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NanoElectronics Roadmap for Europe:From Nanodevices and Innovative Materials to System Integration

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NanoElectronics Roadmap for Europe: From Nanodevices and Innovative Materials to System Integration

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Abstract—**The NEREID project ("NanoElectronics Roadmap for Europe: Identification and Dissemination") is dedicated to mapping the future of European Nanoelectronics. NEREID's objective is to develop a medium and long term roadmap for the European nanoelectronics industry, starting from the needs of applications to address societal challenges and leveraging the strengths of the European eco-system. The roadmap will also identify promising novel nanoelectronic technologies, based on the advanced concepts developed by Research Centres and Universities, as well as identification of potential bottlenecks along the innovation (value) chain. Industry applications include Energy, Automotive, Medical/Life Science, Security, loT, Mobile Convergence and Digital Manufacturing. The NEREID roadmap covers Advanced Logic and Connectivity, Functional Diversification (Smart Sensors, Smart Energy and Energy for Autonomous Systems), Beyond-CMOS, Heterogeneous Integration and System Design as well as Equipment, Materials and Manufacturing Science. This article gives an overview of the roadmap's structure and content.**

Keywords: Nanoelectronics, Roadmap, Beyond CMOS, More Moore, More than Moore, Design-technology gap, Heterogeneous integration, System design, Novel materials, Equipments and manufacturing.

I. INTRODUCTION

Roadmaps are highly beneficial for all high tech sectors, like Nanoelectronics, to improve links between academic and industrial research, to drive investments, to provide inputs for future research programmes and to coordinate efforts to overcome the main technology challenges.

For more than 20 years, the International Technology Roadmap for Semiconductors (ITRS) has guided the industry to follow Moore's Law, with a constant reduction in device costs and an exponential growth of the semiconductor market. The main role of ITRS has been in providing research guidance for the many actors of the semiconductor ecosystem, in synchronizing the technology development and the timely availability of manufacturing equipment and methods and in providing focus on critical bottlenecks.

However, the "technology push" that has been at the base of ITRS has shown in recent years its limits: device size and speed are no longer the only parameters of importance, and system-driven technologies have been considered by the new IRDS Roadmap (International Roadmap for Devices and Systems), focusing on computing systems.

On the other hand, the integration of new functionalities, required by new applications, needs the incorporation of special metrics for technologies that do not necessarily scale according to "Moore's Law", expanding the focus from chips to different kinds of systems. This trend is especially relevant for the European semiconductor industry that has focused on segments of greater relevance for the European industry applications, like Automotive, Industrial and Medical. Therefore, an appropriate kind of roadmap is needed for Europe which focuses on nanoelectronics with respect to the European abilities and strengths.

The NEREID roadmap for European Nanoelectronics covers both application and technology sectors. This comprises applications in the field of Energy, Automotive, Medical/Life Science, Security, loT, Mobile Convergence and Digital Manufacturing as well as technologies like Advanced Logic and Connectivity, Functional Diversification (Smart Sensors, Smart Energy and Energy for Autonomous Systems), Beyond-CMOS,

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Heterogeneous Integration and System Design and Equipment, Materials and Manufacturing Science.

With its mid/long term focus, the NEREID Roadmap is complementary to the European ECSEL ECS Strategic Research Agenda, which is focusing on shorter term horizons. Nevertheless, NEREID has also developed collaboration with, and is in part complementary to, the new International Roadmap for Devices and Systems (IRDS) in the Europe-led More than Moore domain (e.g. Smart Sensors, Energy, Energy Harvesting) leading to beyond-computing systems (s. Figure 1.).

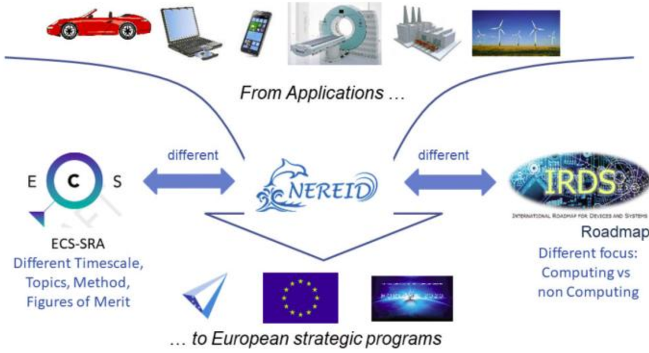

Figure 1. NEREID Roadmap Objective

The important assets of NEREID are the following:

- the projection of the evolution of many Figures of Merit (FoMs) vs time for covering the most promising technologies including novel functionalities
- the understanding of the dependencies between short/ medium term (e.g. More Moore and More than Moore) and long/very long term (e.g. Beyond CMOS) activities
- the strong interaction between application and technology experts, coming from leading research players in industry and academia, especially with the organization of many Workshops.
- the combination of a top-down approach, which is application driven, and a bottom-up one, based on planned technology evolution to prompt new ideas for disruptive products and applications (s. Figure 2.).

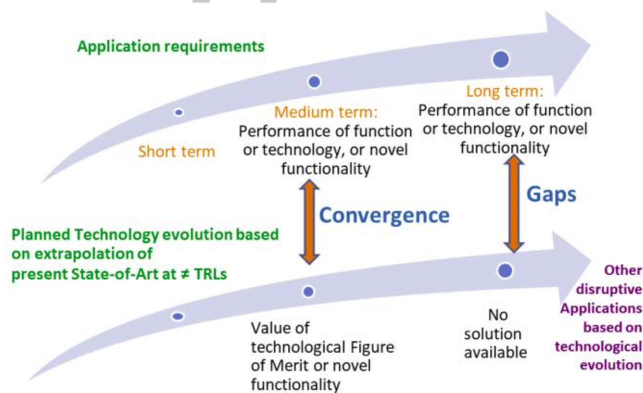

Figure 2. NEREID Roadmap Approach

II. Structure of the NEREID Roadmap

The NEREID roadmap is structured by the following technology sectors, which are covered in different sub-sections in this article:

- Advanced Logic/Memories and Connectivity
- Functional Diversification (Smart Sensors, Smart Energy and Energy for Autonomous Systems)
- System Design and Heterogeneous Integration
- Equipment and Manufacturing Science
- Beyond-CMOS (Emerging devices and Computing Paradigms)

A. *Advanced Logic and Memories*

The historical trend in micro-/nanoelectronics over the last 40 years has been to increase both speed and density by scaling down the size of electronic devices, together with reduced energy dissipation per binary transition, and to develop many novel functionalities for future electronic systems. We are facing today dramatic challenges for More Moore and More than Moore applications: substantial increase of energy consumption and heating which can jeopardize future IC integration and performance, reduced performance due to limitation in traditional high conductivity metal/low k dielectric interconnects, limit of optical lithography, heterogeneous integration of new functionalities for future Nano systems, etc.

Therefore, many breakthroughs, disruptive technologies, novel materials, and innovative devices are needed in the next two decades. [1] [2]

In the More Moore domain there is strong interest in Europe for specific activities dealing with very low power systems, leading to possible disruptive applications for instance for future IoT systems, or for application driven performance, e.g. high temperature operation for the automotive industry, and also for embedded memories.

We have chosen some core technologies that we think are the most promising for many future applications in order to overcome the number of challenges we are facing for future ICs, in particular:

- High performance
- Low/very low static and dynamic power consumption
- Device scaling
- Low variability
- Affordable cost

Considering these challenges, the following nanodevices and technologies have been considered as very relevant for future Nanoscale FETs:

- FD (Fully Depleted) SOI (Silicon-On-Insulator) MOSFET: for low power applications and low variability
- FinFET (or Trigate FET): for high performance and/or low power applications

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- Nanowire FET: for high performance and low power applications and ultimate integration
- CNTFET/Carbon NanoTube FET: for very fast and possibly ultimately scaled transistors for logic applications, with self-assembly based fabrication
- NCFET/Negative Capacitance FET: for very low power applications using steep subthreshold slope
- Non-charge-based Resistive Memories or alternative charge-based Memories: to replace charge-based memories using PCRAM (Phase Change RAM), RRAM (Resistive RAM using a nanofilament), MRAM (Magnetic RAM, especially STT/Spin Transfer Torque MRAM), or FeRAM or FeFET (using the polarization of a ferroelectric material)
- Sequential 3D integration: for increasing device integration (transistors, memories, sensors, etc.) and performance using 3D stacking

The roadmap also covers the future modelling and characterization tools needed for developing these future devices and technologies.

A major challenge we are facing is the energy consumption of future devices and systems. Figure 3 presents the comparison of the subthreshold swing obtained by numerical simulation, a fundamental parameter for low power operation, for the most advanced nanoscale FET architectures and the most promising materials of the literature as a function of the gate length and/or time horizons.

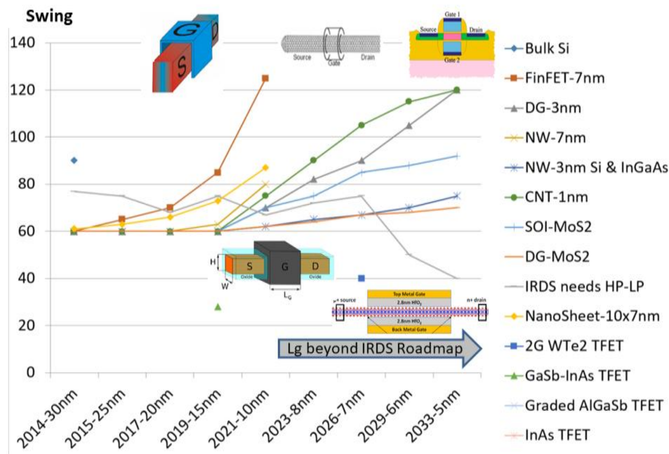

Figure 3. Advanced simulations of subthreshold swing (mV/decade) vs. gate length (beyond the IRDS Roadmap) or time horizon for various device architectures (Bulk Si, FinFET, Double Gate, Nanowire with various diameters, Carbon NanoTube, MOSFET on Insulator, Nanosheet, Tunnel FET) and channel materials (Si, InGaAs, InAs, Heterojunction GaSb-InAs, Graded AlGaSb, MoS2, WTe2), compared with IRDS needs for the next 15 years; Negative Capacitance FETs are also a possible solution for sub-60mV/dec swing but they are not represented in this plot because there isn't any result for sub-30nm gate length.

The IRDS needs for logic devices are also shown (vs time horizons). The best performance of CMOS devices at the end of the Roadmap (swing close to 60mV/dec) is obtained for Multi-gate Nanowire FET with very small wire diameter (3nm) and Double Gate MOSFET with 2D/TMD channel material (MoS_2 in the figure). However, at the end of the next decade, sub-60mV/decade swing will be needed, which can only be obtained with small slope switches (Tunnel FET with III-V or 2D channels in the figure, or NCFET, or hybrid devices) using boosters developed for CMOS (alternative channel materials, high k dielectrics, multi-gates, thin layers, heterostructures, etc.).

B. Connectivity

The connectivity functions are everywhere to make the link between all other electronic functions. From the sensors and actuators to the processors and microcontrollers, from the sensor nodes to the gateways, from the gateways to the cells from the cells to the data centres, and all over the world. Inside each of these units, the connectivity links the processors to the memories, the core of multicores in High performance computing applications, and the peripheral devices to the central computing units.

They are differentiated depending on the range and the nature. The nature is either wireless (in radio frequency mmW, THz bands, or visible light), or wireline (in copper or optical fibre). The range of such functions can be sorted according to the distance; the ultra-short range in the µm to cm distance, the short range is under 100m, while the long-range covers distances over 100m.

The most important connectivity market is dedicated to data communications, especially for cellular (WAN), WLAN, WPAN, NFC, and incoming WSN and IoT communications. Next, we can distinguish two other markets, especially in Europe, even if they use, or are be connected to the first one: the automotive market which is on the eve of the autonomous vehicle revolution, and the "health & security" market which will transform drastically our way of life in the next decades.

In the data communication field, we can distinguish three main families using the link distance criteria (Fig. 4); outdoor and cellular communications, including 5G and future generations, indoor communications mainly represented today by WiFi links, and finally a less visible one, which can be defined as In Device communication between dies and packages in an equipment.

If we look at the expectations on the technologies, the evolution is mainly visible in the different functions including Power Amplifiers, Low noise Amplifiers, Antennas in the Wireless field, or Modulator Drivers, Laser Drivers, Trans Impedance Amplifiers, Modulators, Laser Diodes, and PIN diodes in the Wireline field, we have to implement for the different transceivers. In this domain, the More Than Moore axe is privileged, (actives, NEMs and MEMs, and passive components), and the multi-physics assembly can bring advantages versus present solutions. On the other hand, we can notice that, whichever the transceiver, we have common functions such as the Phase Frequency generation and Local Oscillators in the Wireless field, Phase Frequency Lock Loop and Clock Recovery in the Wireline field. For these functions, the expectations are similar regardless of the selected communication link. In this domain, the More Than Moore axe is also privileged, (actives, NEMs and MEMs, and passive components). As previously, the multi-physics assembly can bring advantages versus

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existing solutions. Concerning the signal modulations and demodulations, the difference is mostly done through design, the functions are done in an analog approach or a digital one. Then, depending on the approach, the technology expectations are different. In an analog approach, the active More Than Moore axe is privileged, and, in a digital or "digital like" approach, the More Moore will bring the cost reduction and the efficiency.

How to evaluate the Figure of Merit of a function? – The industrial value is to evaluate the efficiency of a function versus the cost of this function. The cost is very complex to estimate, as we don't have the information, it could be composed of the fabrication cost (initial cost), depending on the technology cost, the packaging cost, the test cost, and the exploitation cost.

The proposed formula for the technical efficiency FoM is the following:

FoM = Data_rate (Gbs, Mbs, Kbs) × ??istance (??, km);

In addition, depending on the specificities, power consumption and bit error rate (BER) can be added as challenges.

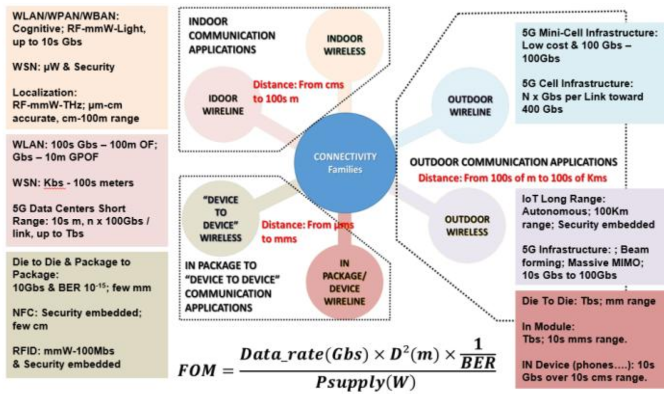

Figure 4. Connectivity Challenges in the next five years

C. Smart Sensors

Technology is moving from basic sensing to smart sensing in nearly every domain of applications. A smart sensor is a sensing system that combines the sensing element with local analog and digital signal processing, energy management (and possibly, energy harvesting) and wireless connectivity. Moreover, it can include multiple transducers for multi-parametric sensing. The information provided by smart sensors allows for efficient use of resources, higher productivity and better decision making. As smart sensing continues to evolve, intelligent autonomous activities will become possible, such as automated driving and automated logistics. In order to anticipate these evolutions, future sensor developments with their needed figures of merit are addressed in NEREID in sensors roadmaps. The exercise of performing a European smart sensor roadmap is broad, complex and diverse because sensing technologies are not driven just by scaling and costs, as was the case of CMOS. NEREID decided to focus on two families of smart sensors that are highly relevant for European scientific and industrial leadership, economy and society: *automotive sensors* (Fig. 5), and, *medical and healthcare sensors* (Fig. 6).

1) Automotive Sensors

European leadership in automotive is expected to be reinforced in the future thanks to major European technology manufacturers, early commercialization of smart vehicles and public organizations supporting the advancement of these vehicles [3][4]. The European road transport [5] sector has set as targets: (i) a 50% more efficient fleet by 2030, (ii) CO2 emissions reduced significantly (by 80% in cars, by 40% in trucks), with new fuels entering the market, and, (iii) mobility to be 50% more reliable and (iv) traffic safety improved significantly (by reducing road accidents by around 60%). Car-makers will have to re-think their business; probably considering to go in the direction of "mobility-as-a-service" with providers offering electrical vehicles, car sharing, etc. NEREID's automotive sensors roadmap has been structured in three layers, with benchmarking at various time horizons:

(I) Sensors for car system performance, navigation, inertial and motion sensors;

(II) Advance Driver Assistance System (ADAS) sensory systems: Radars (for short and long range), Lidar, image, infrared and ultrasonic sensors:

(III) Sensors for environmental monitoring, including temperature, rain, humidity, gas and particles.

It is worth noting that there is increased interest in the automotive industry to further extend the monitoring capability from the car to the *driver's health, alertness and fatigue*. This is certainly a very interesting direction involving specific sensor technologies, some creating new interactions with the healthcare sensor roadmap but not limited to. In the current version of the NEREID roadmap this aspect is not directly addressed but is under consideration for the final version of the roadmap.

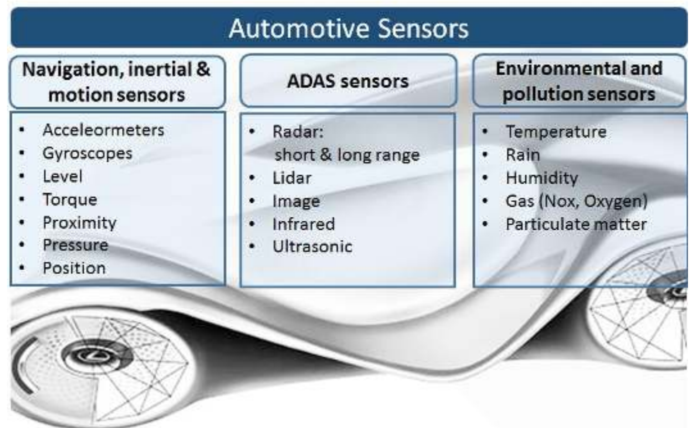

Figure 5. Automotive sensors roadmap,with its main subcategories and priority keywords, as structured by NEREID.

There are some particular features that automotive smart sensors of any kind (including MEMS and solid-state sensors) share and make their development very challenging:

- All sensor figures of merit are guided by safety regulations;
- Data safety and privacy, extendable to big data;
- Transferability to all vehicle types;

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- Robustness in all weather conditions;
- Stability in large temperature ranges
- Redundancy;
- Long life-time, low power and low cost;
- Miniaturization
- High quality standards and performance optimization.

Finally, it is worth noting that challenges from the automotive markets cover both sensor technology and their packaging, in a larger eco-system dealing with multi-domain co-design (chip, package, system) and with a high importance given to reliability.

2) Medical and Healthcare Sensors

The domain of smart health is of critical importance for the future of Europe because it addresses aspects of sustainability and Quality of Life in the ageing society. Recent research trends in IoT-based health go beyond the base-technology and include network architectures and platforms, new services and applications, interoperability, and security aspects [6]. Any paradigm shift in healthcare from traditional reactive, intervention-based to proactive, personalized and preventive healthcare [7] requires the development of a future sensory platform to serve the generation of medical big data of every patient to be combined with omics and imaging data. NEREID road mapping in this field identified three main categories of smart sensor technologies (Fig. 6) that need particular attention:

(I) *Wearable sensors* – including all types of vital signs sensors, neurological sensing interfaces, sensors for smarter therapeutics (to better manage pain and rehabilitation) and sensor to address the metabolic diseases (such as glucose sensors for diabetes). Wearable sensors [8] should be non-invasive, have local signal processing capability and wireless connectivity and large autonomy (days to months);

(II) *Implantable sensors* - Bionics or biomedical implants are artificial addition to the body, to address a certain loss of function. Implantable sensors are today a reality and will be even more prevalent in the future in the fields of: vision (e.g. bionic eye), hearing (e.g. cochlear or auditory brainstem implants), orthopedic (e.g. electrical bone growth stimulators), cardiac (e.g. pacemaker, artificial heart or heart valves, ventricular assist device), neural/brain (e.g. neurostimulators). Specific requirements and challenges include biocompatibility, long life operation without failure and in-body communications.

(III) *Molecular diagnostic and drug development sensors* – used to detect specific sequences in DNA or RNA, deletions, rearrangements, insertions, for analysing biological markers at the molecular level, such as genome and proteome. They cover advanced future portable diagnosis of infectious diseases, cancer, and other diseases/disorders and checking the risk of genetic predisposition for a disease. The most notable directions are based on *Lab on Chip* [9] & *Organ-on-Chip* [10] technological approaches.

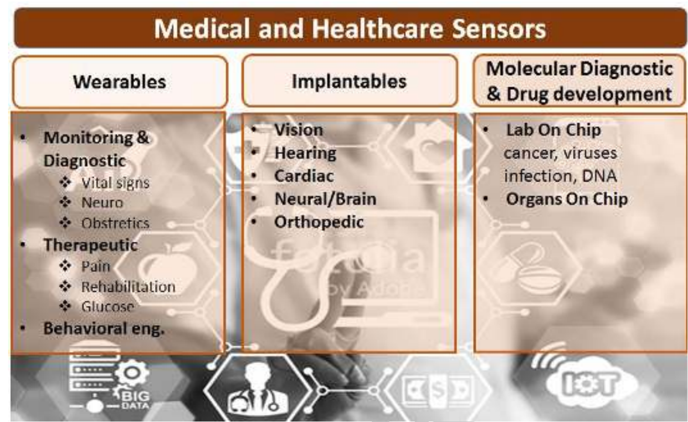

Figure 6. Medical and Healtcare sensors rodmap, with its main subcategories and priority keywords, as structured by NEREID.

D. Smart Energy

Power devices based on wide bandgap semiconductors (WBS) like GaN, SiC, Ga2O3, are poised to play an important role in future power electronics systems in addition to Si based workhorse technologies like IGBTs, Superjunction MOSFETs (e.g. CoolMOS) and low/medium voltage MOSFETs (e.g. OptiMOS) and smart power BCD devices. WBS have a high breakdown strength and, in the case of GaN, allows for fabrication of high electron mobility lateral transistors, for which the electron mobility is not degraded as would be the case for traditional silicon MOSFETs. Together, these facts allow the fabrication of devices, which have orders of magnitude better trade-off between the specific on-resistance and the breakdown voltage. The roadmap for devices has been set up along four tracks, the first considers the Si-based power technologies (Super-Junction devices, IGBTs and Smart Power BCD). The second considers the GaN based devices starting from materials towards integration. The third track is related to the evolution of SiC (again from materials to applications). Finally, future material systems (AlN, Diamond, Ga2O3) are considered which could offer benefits over the actual WBS in certain domains.

1) Si based power devices

a) Super-junction (SJ) devices.

Silicon based power devices are rather mature from the semiconductor technology point of view. This maturity combined with the low area-specific resistance unit cost of super-junction (SJ) technology enables the power-conversion market dominance of these devices in various application segments. Further research in this field should improve (or at least preserve) the market share of European manufacturers in the competitive and cost sensitive SJ market.

b) Insulated Gate Bipolar Transistor (IGBT).

Further development steps on Si-based IGBT technology are possible and crucial for future business success although this technology is mature and approaching its limits.

c) Smart Power BCD Technology Platform.

Thanks to the availability of a wide variety of elementary devices (Bipolar, CMOS, POWER Lateral DMOS and Passive) BCD products are present in almost all the current applications.

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As for all the technology in the More than Moore arena, the evolution of this platform is driven by the application requirements and evolution.

2) GaN-Based Technologies:

GaN semiconductor devices provide a competitive advantage in terms of thermal performance, efficiency, weight and size. GaN is anticipated to be the next generation power semiconductor and thus many companies are indulged in developing widespread applications of GaN semiconductors. The wide band gap semiconductor technology has matured rapidly over several years. In fact, Gallium Nitride High Electron Mobility Transistors (GaN HEMTs) have been available as commercial off-the-shelf devices since 2005. One of the major restraints of the GaN semiconductor devices market is the high production cost of pure GaN as compared to Silicon carbide, which has been, in addition to main-stream Silicon, a dominant semiconductor material for high voltage power electronics for a decade. Beside costs, breakdown voltage and reliability, the two most important Figures of Merit (FoM) are on-resistance (R_{on}) times area and threshold voltage (of normally off transistors), see **Error! Reference source not found.**Concerning the on-resistance times area, this FOM is focusing to the reduction of the on-resistance (that lower the conversion losses) while keeping the device area as small as possible (either to reduce parasitic capacitances as well as for reducing the chip-size and costs).

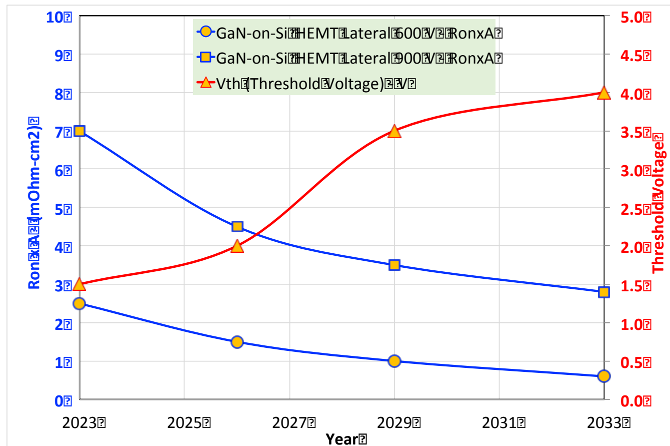

Figure 7. On resistance and threshold voltage evolution in GaN-based devices

3) SiC-based substrates.

Compared to the standard bulk Silicon, SiC has superior properties for application in power electronics, i.e. higher breakdown voltage, lower losses as well as the capability for high frequency switching and high temperature operation. These performance data are related to important material properties, e.g. higher energy bandgap, breakdown electric field, and thermal conductivity. The current maximum SiC wafer size in production is 150mm. Recently, SiC devices with breakdown voltages of 10 kV and higher have been developed for MV applications. This voltage rating noticeably surpasses that of commercial Si devices, such as 6.5 kV IGBTs. It is highly recommend focusing on the growth of thick epitaxial layers with low defect densities, e.g. very high current values (50 A & above), and high carrier lifetimes for high voltage devices, e.g. bipolar devices.

4) Alternative Wide Bandgap Semiconductors

Besides GaN and SiC, a number of other wide-bandgap materials exist. The most cited is diamond that is considered to be the "ultimate material". However, technological obstacles (lack of efficient n-type doping, conductive surface channels and difficulties to make ohmic contacts) have for a long time blocked the demonstration of high performance devices. Unless spectacular progress is made on these issues, no real-world implementations are foreseen and as such, diamond is not included in the roadmap. Besides SiC (for which a separate part of the roadmap is dedicated), we identify two major candidate materials: AlN and Ga_2O_3.

E. Energy for Autonomous Systems

As the communicating systems market is booming, the role of energy harvesting (EH) will be growing. Indeed, the number of connected devices is planned to increase by a huge factor of 200, while the number of mobile phones is just planned to increase by a factor 3 over a similar period. Connected devices are going to be used more and more in fields such as healthcare, wearables, home automation, etc. The Internet of Things (IoT) market grows considerably leading also to the boom of connected devices, and so highlighting the importance of energy needed to supply them in view of the limitations of current battery technology. This is important in applications with specific requirements, where a simple battery would not be sufficient, where using power connections increases largely the cost or complexity (i.e. avionics), or when the number of devices are so numerous that changing batteries could increase the maintenance cost. Other examples are in harsh environment were the electronic devices could not be reached easily, or in biomedical devices. In the roadmap, we are focusing on small connected devices with low power consumption below a few mW (or even a few tens of µW).

Various neglected energy sources can be exploited and converted into electricity: sun or artificial light, heat, RF power (either intentionally transferred), mechanical movements and vibrations. Moreover, this converted energy should be used and transferred wisely to sensors, microcontrollers or other electronic components included in the system. Thus, power management circuits and energy storage devices become essential.

In the roadmap, we have chosen several technologies that we think are the most promising for future autonomous devices:

First of all, mechanical EH was covered with three concepts, relying typically on input vibrations, with challenges in the compatibility with low frequency vibration sources and the increase of the operational frequency bandwidth:

- Electrostatic transduction [11]: where very small devices can be fabricated with MEMS technologies (CMOS compatible) but with challenges in the development of materials to keep electrical charges (electrets) over many years.
- Piezoelectric transduction [12]: where devices are easy to fabricate and CMOS compatible by using MEMS technolo-

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gies, with challenges in the replacement of some toxic materials.

- Electromagnetic transduction [13]: where macro-devices have been vastly explored (with higher performance compared to the other 2 technologies) but with lower performance at the MEMS scale.

Furthermore, other (non-mechanical) EH technologies have been considered as well:

- Thermal EH [14]: where power is proportional to the temperature gradient along the device, thus requiring usually big heat sinks to increase its performance.
- Photovoltaic EH [15]: being a mature (Si based) technology for both outdoor/indoor applications, but with spectral sensitivity and efficiency depending on the light spectrum. Challenges are related to the definition of standard measurement conditions for indoor applications and optimization of structures for indoor and/or outdoor applications.
- RF EH and wireless power transfer [16]: where very low power densities harvested are typical because of RF regulations, RF power transfer "on demand" solutions are preferred and exploited in many passive applications (RFID), wearable or implantable devices.

Concerning energy storage devices, two technologies were considered:

- Micro batteries [17]: based on thin films solid-state solutions. More energy dense and higher power options at lower cost are required.
- Micro capacitors [18]: with Si integration compatibility, a higher robustness and voltage operation, but lower capacitance density. Challenges are related to the reduction of leakage currents and series resistance, and the development of 3D structures to increase the capacitance.
- And finally, micro power Management circuits [19], with challenges related to the miniaturization embedding power converters, the reduction of the power consumption and the development of energy-aware circuit design techniques.

The energy that can be generated from small EH devices is quite low with most of these technologies, but this could be sufficient for many sensing applications, given the fact that energy is in general randomly generated. In addition, research is progressing towards the development of micro-power architectures of application circuits. The evolution of the EH technologies will enable a growing number of possible applications and products to be placed on the market, which were unfeasible up to now. In the medium (>5 years) and long term (>10 years) roadmap of the covered technologies, we expect an increase on their performance or efficiency (more electrical energy produced for a given available energy) (See Figure 8.).

For the long term in particular, new materials (polymers, triboelectric materials, organic, perovskites…) and nanotechnologies will be used to obtain higher performances but also to replace toxic/rare materials used today (i.e. Bi_2Te_3 in thermal EH and Pb-based materials for piezoelectric conversion, rare earth based magnetic materials, e.g. DfES, for electromagnetic conversion). Energy storage for combination with the EH will require advances in storage capacity per unit footprint and power capability during device interrogation and transmission. Power management circuits are expected to require lower input power (<100nW) and voltage (<10mV) (see Figure 8.) with smaller surfaces (<mm^2) in the long term.

The interest of the EH concept will be also to develop new devices compatible with silicon technologies for implementation in the fabrication line, which would attract the interest of semiconductor companies. Adding flexibility and/or transparency is also an increasing demand for compatibility with wearables applications.

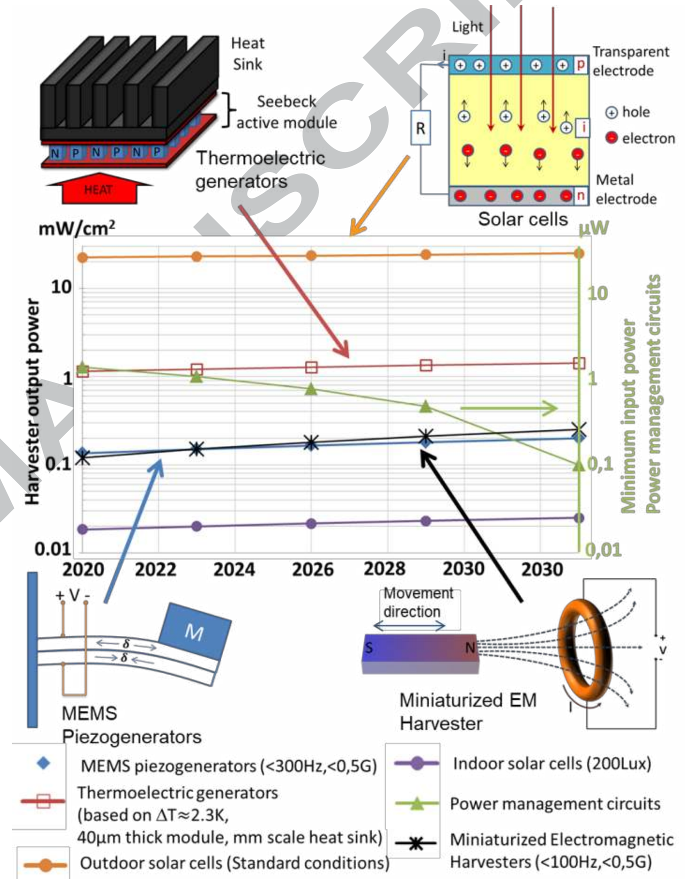

Figure 8. Expected performance of some selected EH technologies at some specific ambient conditions (right scale-har-vested surface output power density) and minimum input power (right scale) of power management circuits in function of time for the next 15 years.

F. System Design and Heterogeneous Integration

Building a roadmap for System Design and Heterogeneous Integration is a tough challenge, because of the variety of applications involved, demanding very different requirements, sometimes even contrasting in terms of values, limits and importance. Several road mapping attempts have been done in the past. The first example is the 2007 revision of ITRS [20] where some quantitative Figures of Merit (FoM) were given in terms of percentage of improvement over standards or targets. In the following ITRS revisions of 2009 [21] and 2011 [22], quantita-

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tive FoMs have been replaced by bar charts, related to the topic's development status with respect to the time horizon.

It is therefore justified to consider a new approach for road mapping System Design and System Level Applications, which goes beyond the simple inclusion of static numerical tables. The NEREID approach is to build a general Top-Down description of the requirements [23] (a hierarchical map) that has to be met in a Bottom-Up process, with concepts, methods, values and expectations strictly related to the application of reference. The Application is the Driver of the System level activities, and so road mapping has to start from this basic principle and consequently, the functionalities and methodologies for implementing a system are derived from the application.

System design and heterogeneous integration are core facilitators for overcoming the design challenges due to the ever-increasing complexity of embedded systems, which require designing System on Chips with integration of digital and analog.

The first step for building the roadmap is to design a structure suitable for having a common (and practical) scheme to be applied and tailored as needed in the different application domains of reference. The basic idea is to consider the functionalities that are of particular interest in future electronic systems. Starting from this consideration, the roadmap structure is built by connecting five different elements of Application-Aware Hardware-Software-Co-Design, as depicted in Figure 9.

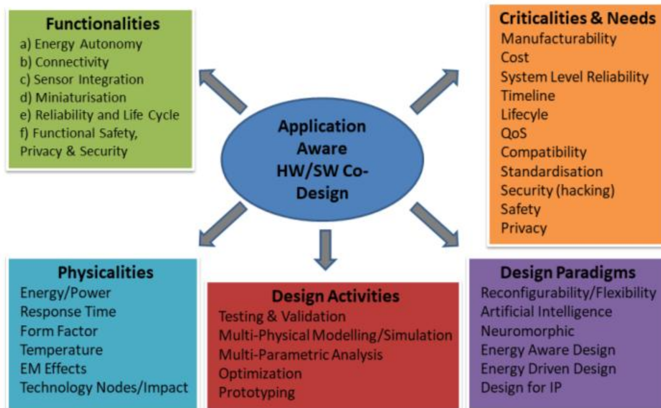

Figure 9. Application-driven Methodology for the roadmap structure

These five elements comprise a list of Functionalities, three kinds of Implementation Qualities (Physicalities, Design Activities and Design Paradigms) and Criticalities and Needs. Some definitions are:

- *Functionalities*, the reference functions that were identified as the common denominator for System Design and Heterogeneous Integration needs in terms of technology or implementation requests. The identified ones are:
  - *a) Energy Autonomy*
  - *b) Connectivity*
  - *c) Sensor Integration*
  - *d) Miniaturisation*
  - *e) Reliability and Life Cycle*
  - *f) Functional Safety, Privacy & Security*
- The *Implementation Qualities* are;
  - *Design Paradigms*, the possible design paradigms useful for serving the functionality needs, evaluated in terms of figure of merit, reporting the importance of the paradigm in solving the functionality needs;
  - *Design Tools*, useful for implementing the functionality, also evaluated with a figure of merit;
  - *Physicalities (i.e. Physical and technological requirements)*, i.e. the physical implementation requests in terms of heterogeneous technologies and processes;
- *Criticalities and Needs* are specific challenges within the Implementation Qualities domain that need to be addressed before they become critical bottlenecks for the system level application.

The aforementioned connection of the five elements is performed by mapping each of the five functionalities to related Implementation Qualities from which specific Criticalities and Needs are derived which results in a roadmap structure, shown in Figure 10. .

Figure 10. General structure of the roadmap

In practice, different tables were built, each one referred to an application domain under consideration. These tables indicate for each Functionality:

- The importance of the Functionality for the specific Application (with asterisks, having *** indicating very much important, * indicating low importance) and the TRL level expected/targeted for that Functionality; both measures were indicated in two time horizons of more than 5 years (5+) and more than 10 years (10+);
- The Implementation Qualities, split in three main implementation targets: a) Physicalities; b) Design Methods and Tools and c) Design Paradigms.
- The Figures of Merits of the Implementation Qualities, in 5+ and 10+ time horizons, are filled in, where possible, with quantitative measures (for example power consumption in nW or time in months/years) and where not possible with a qualitative indication (again with asterisks ***, ** or *);

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- The Criticalities and Needs, related to the Implementation Qualities, are also measured in terms of importance in the 5+ and 10+ time horizons.

From the general roadmap structure, considering, as highlighted, that the Applications are the core and the starting point of the roadmap, the three important application domains Automated Driving; Implantable Devices and Environmental Monitoring and Wearable Systems have been selected to apply the novel model. The rationale of choosing these specific applications stems from their importance in European industrial scenarios and from the broad coverage they offer in terms of addressing most of the technology requests useful for building the basis of an effective roadmap. Accordingly, these three applications lead to three different tables as shown in Figure 10.

Out of the work done, it was possible to generate the first general recommendations for the future of System Design and Heterogeneous Integration in Europe which are summarised as:

- Validation emerged as the most widespread need and challenge for future systems;
- Add Software in the middle, starting from the application;
- The value is not in the device itself, but in system integration and in the related data, the information is at system level;
- Balance of how much calculation is done at each node versus the energy for transmission (for reliability/security reasons as well);
- It is strategic to decide where to position the intelligence;
- The future is to move from Embedded Computing to Embedded Intelligence;
- It is important to define standards for interoperability. Openness of standards cannot prevent monetisation;
- Re-Usability / Reconfigurability have to be considered;
- Software-like re-programmability with (almost) hardware like efficiency;
- Energy management is key, in particular for limiting Consumption and categorizing the application in terms of Energy Boundaries;
- Automated Design Space Exploration and Automated Design Decisions have to be inserted in future tools;
- Transition from Connected Devices to Distributed Embedded Systems (System of Systems) leading to Network Synthesis, Network as a Design Dimension;
- Environment is Part of the System.

It was highlighted the importance of Sensor Fusion and Validation at system level, taking into consideration the environment where a system will operate (Environment-aware Design).

The strategic conclusion of the road mapping work was that it is for Europe a very good opportunity to drive an increase in System Knowledge. In Europe many important stakeholders are present, with original knowledge, bringing Europe to a leading possibility for System Level Applications.

G. *Equipment and Manufacturing Science*

Processing tools and high-quality materials have been the key enabling factors in the evolution of Nanoelectronics, and in particular in the area of More Moore, where scaling according to Moore's Law was one of the key drivers. The objective on Equipment and Manufacturing Science within NEREID was to extend this benefit to the increased complexity and variety of technologies developed for More-than-Moore, but also for nanoscale FET and Beyond CMOS.

The scaling down of the MOS transistor has driven the progress in the ICs performance and the cost per function of the devices has dropped accordingly. For complex devices, the decrease of the cost per functions is achieved by the development of derivative options on top of the core processes and the integration of heterogeneous processes. This leads to increasingly complex line management driven by many process generations, multiple products with short life cycle and high variability in terms of demand. The roadmap aims to activate a converging network of experience and competency involving the academic community for the development of new tools and methods for fab productivity needed to increase efficiency in the fab by managing cycle time, advancing equipment and process control and yield enhancement by providing a reference schedule.

The section of the roadmap on Equipment and Manufacturing Science was drafted after several consultations with technical experts during domain workshops, by analyzing the available information of the other work packages, by reviewing the application-oriented talks presented during the general workshops and the presentations given at the cross-domain workshop and by aligning with the "Electronic Components and Systems Strategic Research Agenda (ECS SRA)" (s. Figure 11.).

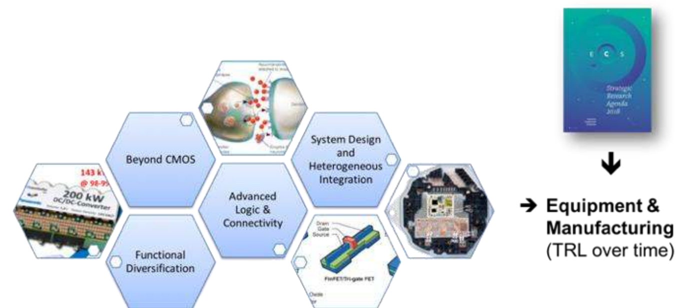

Figure 11. Information gathering process for roadmap creation on Equipmnet and manufactuirng

In the context of equipment and manufacturing science no real figures of merits were given, but comprehensive tables were developed, which depict the maturity level (TRL) over time for the individual solutions to be considered. This part of the roadmap is divided in three areas, which are further structured in several main topics:

- More Moore including Conventional technology (i.e. Technologies, Interconnects, Material/thin film growth, Patterning and Metrology) and Beyond CMOS, new compute paradigms and memory systems,
- More-than-Moore including Heterogeneous System-on-Chips integration and Process technology for applications,
- Manufacturing Science including Equipment, Safety, Health (ESH), Productivity, Automation and Yield.

The feeling exists, that with the worldwide effort on materials, processes and manufacturing in the domain of More Moore, the imminent needs of European application domains is covered. However, in this part of the roadmap activities were covered, where Europe is leading in terms of materials, processes and manufacturing, but where the demand from application side is stronger outside of Europe (e.g. EUV lithography equipment). For More Moore there is quite a confidence, that nearly all anticipated equipment and materials for the next technology nodes will be timely available, by insuring to manufacturers the long-term visibility needed to allocate the R&D efforts. In the area More Moore, Europe is an important supplier of materials and processes to the international market. There are remaining shortcomings in respect of equipment and material in the area of Beyond CMOS, new compute paradigm and memory systems (see the following section H for further information).

In the More-than-Moore area, where Europe is leading from an application perspective, like automotive, industrial and medical, NEREID identified in the corresponding part of the roadmap only a few issues with the timely availability of equipment and materials. There are still some uncertainties on upcoming materials like Ga_2O_3, AlN and diamond (see also section D). In particular this section on More-than-Moore represents the European abilities and strengths and is a comprehensive extension to the corresponding IRDS chapter.

Regarding Manufacturing Science no serious concerns have been identified. However, activities on yield enhancement and productivity will be continuously executed in order to stay competitive on the global market. Furthermore, upcoming regulations on ESH (like material replacement) might require additional efforts, which are not yet known.

H. Beyond CMOS

The scope of Beyond CMOS activities covers several emerging technologies with TRLs ranging from 0-1 to 4-5 and a wide range of device concepts and materials, some of which are compatible with the current CMOS platform. It also encompasses novel information processing paradigms in the time frame of five to ten years and beyond. The applications could include distributed computation within the expanding IoT or the realisation of accelerators on CMOS platforms to increase processing speed. The focus includes fundamental issues like heat dissipation at the nanoscale, one of the most critical bottlenecks in current IC technology. The target is to identify the potential, challenges and shortcomings of emerging technologies applied to information processing, while keeping in mind the European academic and industrial landscape that somewhat differs from that in the Americas and in Asia. The emerging technologies surveyed included spintronics, neuromorphic computing, nanoscale heat transfer, phononic computing, 2D materials, topological insulators, nano-optomechanics and molecular electronics. Considering the maturity of the device technologies, the suitability of the devices for information processing and their integrability, the selection of topics was narrowed down to photonic and nanomechanical computing, computing with spins and magnons, neuromorphic computing, steep-slope devices, statistical/thermal physics and related computing approaches.

Today's advanced CMOS technology operates at energies of the order of 10^4 k_BT per binary switching, which gives up to about four orders of magnitude for device innovations down to fundamental limits. Since 2010 the voltage scaling has been set at values close to 0.7-0.8 V. This is due to the conventional CMOS electronics relying on thermal excitation of electrons over a barrier, requiring an operating voltage many times larger than the thermal voltage, k_BT/q, needed to maintain a good on-off ratio for a digital switch. Attempts to scale down the threshold voltage will result in an exponential increase of the off, or leakage, current, of at least ten-fold for every 60 mV of V_{th} reduction at room temperature. To address such a fundamental problem, new classes of steep-slope switches have emerged with the main goal to lower the operation voltage and, consequently, the power consumption. One promising candidate for low power switching is the Tunnel FET, a solid-state semiconductor device designed as a gated p-i-n diode that operates in reverse bias and exploits quantum-mechanical band-to-band tunneling at one of the junctions.

In neuromorphic computing, the electronic circuits mimic the operation of neurons and their architectures to enhance the computational efficiency and reduce the power consumption. The circuits can be digital, analog or mixed, and combined with memory functions. Neuromorphic circuits use typically non-von Neumann architectures and can be realized by integrating non-volatile memory cells as the synapse with CMOS circuitry representing the neuron [24]. Recently, photonic synapses based on phase-change materials have also been demonstrated [25]. The circuits can include machine learning algorithms to perform, e.g., pattern recognition. Supervised learning is based on repetition of numerous samples, [26] and unsupervised learning needs a few presentations to master the function [27]

Spintronics [28] has several aspects related to information technology, since spins can be seen as an extra degree of freedom combined with charge [29].

Examples are spin FETs [30] and spin valve devices [31]. Pure spin currents manifest themselves in, e.g., the spin Hall effect, which can be exploited in microwave oscillators [32] and, potentially, in neuromorphic systems [33]. Spin waves in magnetic insulators, arising from coupled precession of magnetic moments, can transfer information without moving charges and, consequently, without Joule heating or dissipation. Spin waves, or magnons when quantized [34], can propagate at wavelengths down to nm and frequencies up to THz.

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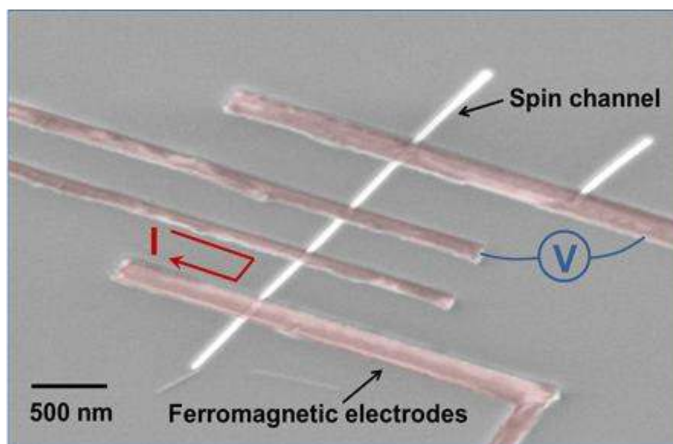

Figure 12. SEM image of a spin-valve device. A current of a few μA flows between the first two ferromagnetic electrodes. Voltage arising from the pure spin-current is measured between the last two electrodes. This is the non-local configuration, where the charge and spin currents are separated (Courtesy of Dr. Marius Costache, ICN2).

Phonons, the quanta of lattice vibrations, and thermal fluctuations are among the lowest energy carriers that can be considered for information processing with energies down to fractions of a meV. With some imagination, fluctuations can be thought of as low-frequency phonons, basically a kind of acoustic phonons. Acoustic phonons are the carriers of thermal energy in non-metallic solids. Brownian motion and fluctuations are also closely intertwined sharing randomness as one of their main characteristics. As physical dimensions decrease, the mechanical modes of a structure can couple to electrons and photons in what is known as nanomechanics [35] and optomechanics [36], respectively, providing new possibilities to develop very low, even entropy-driven, information technology.

Within quantum technologies photonics holds the key for quantum repeaters, for which long-distance transport of qubits is essential. Europe has a strong base in silicon and III-V photonics which, combined with silicon electronics, results in a silicon-based platform for a myriad of quantum technologies and their applications. Alternative computing based on photonics offers a number of advantages. In particular, unlike most other qubits, photons do not suffer from decoherence and it is possible to use linear circuits to perform quantum computing [37].

III. Conclusions and Recommendations (I)

The presented article summarizes the three years' work of the very successful NEREID Project which led to an ambitious Nanoelectronic Roadmap including all the important technologies for many applications representing large future markets. The NEREID Roadmap considers the specificity of the European industrial and academic landscape and will be very useful for equipment, semiconductors and application developments.

The project supported the participation of more than 100 application and technology experts, coming from leading research actors in industry and academia, to General and Domain Workshops. These Workshops enabled the consortium to better define the technology roadmap in terms of application requirements (in the fields of Energy, Automotive, Medical/Life science, Security, IoT/Smart connected objects, Mobile convergence and Digital Manufacturing) and technology evolution (Advanced Logic and Connectivity, Functional Diversification, Beyond CMOS, Heterogeneous Integration and System Design, Equipment, Materials and Manufacturing Science).

The NEREID Roadmap combined the "application pull" approach, focusing on the requirements of European semiconductor and applications industry and main societal challenges, with the "technology push" coming from the advanced concepts developed by Research Centres and Universities, in order to achieve an early identification of promising novel technologies, and cover the R&D needs all along the innovation chain.

This combined approach allowed the convergence between applications and technologies. The presented common work between technology and applications led to the early identification of the main challenges and the most promising technologies needing additional R&D activities, which will be very useful for the future electronic components systems of European companies leading to a strong impact on the European economy and society.

At the time when this manuscript has been completed the NEREID project is proceeding towards its conclusion and it is wrapping-up the results to publish the final version of the Roadmap with the detailed recommendations. Today the "pre-final version of the NEREID Roadmap can be found on https://www.nereid-h2020.eu/roadmap. By the time of publication, the final Roadmap and recommendations will be available on the website.

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The important assets of the NEREID roadmap are the following:

- This paper introduces the new NanoElectronics Roadmap for Europe covering topics from Nanodevices beyond CMOS and Innovative Materials to System Integration
- The roadmap has been worked by the European CSA project NEREID which has been funded by the European Union's Horizon 2020 research and innovation programme under grant agreement No 685559
- The NEREID roadmap gives a projection of the evolution of many Figures of Merit (FoMs) vs time for covering the most promising technologies including novel functionalities
- The NEREID roadmap delivers an understanding of the dependencies between short/ medium term (e.g. More Moore and More than Moore) and long/very long term (e.g. Beyond CMOS) activities
- The NEREID roadmap is based on a strong interaction between application and technology experts, coming from leading research players in industry and academia, especially by face to face exchange during many Workshops.
- The NEREID roadmap is created in a combination of a top-down approach, which is application driven, and a bottom-up one, based on planned technology evolution to prompt new ideas for disruptive products and applications

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