense against threats, including terrorism, organized crime and espionage. It entails wearable sensor and communication devices, virtual and augmented reality and the use of robotics to achieve an optimal division of tasks and cooperation between man and machine for the performance of defense and security tasks. Electronics at Terahertz frequencies enable the need to develop broadband sources and matrix detectors for detecting explosives and concealed weapons.

1.2.5. Key Technologies

From the perspective of technology's potential contribution to societal challenges in the Netherlands, the Ministry of Economic Affairs and Climate Policy has identified eight clusters of Key Enabling Technologies ("*sleuteltechnologieën*") : Chemical Technologies, Digital Technologies, Engineering and Fabrication Technologies (including High frequency and mixed signal technologies & Sensors and actuators), Photonics and Light Technologies, Advanced Materials, Quantum Technologies, Life science technologies, Nanotechnologies.

A Knowledge and Innovation Agenda (KIA), including multi-year programs and an overview of scientific challenges, has been drawn up for these KETs.

Electronics is an important enabler for many key technologies, such as Photonics and Light Technologies, Nanotechnologies and Quantum Technologies. These key technologies will benefit directly from further progress in electronics development, as shown by a number of research questions[3] and the role of electronics in the multi-year programs[4]. Examples include the further development of bio-chips and sensors (Life Science Technologies), lab on a chip technology (nanotechnologies) and the sensors and actuators necessary for robots (Engineering and Fabrication Technologies/MJP MedTech). Also the development of a quantum computer and photonics (MJP Integrated Photonics) push the state of the art of electronics onward.

In conclusion:
Electronics – is enabling for many other HTSM Roadmaps and supports all Societal Themes (KIAs) and the KIA *Sleuteltechnologieën*.

1.3 Dutch perspective

The Netherlands is one of the most important European design and manufacturing countries for electronic components & circuits. Some of the world's major players in this field have major R&D activities here: ASML, Broadcom, Dialog, Ericsson, Maxim, NXP, Ampleon, Nexperia, Philips, STM, Synopsys, Teledyne DALSA, QUALCOMM, Thales Nederland, TI, Tyageo, Qorvo etc. Four of these companies are ranked among the best 10 of the R&D 2020 Top 30[5] of companies with highest R&D expenditure in The Netherlands. Many Dutch SMEs operate at the forefront of new innovations, design, technology and applications. The production value represents a substantial portion of the total HTSM sector of double digit B€.

Table 1 gives a financial summary of the top 30 R&D activities in the Netherlands for the year 2018, organized according to activities directly coupled to the Roadmap (i.e., directly active in business related to electronics) and activities that are supported by the Roadmap (i.e., based to a very large extent on electronics as underlying technology for the business, but not directly active in electronics as business by itself). This table shows very clearly in a quantitative way the size and importance of the electronics industry and the associated ecosystem of universities and research institutes for the Netherlands.

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[3] Detailed research questions to the key technologies can be found in (Dutch only): https://www.hollandhightech.nl/sites/www.hollandhightech.nl/files/inline-files/20190712%20KIA-ST%20Bijlage%20A%20-%20Kennis-%20en%20innovatievragen.pdf

[4] https://www.hollandhightech.nl/sites/www.hollandhightech.nl/files/inline-files/20191024%20KIA-ST%20Bijlage%20B%20-%20MJP%27s%20overzicht_0.pdf

[5] https://www.technischweekblad.nl/files/142e7969cd74c7e5358c496ee71c7d08.pdf

Summary of Top 30 R&D activities in the Netherlands (2018)[6]	
Directly coupled to HTSM Roadmap Electronics	
R&D expenditures (M€)	559
Turnover worldwide (M€)	11392
R&D personnel in NL (fte)	3634
Supported by HTSM Roadmap Electronics	
R&D expenditures (M€)	2185
Turnover worldwide (M€)	36035
R&D personnel in NL (fte)	12404

Table 1 Summary of Top 30 R&D activities in the Netherlands (2018)

Dutch universities (TU Delft, TU Eindhoven and University of Twente) and knowledge institutes (ASTRON, CTIT, CWTe, Else Kooi Lab, ESI, Holst Centre (TNO & IMEC), MESA+, SRON, NIKHEF and TNO) rank amongst the most productive. The good position of Dutch industry is due to a long-lasting collaboration between industrial laboratories, research institutes and academia in the domains of technology, design, manufacturing and application. A large informal network allows the effective utilization of resources, resulting in joint product development, roadmaps and ecosystems around processing, circuit design, sensors and packaging and system development.

On 22 March 2019, ARTEMIS Industry Association released the results of a study into the economic and technical outlook for Embedded Intelligence [2]. Conducted by independent consultant Advancy, this report analyses the EU's Electronic Components and Systems value chain through a global lens. In doing so, it identifies areas in which further R&D&I investments will be vital in consolidating Europe's lead or in catching up with other international powerhouses. Currently, the EU is being outspent by the US, China, Japan and (in relation to GDP) South Korea.

According to the report, the world is on the verge of a "new industrial revolution." This represents not only an emerging General-Purpose Technology platform, but also a paradigm shift towards decentralized and software-oriented means of production. Embedded Intelligence – incorporating Systems of Systems, Embedded & Cyber-Physical Systems, Electronic Components and Embedded Software Technologies – is at the heart of this. Cyber-Physical Systems, in particular, serve as a bridge between the technology-rich, vertically-integrated physical world and the data-rich, lateral interaction-based cyber world. With factors like cybersecurity and interoperability as cornerstones, Embedded Intelligence lays the foundation for future breakthroughs such as edge AI, predictive maintenance and augmented reality.

Europe's major challenge is twofold: value is shifting not only geographically, but also along the value chain itself. China is a leading force in this; having overtaken the EU in terms of relative weight of GERD (Gross Domestic Expenditure on R&D) in recent years, it also announced an investment of USD 100 billion in its ongoing Five-Year Plan and 'Made in China 2025' initiative. Meanwhile, value is moving away from hardware and towards Systems of Systems, applications and solutions. This segment of the value chain is expected to grow tenfold over the next decade (reaching somewhere between USD 3.9 and 11.1 trillion), so Europe must position itself carefully in order to remain competitive[7].

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[6] R&D overzicht NL bedrijven 2019, Technisch Weekblad (https://www.technischweekblad.nl/files/e0f3dccb61897cc68a786ec53ddb039d.pdf)

Europe requires major contributions from the electronics industry to tackle the Grand Challenges of the 21st century as outlined by the European Commission. Based on the technological progress anticipated in the near future, there are excellent opportunities to realize break-throughs that will benefit society.

The EU has put an effort in becoming self-sufficient and independent on important critical areas of technology for high tech systems. The Netherlands has a strong position in several of these domains, from material analysis, wireless communication, and medical instrumentation, to detectors for particle physics and space exploration.

This roadmap has the ambition to expand this position in the next decade and outlines the necessary research directions. Two perspectives are essential: technological development (both process and design technology) and applications' focus. The crossings of these axes yield the most promising implementations.

2. Applications and technologies

2 .1 Technological development

Figure 1 below depicts the two essential technology developments that underpin the Electronics Roadmap: Miniaturization through More Moore and Diversification through More than Moore. They are described in detail in sections 2.1.1. and 2.1.2.

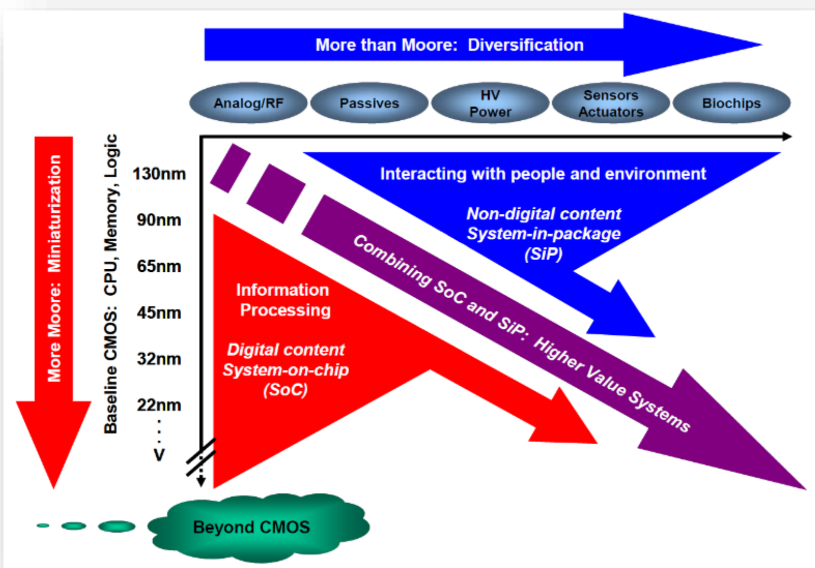

Figure 1 The combined need for digital and non-digital functionalities in an integrated system is translated as a dual trend in the International Technology Roadmap for Semiconductors: miniaturization of the digital functions ("More Moore") and functional diversification ("More-than-Moore").

2.1.1. More Moore

The main line of technology development under Moore's law is focused on digital CMOS scaling.

New hardware/software building blocks for advanced signal processing functions target mobile, IoT, Artificial Intelligence (AI) and automotive applications. The challenge is to deal with design complexity, product configurability and performance aspects (including power). This requires innovative hardware/software (multi-core) architectures in conjunction with new hardware/software verification technologies to master design complexity under stringent performance, energy and reliability constraints.

Advancements in technology push for growing integration of functions on a single die. Digital functions are extended with memories, input-output drivers, analog-to-digital interface, wireless interfaces and power management. Further functional integration will lead to system solutions with a minimum number of external components, thereby reducing the system cost and the energy consumption.

Extremely small dimensions and new materials (metal-gate, graphene, etc.) require design and model adaptations for every process node: new phenomena appear and old worries vanish. Slow degradation over life time, radiation hardness, reliability of components and the inherent variability require more attention. Future RF, analog and also digital design methodology will need to adapt to these new phenomena. Topics in the Dutch context: modeling of advanced devices and structures, incorporation in EDA tools, testing, advanced libraries and DSP architectures.

Downscaling and reliability demand circuit operation at (very) low voltages and power levels. New insights in circuit design, new technology options and the possibility to design intelligent analog and digital calibration mechanisms demand new system partitioning. Analog and RF components designed in scaled technologies can benefit from digitally-assisted and digitally-dominant design methodologies.

Dutch industry and academic research has an excellent reputation improving the performance of communication, radar, automotive and signal-processing circuits.

As the technological progress of advanced CMOS still continues, more advances in the neighboring "More-than-Moore" areas can be expected. Many "More-than-Moore" technologies exist because they enrich the circuits to a diversification available in CMOS technology.

2.1.2. More-than-Moore

Analog and RF / High Frequency and Mixed Signal Technologies

From the onset of the semiconductor industry, analog performance improvement has been at the top of the agenda. This is because overall electronic system performance depends crucially on the performance of the analog parts. Especially nowadays, given for example the increasing demands on bandwidth under severe power constraints, improving the analog (RF and mixed signal) performance remains a top priority.

Where in the early days advances in performance were primarily connected to technology improvements (e.g. for low noise or high power), nowadays researchers also use a highly creative toolbox and increasingly complex architectures to achieve the requirements set for future systems. Fueled by digital technologies, electronic systems have become extremely complex, in which analog, RF and mixed signal functionality is the main differentiator.

The Netherlands is world leading in this field. The presence of the complete chain, from research to end-user, in the form of academia, institutes, design houses, manufacturing SME's and system integrators consistently leads to analog innovations with a worldwide impact. In the past Philips led the global TV market with their “one chip TV”. Bluetooth and Wifi are Dutch inventions and these chips were and still are being developed in the Netherlands, making them better, faster and cheaper. Today we find Dutch analog/RF innovations in almost every electronic product: noise cancelling amplifiers and filters in smartphones, extreme low power wireless chips for communications including IoT and 5G , (defence) radar systems, but also precision sensor and actuator (audio) interfaces, circuits for power conversion, RF power generation and drivers. This has led to strong ecosystems of analog design companies clustering in the Eindhoven, Twente and Delft regions. Moreover, the demand from industry for analog and RF talent from universities in still undiminished. Global players even move design centers to the Netherlands because of the high quality and talent present in our ecosystems .

All large companies, design houses and SME’s recognize that despite the big words about digitization in today’s society, analog/RF design innovations are, and will remain, crucial. The Netherlands is and will remain the global hotspot in analog/RF design..

Sensors and actuators

Sensors and Micro-Electro-mechanical systems (MEMs) can be seen as the eyes, nose and ears of mobile systems, such as mobile phones, cars, and robots. Similarly, actuators, such as motors, loudspeakers and valves can be seen as their hands and feet. Together, sensors and actuators are used in a vast range of applications, ranging from motor vehicles, water quality, chemical detection, personal security, condition-based sensing to medical diagnosis. In the near future, sensors will be embedded everywhere, in our clothes or even on and in our bodies. Together with local artificial intelligence, they will make everything “smarter”. Smart sensors will be interconnected via the internet (the Internet of Things), respond in real-time to dynamic and complex situations, while maintaining control, system safety and reliability. In turn, they will enable smart systems that are self-adaptive, robust, safe, and intuitive.

The leading position of Dutch academia, institutions and industry in this field is based on an excellent educational system, the presence of several top experts, and a strong focus on applications. In the short term, sensors based on standard IC/MEMS technology such as temperature sensors, force sensors and Coriolis flow sensors will soon be on the market. Medium term topics are gas sensors (Micro-Gas Chromatographs for food monitoring or for health applications), various (3D) imaging technologies, and advanced patient monitoring systems. Micro-actuators are still relatively unexplored, and have a large long-term potential. Also on the horizon are radical new solutions, which will gradually make their way to the market. Some promising examples are lab-on-a-chip systems and nuclear magnetic resonance (NMR) systems for low-cost chemical analysis, THz imagers for non-destructive material analysis, implantable actuators and sensors, and the integration of photonic functions on CMOS. New material such as graphene and silicon carbide will open the way to sensors that can function in harsh environments, while sensors based on quantum principles, e.g. kinetic inductance detectors (KIDs) will achieve fundamental detection limits.

High Voltage and Energy

High power electronics is required for conversion of electrical energy for transport, storage or usage of electrical energy. With the strong trend towards a more electrical society, the need for high performance power electronic systems increases. Especially for industrial and energy applications this requires high reliability, long life time high efficiency and low cost of ownership.

Latest wide bandgap devices (such as SiC and GaN) promise huge improvement on component level with respect to high working voltage and efficiency. But new packages, topologies and design rules are required to make full use of these promises. With lower switching losses the switching speeds can be significantly increased, which results in converters with smaller magnetics, higher power density and, in the end, lower cost. The high switching frequency can also help in those applications which require both high power and high accuracy, for example in positioning, imaging, or plasma processing. A big challenge with the increased switching frequencies is to comply with the latest EMI requirements, especially if power electronic converters are used close to residential users.

For very high power applications (for example, energy storage or electrolysis), stacking of topologies is required both in voltage as in current levels to reach the demanded power levels. This ads more complexity in control, but also the possibility to make the system redundant for component failures. With the foreseen large penetration of electronic converters, the interaction between the converters can become critical. This requires new 'resilient' control and communication approaches, which are only possible with advanced digital control, including AI.

Large Area and Flexible Electronics

Flexible electronics will lead to ultra-thin, flexible electronic products such as curved photodetectors, foldable displays and skin patches that measure vital signs. New printing technologies allow for a relatively easy realization of distributed electronic functionalities on large surfaces. There has been already for a number of years strong industrial interest to print arrays of sensors on such large surfaces. Examples are photodetectors for imaging and sensing applications, pressure sensors (shoe inlays, smart bedding) and also temperature sensors (thermal mapping). The capability of the printed sensors will be further increased in the coming years by materials and technology innovation, in a close interaction between academia, research institutes and industry.

The use of flexible substrates in combination with novel deposition technologies also enables new production methods of solid-state batteries that will play a critical role in the energy transition, for transport (electric vehicles) and energy storage (smart grid), as well as IoT and consumer and health applications.

Terahertz

Terahertz sensor technology has been identified as an important tool in the areas of safety, security, non-destructive inspection of materials, for instance in process control and medical diagnostics applications. The THz frequency band ranging from 100 GHz to 3000 GHz is also of high relevance for future 6G high-speed short-distance communication applications. Research and development in this area will lead to communications systems with much higher data rates, better radar and localization systems, high-resolution imaging and better ways of identifying dangerous substances and control production processes. 5G and future 6G high data rate communication systems and high frequency car-radar systems will grow continuously over the coming 10 years with large industrial players. Strategic new terahertz applications in sensing and imaging are currently in the developing phase often in niche markets, opening opportunities for SMEs. Some concrete examples, relevant for the Dutch industrial ecosystem, include measurements on plants in greenhouses to reduce the use of pesticides, high resolution terahertz microscopy for e.g. cancer margin detection and security control cameras at harbors, airports and sports stadia.

Many challenges need to be overcome to build systems in this region of the spectrum. Specifically, signal generation, conditioning and detection in Silicon as well as III-V technologies or in hybrid electronic-photonic modules should be addressed to improve the performance in the lower THz range and enable systems in the frequency range above 1 THz. Next to this, for successful system integration, antenna/antenna array technology, novel beam steering systems as well as fast AD/DA converters and advanced signal analysis needs to be researched and developed for the different application areas.

The research effort should be focused on two areas: 1. Affordable high performance systems for imaging, spectroscopy, localization and communication and 2. Study of new applications in the THz frequency range, including the required signal processing and the use of artificial intelligence techniques. On the medium to long term, the use of terahertz technology by non-specialists outside the laboratory walls can lead to a multiplier effect that can grow the market volume in the future.

From packaging to system integration

The integrated circuit is today synonymous with the concept of technological progress. Integrated circuit (IC) chips are now much faster and smaller and the packaging is more efficient, reliable, and cost effective. Historically, the leading industry trend was or still is in Moore's Law, elaborated in roadmaps such as the NTRS, ITRS and IDRS [3, 4]. However, as downscaling becomes more costly, fewer companies are capable to follow Moore's law [5, 6, 7]. Although novel 3D device architectures are proposed to keep Moore's law in its scaling path [8], packaging is increasingly recognized as a means of driving the performance growth of microelectronics. [9, 10, 11] and is further elaborated in the heterogeneous integration roadmap (HIR) [12, 13]. As evolved from the NTRS and ITRS, the IDRS is focussing on front end semiconductor/computing domains, while the HIR has the focus on the integration of separately manufactured components from very different domains into a higher-level assembly (System in Package SiP) that provides enhanced functionality and improved operating characteristics [11].

An example of such an higher level assembly is given in [14], Multi domain/heterogeneous or 3D integration examples can be found in [15], [16] (liquid cooling for computing and power respectively) and [17, 18] (RF and 5G applications). Furthermore, integration of more components in a SiP enables health monitoring [19] for advance life cycle management.

Aside from the integration to enhance the SiP functionality, the conventional method of building increasingly larger systems on chips (SOC) has become less and less appealing, both technically and financially. Hence, major semiconductor companies are designing products that break the larger designs into smaller pieces ("chiplets") and combine them [11, 20, 21]. This not only enables the integration of known good dies (KGD), but it also enables the re-use of IP blocks in other or future SiP products. Currently, chiplet technology is applied in the computing domain, however as this technology matures, applications in other HIR domains will follow, a trend that will put packaging in the center of system integration.

Not only the requirements of enhanced functionality drives the packaging R&D, emerging wide bandgap semiconductors (WBS) with their higher operating temperatures, requires novel packaging materials and processes such as nano metallic die attach and sintering processes[22, 23, 24] and ceramic encapsulation [25]. Also trends such as a cost reduction requirement in ultra-small discrete device packaging or micro led displays requires solutions for high volume pick & place, die attach and encapsulation.

In the broad field of micro technologies, packaging is the final manufacturing process transforming semiconductor or micro devices into functional products for the end user. Therefore, the packaging industry has developed specific encapsulations for a broad range of devices from different domains such as microelectromechanical systems (MEMS), bio-MEMS, and nanoelectronics, bioelectronics, RF and power electronics and organic light-emitting diodes (OLEDs), photovoltaics, and optoelectronics etc..

Obviously, in device packaging, the materials and processes are optimised to match with the device characteristics. However, as conventional packaging will evolve towards system integration enabling multi device package or system in package (SiP) processes and materials must meet more boundary conditions compared to packaging a single device. There is no single packaging technology that can serve this multi scale multi domain needs, hence it is clear that either monolithic homogeneous or heterogeneous integration at the die level or heterogeneous integration at the package level requires novel packaging solutions to optimize system performance and minimize cost.

Global trends in micro system technologies will put packaging in the center of system integration, not only for the high end SiP's, where packaging is the enabler for system integrations, also for applications such as discrete and power packages, where the right materials and processes enables the system to operate reliable at low cost. Furthermore, heterogeneous integration (HI) will broaden the spectrum of applications for which packaging solutions are required, hence the increasing volumes are spread over multiple applications with shorter time to market and closer to the regional markets.

Micro System Integration

Dutch companies have developed a strong presence in the fields of design, fabrication and applications of novel microsystems. The already available know-how in microelectronic IC technology enabled this development to cover areas such as photonic communication & sensing technologies and more currently bio- and nano-enabled devices like fluidics and biosensing. Companies such as Micronit, Phillips Innovation Services, Smart Photonics, Lionix, Bronkhorst, SmartTip, Mimetas, etc. lead the transformation of established microelectronic technologies into wide-use microsystem platforms where applications meet solutions through design, knowledge and adaptability.

Fluidic devices with integrated electronic as well as biological functions, when miniaturized and applied on the large scale, are set to address the challenges of Health & Care via improved diagnostics in home situations and in infectious disease prevention. MEMS sensing & control devices with integrated electronic and fluidic aspects find their way to portable desalination machines and in other purification apparatus with large impact towards solving the challenges of Water, Food and Agriculture. Others use integration of sensitive IC electronics and chemical nano-coatings to sense ppm or even ppb concentrations of gaseous volatiles in air.

Nevertheless, the inherent complexity of these combined-aspect devices requires knowledge of the various interactions across the functional domains: electric-chemical-optical-fluidic-biological. In order to address the modern societal challenges in the Energy, Healthcare, Food and Security areas, efforts will need to focus on several areas: a) knowledge, methods and tools in the areas of predicting device reliability, b) improving designability via smart EDA tools suited for multi-physics design flows, c) improving production & test technologies as well as d) continue transferring knowledge between the functional domains.

3. Priorities and implementation

3.1 Roadmap program

The ambitions of the HTSM-roadmap on Electronics have been captured in five themes that cover both the industrial research ambitions in this roadmap as well as the directions in which the academic education and research will develop. The themes are driven by the many needs of the applications that depend on the developments in Electronics. These requirements and applications have been described in the previous chapters.

The topics that are executed within the program on Electronics can be grouped in the following five themes.

Theme 1: Dealing with technology progression in terms of performance, reliability, functional safety and circularity.

Every new process node or derivative requires adapting the electronic system and its components to the changing set of boundary conditions which are driven by application mission profiles. With new demands on power supply, increased variability, and higher performance and safety targets at lower energy consumption, often radical concept changes are needed. Due to the reducing margins in technology, new green packaging materials, reliability issues and (slow) degradation, achieving a good performance over the entire lifetime is not trivial. These problems are accelerated with aggressive voltage scaling all the way to the near threshold to improve the energy efficiency under limited performance conditions.

The focus area is not confined to the More Moore technology only. Also More-than-Moore devices, like the integration of sensors in silicon, high voltage and high power devices, or integration of passives will lead to additional, performance, reliability and robustness problems. Physics of failure, new materials for chip integration and packaging, new models such as digital twins to predict failure and monitor degradation and new circuit topologies and subsystem solutions (reconfigurable, modular, low-power signal processors) are needed in communication domains, sensor interfaces and energy converters. The challenges are multi-disciplinary, multi-scale (failures start e.g. at the passivation layers, crack growth is nano/micro-scale, diffusion and corrosion through ion-transport and can affect system level), multi-physical (thermo-mechanical stress, electro galvanic corrosion, material diffusion processes, e.g. mechanical, electronic, material or thermal failures etc.) and require interaction between technology, different fields of expertise (material science, electrical and mechanical engineering) circuits, architecture, and system.

Another factor in the guaranteed lifetime of an electronic solution is the upgradeability and predictive maintenance of the system. By monitoring critical electronic systems, with dedicated build in sensors and monitoring devices and connecting it to a digital twin one can plan for maintenance before a system breaks down, thereby preventing unnecessary risk and cost of random failures. E.g. the lifetime of a car may be reduced if the electronic hart of the car can’t be upgraded to new standards or new technology advancements.

At the same time that life time is a challenge as described we need to guarantee the safety for the users and their environment.

Functional safety is the part of the overall safety of a system or piece of equipment that depends on automatic protection operating correctly in response to its inputs or failure in a predictable manner (fail-safe). The automatic protection system should be designed to properly handle likely human errors, hardware failures and operational/environmental stress.

Several Safety Standards and regulations are there for Automotive, Medical devices, Transport sector, Nuclear plants etc. The use of automated electronic control systems is expanding in recent years, and reliability and safety requirements are becoming very important factors in electronics and system design.

Although electronics constitute an indispensable part of everyday life, their hazardous effects on the environment cannot be overlooked or underestimated. The interface between electrical and electronic equipment, new materials and the environment takes place during the manufacturing, reprocessing, and disposal of these products. Urban mining and the reprocessing of materials from electronic waste can result in reduced demand for raw materials, reduced consumption of basic resources, allows for job creation and less energy used in the manufacturing process.

The emission of fumes, gases, and particulate matter into the air, the discharge of liquid waste into water and drainage systems, and the disposal of hazardous wastes contribute to environmental degradation. In addition to tighten regulation of E-waste recycling and disposal, there is a need for policies that extend the responsibility of all stakeholders, particularly the producers, beyond the point of sale and up to the end of product life and a technical need to enable circularity: use of new and better (green) materials in our electronic assemblies which are easier to separate and reuse, for example eliminating Au and Pb and replacing it with Cu.

The electronic industry needs to bring innovations within the theme of extending life time of solutions and products to guarantee less E-waste at the same time as guaranteeing fail safe solutions. Moreover, technology progression can also lead to more integration, miniaturization, modularity, recyclability and therefore less E-waste. The research that drives technology progression with the goal of E-waste reduction and system upgradeability are key areas to be addressed.

Theme 1 partners: Dialog, Else Kooi Lab, Holst Centre (TNO & IMEC), MESA+, NEXPERIA, NXP, Salland Engineering, Synopsys, Technolution, TNO, 4TU, SystematIC,

Theme 2: Electronics for radio communication and radar.

Communication systems connect the world. This application field will remain for decades one of the dominant system drivers for electronic components and circuits. Ranging from relatively low-performance but ultra-low energy sensor communication to high-performance radar systems, many novel applications and implementations are expected.

With cheaper components in smart packages, Ultra Low Power Networks (LAN, PAN, BAN, zero net power) equipped with sensors will enable the monitoring of parameters, going from body centric to large and complex infrastructures “Internet of Things”. An optimum integration in the network is required. The ultimate goal is to strive for net-zero power devices, where nodes in a network harvest their energy from the environment. Electronics for IoT is described in detail in Theme 3. A system-level power optimization approach by applying the broader concept of RF/analog/digital co-design will enable a mixed-signal design and/or heterogeneous design containing More-than-Moore components.

Co-operative networks and cognitive radios use the available bandwidth and are carrier-frequency adaptive. Especially in the lower frequency bands (< 5 GHz) traffic congestion can be avoided. On electronics level this requires broadband radio circuits. The traditional radio paradigm, from antenna, architecture and circuit design must be reinvented. The push towards higher bandwidths, accuracies and higher energy efficiencies in RF circuits, conversion topologies, drivers, power-amplifiers etc. is essential to enable this development.

The need for more bandwidth on one hand and the issues related to efficient spectrum management on the other hand will require very demanding specifications on analogue and mixed-signal circuits with respect to pulse shaping/modulation, robustness, resilience, re-configurability, frequency selectivity and linearity. Technology breakthroughs in these areas are necessary. Future 5G systems will open a mass market for millimeter-wave circuits and advanced beamforming architectures.

More and more high-frequency electronics are needed for the ever-increasing data throughput on a ubiquitous wireless infrastructure. 60GHz wireless systems have been developed, car radar electronics will be centered around 77 GHz, and Terahertz frequencies will be introduced. The THz frequency band has unique properties as spectroscopy of materials, imaging capabilities and an extremely high bandwidth for future communication systems. These unprecedented high frequency and high bandwidth systems are an enormous challenge for electronics and require new insights in working principles of new electronic devices working far beyond today’s frequency limits. Applications range from astrophysical research to security. Sensors developed in the THz domain for professional applications (e.g. space) will penetrate in other application areas (security, health).

Active digitized arrays will steadily replace single receivers and transmitters. Individual users will receive their information through tailored, user-centered beams. Depending on the optimal partitioning of the system digitization will be performed on either the element level or on array level.

Theme 2 partners: Ampleon, Ansem, Antenna Company, ASTRON, Boschman, Bruco, CTIT, CWTe, Dialog, DIMES, Holst Centre (TNO & IMEC), ItoM, Keysight, MESA+, NXP, Salland Engineering, Sencio, Qorvo, Qualcomm, SRON, Teledyne DALSA, Thales Nederland, TNO, 4TU

Theme 3: Smart circuitry for Internet of Things, home-, building- and industrial automation.

The last decade has seen great advances in the realization of the Internet of Things (IoT). Not only through the introduction of new enabling technologies such as Narrowband-IoT and 5G connectivity, but also with the penetration of a wide range of applications in multiple domains. This has a considerable impact on the way we live and work. Combining a combination of several functions is essential to come to self-managed, cost-effective and durable solutions:

- Sensors are the essential *eyes and ears* of the Internet of Things. From basic physical parameters (acceleration, temperature, pressure, ...) via monitoring activity (presence, motion, ...) and vital signs (ECG, breathing rate, ...) to awareness of our surroundings (air quality, light conditions, proximity, ...). Specific solutions often require today a More-than-Moore implementation, but a relentless drive will continue to push sensor systems to CMOS implementation for cost reasons and mass adoption.
- Low power radios of multiple standards are employed in parallel or combined, and new standards will emerge over time to facilitate solutions that build on information from multiple domains.
- The implementation of smart algorithms enhances sensor readings. Combining data from multiple sensor modalities with advanced algorithmic approaches will allow for feature extraction in the sensor unit itself. Artificial Intelligence is rapidly becoming a key ingredient, not only in the cloud, but also in distributed (extreme) edge nodes with severe power and size constraints.
- A connected world with distributed data analysis needs a high level of security that is built into the solutions from the very beginning. Security and user authentication are essential ingredients to create trust in safety critical applications.

Today, these developments provide the means to make the next step in automation of homes, buildings, and industrial sites. Multimodal interconnected sensor nodes embedded in our environment facilitate the transition to surroundings that predict what is needed instead of react to what has already happened. This step from 'one size fits all' to truly personalized solutions will open a realm of new possibilities that build on the Internet of Things

Theme 3 partners: Ansem, Bruco, Dialog, Eindhoven Energy Institute, Holst Centre (TNO & IMEC), Keysight, NXP, Technolution, Sencio, Systematic, Teledyne DALSA, TNO, 4TU, CTIT, CWTe

Theme 4: Heterogeneous integration and packaging.

Heterogeneous Integration refers to the assembly and packaging of multiple separately manufactured components onto a single chip in order to improve functionality and enhance operating characteristics.

Since the start integration of more than one transistor we followed Moor's law to decrease the technology and on the other hand to increase functionality per area. Figure 2 shows the functional density over the years and Figure 3 shows the performance increase over the years. The growth rate of the functional density as well as the performance per area is slowing done even more efforts has been spent. The only way to get a suitable growth rate is to use the right chip technology (Si, GaN, SiC, GaAs) for the right functionality and to integrate these different technologies into one package. This means a totally different thinking of circuit design as the package and assembly technology need to be considered from the start of the development.

Application driven

The upcoming markets like IoT or 5G require high bandwidth networks to cope with all the generated data. Artificial Intelligence (AI), crypto currencies and data security require huge calculation power. So high bandwidth and high computing power are the main driving factors for a higher integration level.

Challenges

The main challenge is on the one hand the energy required to run the application driven demands and on the other hand to get rid of the generated heat by the applications. The higher the computing power or the frequency of high bandwidth connections the shorter the interconnects between different electronics devices should be, as longer lines/interconnects mean transmission loss or unexpected radiated transmissions or cross-talk which all degrade the entire system performance. Higher bandwidth or more computing power requires also increasing amounts of interconnections like e.g. 2.500 connects within an area of 5x5 mm.

A lot of these challenges can be addressed by heterogenous integration and packaging.

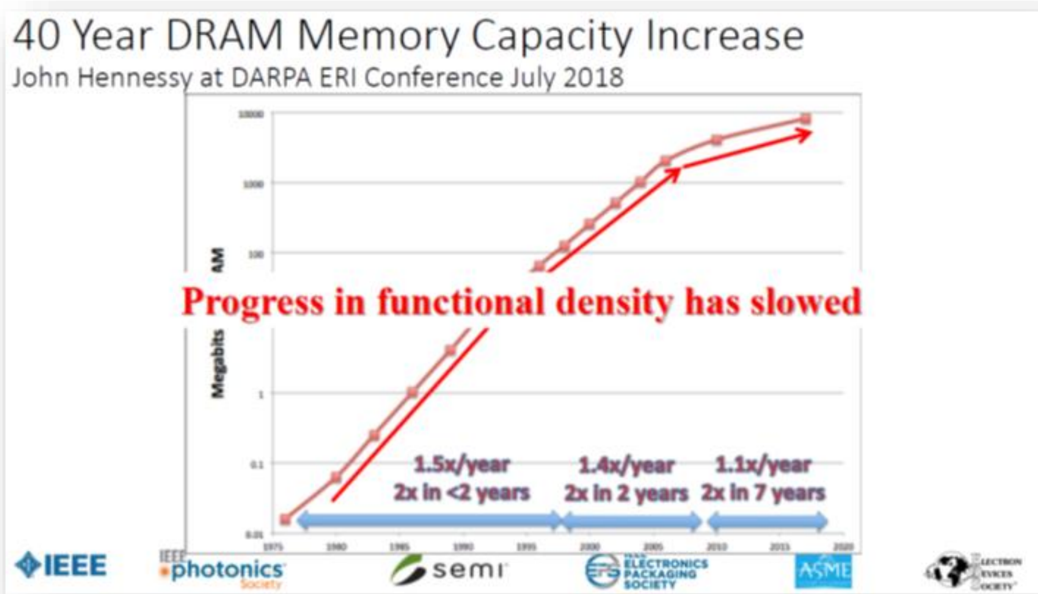

Figure 2 Increase of functional density

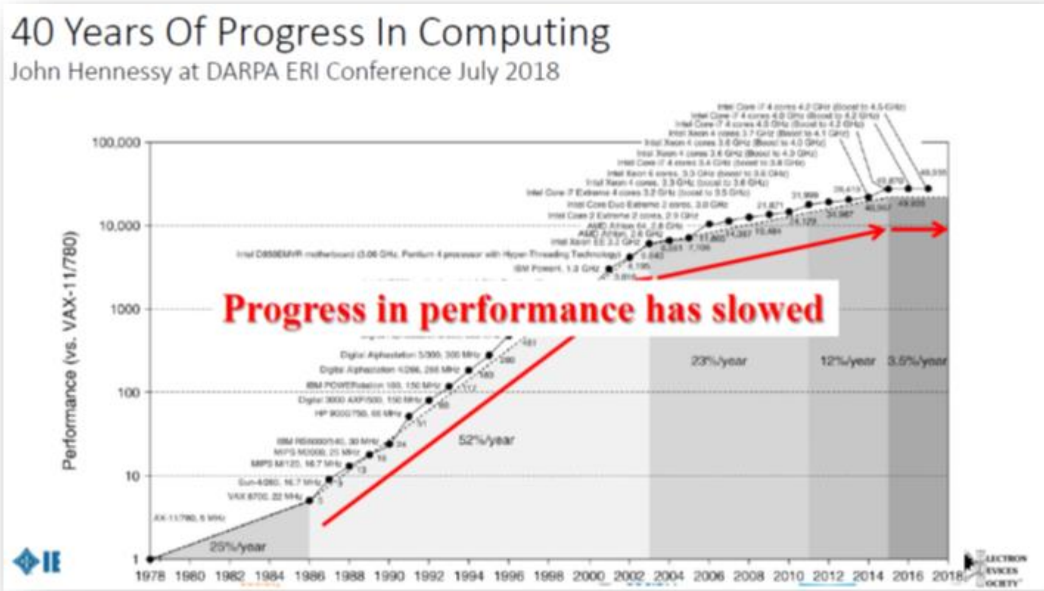

Figure 3 Performance increase

Theme 4 partners: Holst Centre (TNO & IMEC), NXP, CITC, Sencio

Theme 5 Electronics for scientific instrumentation and for harsh conditions.

Advanced components and circuits with extreme performance levels allow building instruments that enable breakthroughs in many scientific areas. The Netherlands has a strong position in several of these domains (material analysis, medical, robotics, microscopy, lithography, photonics, and detectors for particle physics and space exploration).

This field produces vehicles to explore extreme operating conditions and is of significant value for industrial and scientific instruments.

The instrumentation and space challenges lie in the field of very low power and low noise circuitry, increased intelligence per pixel (per square micron), radiation hard electronics, and high speed (wireless) data transceivers. Another challenge is the low-cost and efficient integration of electronic circuitry with photonics for various applications, from new sensors with interferometric readout to very high-speed data communication links. Further research is required on 3D integration & packaging, temperature stability, and cooling for optimal integration of components in a final instrument.

For automotive (under the hood) and industrial applications, high temperature reliable operation is an important area of study. The harsh environment where these circuits operate requires improved reliability, packaging, and increased lifetime.

Theme 5 partners: Adimec. ASTRON, Bright Photonics Bruco, Nikhef, NXP, Panalytical, Sencio, SMART Photonics, SRON, Systematic, Technolution, Teledyne DALSA

Theme 6: Power electronics boosting the energy transition

Significant advances in the electrification of mobility and industry is needed to reach the goals of the energy transition. Power electronics will play an important role in the transformation of energy, with high efficiency in the right shape for usage, storage or transport. Generated (renewable) energy has to be connected to the grid or converted in and industrial process to gas or liquid for storage. Energy will be transported as electricity were smart grid technology will help to steer and stabilize the power flow. Industrial users will have to convert the electrical energy to the right shape that fit with their industrial processes or transportation.

Power electronics can only become successful if it matches the high expectations of the industry. Conversion should be done with high efficiency and affordable cost. Reliability and lifetime should be high, under severe load cycles and harsh environments. The inherent controllability of power electronic converters will help to increase the acceptation and implementation. But new solutions are required to guarantee stability and safe usage of large scale distributed control. Security of digital electronic systems which will run for decades will also here become a relevant topic.

New wide bandgap components have the promise to increase efficiency and reduce the overall cost. The accompanying new semiconductor materials, system architectures and use-case scenarios can potentially introduce new and unknown failure modes and safety risks. The high switching frequency will help to increase the power density, but special precautions may be require to comply with EMC regulation. New design methodologies are required to make use of the these possibilities in electronic circuits and systems. High power applications will required scalable concepts with advanced control, redundant operation or health monitoring.

Theme 6 partners: AME, Boschman, Differ, Heliox, Nexperia, NXP, PRE, Prodrive Technologies, Sencio, TUe, TUdelft, UT

4. Partners and process

The roadmap Electronics boasts an active network of many academia partners, institutes and industry representatives. We’ve created an environment where partners meet in special workshops approximately two times a year, sharing the latest insights and preparing the future with thematic hot programs. Clear objective of the workshops is to facilitate the creation of connections and consortia for new business- and research-opportunities. We are keen to welcome new active participants to our workshops and our ecosystem, and are constantly searching for new developments

If you are interested in participating, please contact with us via electronics@hollandhightech.nl.

5. Investments:

R&D in public-private partnership, including contract research; all figures in million euro cash flow per year (cash plus in-kind contribution).

Roadmap	2020	2021	2022	2023
Industry[8]	87,3	87,3	87,3	87,3
TNO (excluding Holst centre)	3,5	3	3	3
HOLST Centre - TNO Holst - Stichting IMEC	 8,8 7,1	 8,7 8,0	 8,8 8,0	 8,8 8,0
NWO-D	2,5	2,5	2,5	2,5
NWO-I	4,1	4,1	4,1	4,1
Universities (4TU)	12	12,1	12,2	12,3
Departments and regions (excluding TKI)	2,5	2,5	2,5	2,5
Grand total	**837,5**	**837,9**	**838,1**	**838,2**

European agenda within roadmap	2020	2021	2022	2023
Industry	45,6	45,6	45,6	45,6
TNO (excluding Holst centre)	1	1	1	1
HOLST Centre - TNO Holst - Stichting IMEC	 3,6 3,5	 3,6 3,5	 3,6 3,5	 3,6 3,5
NWO				
Universities (4TU)	3	3	3	3
EZK co-financing of European programs	10,3	10,3	10,3	10,3
European Commission co-financing	12,5	12,5	12,5	12,5
Grand Total	**77,4**	**77,4**	**77,4**	**77,4**

All figures in million € cash flow per year

[8] R&D expenditure in 2019 for the sector *Elektrotechniek* equals 797 M€ as reported in the 2019 RVO report on WBSO [26, page 21]. The R&D component in PPPs of this expenditure is about 11% being 87,3 M€. https://www.rvo.nl/sites/default/files/2020/06/Focus_op_research_en_development_de_WBSO_in_2019.pdf

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