# Position Papers 2014

HTA – Heterogeneous Technology Alliance

European cooperation in microelectronics

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# Heterogeneous Technology Alliance HTA
# A portal to high-tech for SMEs

***Micro- and Nanoelectronics*** has become the most prevalent key enabling technology. The complexity of electronic systems is steadily increasing, leading from *components* to *Smart Integrated Systems*. Micro-/Nanoelectronics and the closely related MEMS-and nano-technologies are therefore the major building blocks for innovative, competitive and highly performing products needed to serve the global markets.

*Smart Integrated System Solutions* are no longer mere semiconductor based components but are becoming more and more complex heterogeneous integrated systems combining highly miniaturized CMOS ICs ("more Moore") with analogue components, such as: sensors, actuators, RF and power devices, and so on ("more than Moore"). In contrary to advanced CMOS technologies, Europe is still leader in the field of analogue components. This leadership has to be maintained.

The four partners of the *Heterogeneous Technology Alliance (HTA)* – CEA-LETI (FRA), CSEM (SUI), Fraunhofer Mikroelektronik (GER) and VTT (FIN) – are active at all levels of Smart Integrated Systems Solutions dealing with both, higher technological readiness levels (TRLs) and increasing complexity. Within this alliance, the HTA partners are combining forces and have started to create a distributed infrastructure for the **development and small-scale production of *Smart Integrated Systems Solutions (SIS²).*** This $SIS^2$ Facility is an extension of the existing cooperation of major European Research and Technology Organizations (RTOs) comprised in the HTA and acts as a portal to high-tech especially for the European SMEs.

## Bridging the gap from technology towards the grand societal challenges

"Grand Societal Challenges" represent the relevant needs of today's global society. They are the basis for present and future markets, national as well as global ones. Topics like ageing population and health, urbanization and mobility, climate and environment, efficient generation, distribution and consumption of energy, sustainable use and replacement of raw materials, as well as living and working in a knowledge based society are in the main focus of these challenges.

Looking upstream in the value chain, a solution responding to Grand Challenges will require not only services but also innovative products which are based on semiconductor devices & components, equipment and materials. As an example, a knowledge based society will require an extensive exchange of information (services). This will rely on mobile appliances like smart phones and tablet computers (products). Interaction with the external – non digital – world will be done with smart sensors and innovative actuators (devices). To solve the energy issue of such devices, one will need components enabled by nanotechnology based batteries and low-power electronics. At the very beginning of the value chain there will be advanced materials & equipment. All this will need to be packaged, assembled and thoroughly tested. To get materials, components and devices harmoniously integrated into products one will need technologies. Key Enabling Technologies have been identified by the European Commission, as the following: Nanotechnology, Micro- and Nanoelectronics, Photonics, Advanced Manufacturing, Biotechnology and Advanced Materials.

***Micro- and Nanoelectronics*** has become the most prevalent key enabling technology. It is used nearly everywhere in our highly engineered world and practically nothing would be working without it any more. In addition, the complexity of electronic systems is steadily increasing. This is leading to a closer interaction with other key enabling technologies. *New materials*, *Nanotechnologies*, *Advanced Manufacturing Technologies*, and *Photonics* are underpinning the importance of Micro-/ Nanoelectronics and the value chains for most industrial products.

The *Key Enabling Technology* Micro-/Nanoelectronics and the closely related MEMS- and nano-technologies are therefore the major building blocks for innovative, competitive and highly performing products needed to serve the markets mentioned above. Based on these building blocks, the European industry will be able to produce *Smart Integrated System Solutions ($SIS^2$)* needed to address the *Grand Societal Challenges*. The corresponding market segments are often served by small and mediums sized companies which need access to most advanced technologies to maintain their market positions.

*Smart integrated System Solutions* will play a key role in addressing the major societal challenges facing Europe. As an example, an ageing population will require more health care, but will profit most from preventive health monitoring systems that can signal an upcoming health crisis before it occurs. Similarly, an ageing population will prefer to continue to live independently, but having the security of an automatic warning system when an accident occurs at home. Another challenge is the energy consumption of our world. It could be greatly reduced through smart building systems that adjust blinds and heating of our houses depending on our presence and the ambient sunlight conditions.

The *Heterogeneous Technology Alliance (HTA)* is active at all levels of Smart Integrated Systems Solutions: from applied research on materials, processes and equipment through the fabrication of devices and components to the development of new products and services. With a highly qualified work force and state-of-the-art facilities the HTA is a key player in the European RTO landscape. Because the requirements from the industrial customers and the results of the ever increasing miniaturization are leading into both, higher technological readiness levels (TRLs) and increasing complexity, HTA has started to create a distributed ***$SIS^2$ Facility*** which acts as a one-stop-shop for the **development and small-scale**

**production of *Smart Integrated Systems Solutions (SIS²)*** for the European industry, especially SMEs. This SIS² Facility will be an extension of existing cooperation of major European Research and Technology Organizations (RTOs) comprised in HTA: VTT (Finland), CEA-LETI (France), Fraunhofer Mikroelektronik (FhG-VµE, itself a cooperation of 16 Fraunhofer Institutes, Germany), and CSEM (Switzerland).

Within this partnership, it possesses development and small-scale production cleanrooms for micro-electronics, MEMS, power electronics and analogue components. Its wafer handling capacity encompasses wafer sizes ranging from 100, through 150 and 200 to 300 mm.

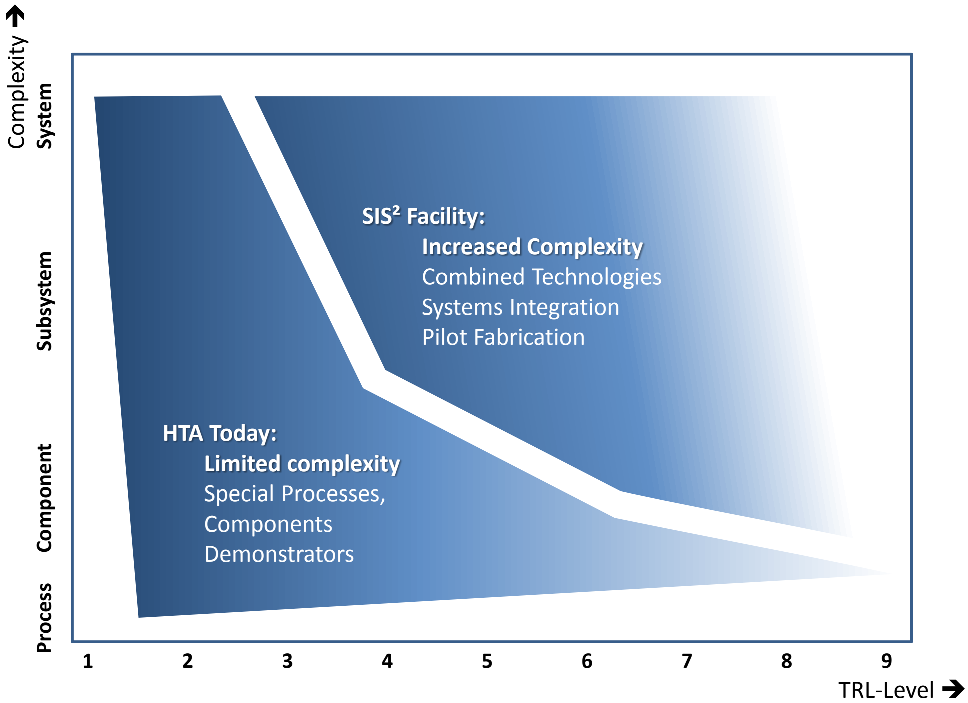



Figure 1: HTA is moving from four single institutes to a joint SIS² Facility.
By this, HTA is aiming at more complex products and higher technology readiness levels.

## HTA – A portal to High-Tech for SMEs

The European industrial landscape for high-tech solutions is dominated by large companies, such as ST Microelectronics and Siemens. However, a significant part of innovation in Europe comes from SMEs. In the last five years 80 percent of the new jobs were created by SMEs. They are a driver of innovation, competitiveness and growth and thus a key element in the Lisbon agenda (**Think Small First** – Considering SME interests in policy-making, Report of the Expert Group to Enterprise & Industry Directorate General, 2009).

The SMEs contribute a disproportionally large share to innovation because their small size gives them the ability to rapidly react to changing circumstances. In today's fast changing world, the technological lifetime of a smart phone is now well below six months, presenting a continuously changing technology environment. New, totally unforeseen applications using platforms like smartphones are currently appearing. An example of such unforeseen application is the intelligent alarm clock application for a smartphone that uses the sensors in the smartphone to wake up a person when he or she is only lightly asleep. Such applications could never be envisioned by developers of smartphones, but were developed by SMEs (Awawella, USA, in this case) that have reaped significant income from them.

The complete development of *Smart Integrated System Solutions* is complex, time-consuming, and expensive for SMEs. The most efficient way to help innovative SMEs would be to allow them to focus on their core competences. For SMEs an easy access to a multidisciplinary toolbox of the different building blocks would facilitate the development and assembly of the Smart Integrated Systems. Each building block must be easy to use and easily interfaced into a more complex system. An example of such easy to use components can be found in the STM32 F3 microcontrollers with their supporting discovery kit. The discovery kit includes, besides the microcontroller, gyroscopes, accelerometers and geomagnetic sensors. The user can directly develop software on the microcontroller without having to know the inner workings of the sensors. These have also easy to use interfaces that allow their assembly into smart systems in a fast and cost-effective way. Within the HTA, a large number of advanced components, devices, and electronic circuits have already been developed. They are forming an extensive toolbox for a whole range of *Smart Integrated System Solutions* for a variety of applications.

HTA partners file IP to protect their partners, large companies and SME's. SME's are particularly vulnerable in protecting IP when facing large industrial groups with heavy legal arsenal. HTA members are committed to protect on behalf of SME's IP and allow them licenses. In addition, they are committed to avoid obstruction of IP usage, through the promotion of adequate measures that enable and optimize usage of IP developed in European Commission funded projects but also bilateral contractual research, in particular by SME, when larger companies are not willing to do so.

## From Technology and Application Platforms towards Smart Integrated Systems

*Smart Integrated Systems* are no longer mere semiconductor based components but are becoming more and more complex and heterogeneous integrated combining highly miniaturized CMOS ICs ("more Moore") with other components, such as sensors, actuators, RF and power devices, and so on ("more than Moore"). While Europe is still leader in the field of these analogue/mixed signal components, especially MEMS-based sensors, this is not the case anymore in the field of CMOS ICs and assembly and packaging, whose centers of industrial activity are now in the Far East.

However, *heterogeneous integration* of the different components of *Smart Integrated Systems* is regarded as an opportunity for European SMEs to maintain an important role in the utilization of miniaturized systems. The analogue components are by far the most difficult to assemble reliably in a heterogeneous system, because of their sensitivity to mechanical stresses and other assembly induced phenomena. The intimate knowledge of these analogue components together with the European R&D and manufacturing facilities offer an advantage in the development of heterogeneous assembly technologies.

This *heterogeneous integration* is mirrored inside HTA by a smart specialization of the partners. On this basis, HTA serves its customers as a One-stop-shop with effective industrialization and production capability. Technology- or application-oriented building blocks help to set up a joint infrastructure for the benefit of the customers.

**Up to now <u>six of these building blocks have been set up</u>:**

The ***<u>Design</u>*** *of Smart Integrated System Solutions* requires a high level of skills to be able to integrate different components, described in different ways and having different interface requirements, and simulate their operation correctly without the need for excessive computation resources.

***<u>SOI MEMS</u>*** is a process platform for research, prototyping and small volume production of Silicon-on-Insulator (SOI) MEMS components. SOI MEMS is typically used for Silicon oscillators, microphones, speakers, compass, navigation, sensors and actuators, energy harvesting, micro fuel cells, microfluidics and other deep reactive ion etched micro structures. Key benefits of the collaborative work within the platform are:

Faster by optimized use of existing process modules
Lower cost by a jointly used equipment base
More innovative solutions due to a wider technology portfolio

The ***<u>Photonics</u>*** platform aims at the development of robust, reliable and low cost processes designed for devices/sensors and complete photonic systems. As a benefit for European customers, the HTA Photonics platform offers development and manufacturing services on miniaturization and integration of photonics components and systems. The Photonics platform comprises many aspects from device to system architecture level utilizing lasers, detectors, modulators, multiplexers, mirrors, etc. based on different materials like silicon, compounds, glass, or $LiNbO_3$. A clear focus is given to optimizing cost, complexity and performance of the system addressing light sources, light processing, light filtering, and light detection, as well as assembly and integration using optical SiP and SoC technologies. Overall goal is to enable photonics to deliver more functionality without adding complexity for the user.

The ***<u>Open 3D</u>*** platform was launched only recently to establish a European complete 3D & packaging integration platform on 200 and 300mm Wafer diameter. 3D Integration is one of the key technologies for further miniaturization of smart systems. As main advantages, 3D enables faster signal speeds and higher bandwidth by shortening of signal lines as well as a significant cost reduction by partitioning of large and expensive chips. Different technologies and functionalities can be merged into a single package and production time can be reduced significantly by parallelization of processes.

Quality and ***Reliability*** are key challenges for the widespread use of smart systems. Products are becoming more and more complex, market needs are increasingly fragmented and value chains are becoming long and specialized. Reliability is therefore key to competitiveness. Within the reliability platform, the key reliability labs of the HTA partners are working closely together along the whole value chain to provide full reliability analyses and failure avoidance strategies on structure, component and system level. This includes analyses under harsh environmental conditions and takes the demands of long term reliability into account.

***Health*** is the first application oriented platform. It is aiming at closing the gap around TRL5. To get a lab demonstrator (TRL4) into relevant environment (TRL5) and to make an industry-like prototype out of it (TRL 6) has proven to be one of the biggest challenges especially in the health business. The Health platform aims at helping the customers to overcome this gap and to bring new product ideas into the market.

# Scalable computing for applications in a connected world

## Background

In the 90th of the past century a trend towards a connected world started, which is still accelerating. Due to a rapid evolution of technologies for communication and computing, applications changed from mainly local approaches to networked systems.

In the communication sector the advent of World Wide Web, the increasing bandwidth of wired networks, and new standards for local and cellular mobile communication changed the way of thinking in system design rapidly. Embedded processors became available which exceed the performance of desktop computers and even servers from the past. Integration of such powerful DSPs and microcontrollers into ASICs allow for local signal processing in a new quality. Furthermore, increasing performance of standard processors and the development of fast memory interfaces paved the way for high performance computing at moderate cost.

In addition, MEMS manufacturing leads to miniaturization of transducers. In combination with embedded processors and communication interfaces a seamless integration of sensors into processes became feasible. As a result today applications are embedded into a heterogeneous ICT landscape. Data are transmitted and processed in hierarchical ICT infrastructures and applications have to deal with different levels (see figure aside):

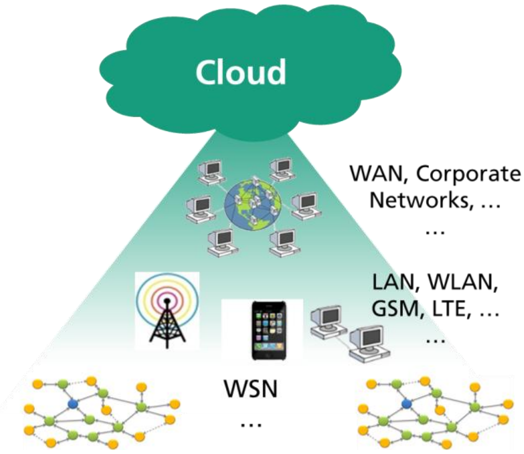


Figure 2: ICT landscape.

- Cloud computing and storage,
- Global communication infrastructures with wired backbone networks,
- Wireless local (e.g. sensor) networks,
- Networked computers and agents as well as mobile devices.

On each of these levels there exist some basic interaction patterns between technical systems, processes, environment, and humans. This includes data acquisition (e.g. of sensor data), data processing, process control and data transmission to the adjacent levels.

For distributed applications covering several levels of the ICT hierarchy, the main design goal is to find a global optimum, i.e. w.r.t performance or energy consumption. Application specific allocations of resources for computing, memory, and communication as well as the consideration of limiting factors like bandwidth, reliability, and thermal constraints are necessary on the different levels. Especially for new applications with a huge number of sensors and a tremendous amount of data, e.g. Internet of Things or Cyber Physical Systems, scalable ultra-low power computing solutions at low cost are essential. The main challenges from the application perspective, which have to be tackled by intelligent platform concepts, are the flexible combination of technologies, efficient system integration and a simple adaptation to specific applications vertically through all levels.

## Technology

CMOS technology has been used for more than 40 years for the fabrication of silicon chips. After a long period of technology happy scaling, one has to face serious technology limitations (leakage, technology variations). However, the most serious limitation comes from applications with a huge number of transistors and for which the power consumption becomes a dramatic problem. Many low-power techniques have been introduced (bulk bias, sleep transistors, regular layout, architecture parallelization), but new innovative techniques and architectures are needed to mitigate the power increase. Innovative systems are based today on a network of sensor nodes with local processing and access to the cloud.

**At the sensor level**, ultra-low power design of both sensors and electronic interfaces (ADC …) has to be performed. To have “Zero Energy” or “Autonomous” devices, one has to introduce dynamic power management taking into account batteries and energy scavenging.

**At the device-network level**, low power techniques have to be used (sub-near-threshold, biasing, parallelization of heterogeneous multicores, hardware accelerators, asynchronous, power management, 3D integration, reliability, low cost). Several CMOS technologies can be used, like conservative 180 nm and 65 nm for low cost, but also very advanced processes like FDSOI 28 nm for much better performances. In the future, new design paradigms have to be used like system adaptivity (to react autonomously to context modification through reconfiguration), energy aware and scheduling policies using also dynamic reconfiguration, hardware scalability (more or less computing cores depending on the workload) and security and cryptography.

**At the cloud level**, one has to develop application-specific computing platforms like microservers providing energy efficiency, modularity and scalability. Based on ARM 64-bit cores and powerful memory hierarchy (non-uniform L3 cache, remote DMA), the scale out architectures from microservers to High Performance Computing (HPC) comprise the same components (modularity) but more or less components (scalability). Energy efficiency is key for next generation of microservers and HPC and can be achieved by 3D integration, biasing, FDSOI to 14 nm, power management and specific interposer.

| Sensor | Devices - Network | Cloud |
|---|---|---|
| Ultra-low power design of sensors and electronic interfaces.<br>Based on "Zero-Energy" or "Autonomous" devices.<br>Dynamic power management (batteries, energy scavenging). | ASIC and SoC low power techniques (sub-near-threshold, biasing, parallelization of heterogeneous multicores, hardware accelerators, asynchronous, power management, 3D integration, reliability, low cost).<br>Use of various microelectronics technologies (180 nm, 65 nm, 28 nm FDSOI).<br>Several new design paradigms (adaptivity, energy-aware, scheduling policies, hardware scalability, security, cryptography). | Application-specific computing solutions providing energy efficiency, modularity and scalability.<br>ARM 64-bit cores.<br>Memory hierarchy (non-uniform L3 cache, Remote DMA).<br>Scale-out architectures<br>Energy efficiency (3D integration, biasing, FDSOI, power management, specific interposer. |

## Markets and Applications

Basically the market for digital circuits is divided into 2 main trends:

- On one side a market seeking raw performance in term of processing speed like **HIGH PERFORMANCE** computers and servers.
- On the other side a market of electronic devices that are battery powered which requires **LOW POWER** technologies (low operating power and/or low standby power).

These two markets tend to have their frontier blurred by new consumer products like smartphone and tablets which constitute a new class of product called the mid-segment where **BOTH PERFORMANCE AND POWER** need to be optimized and which will play a key role in all of the subsequently discussed market areas. Figure 3 shows the growth area of the semiconductor market for the next few years.

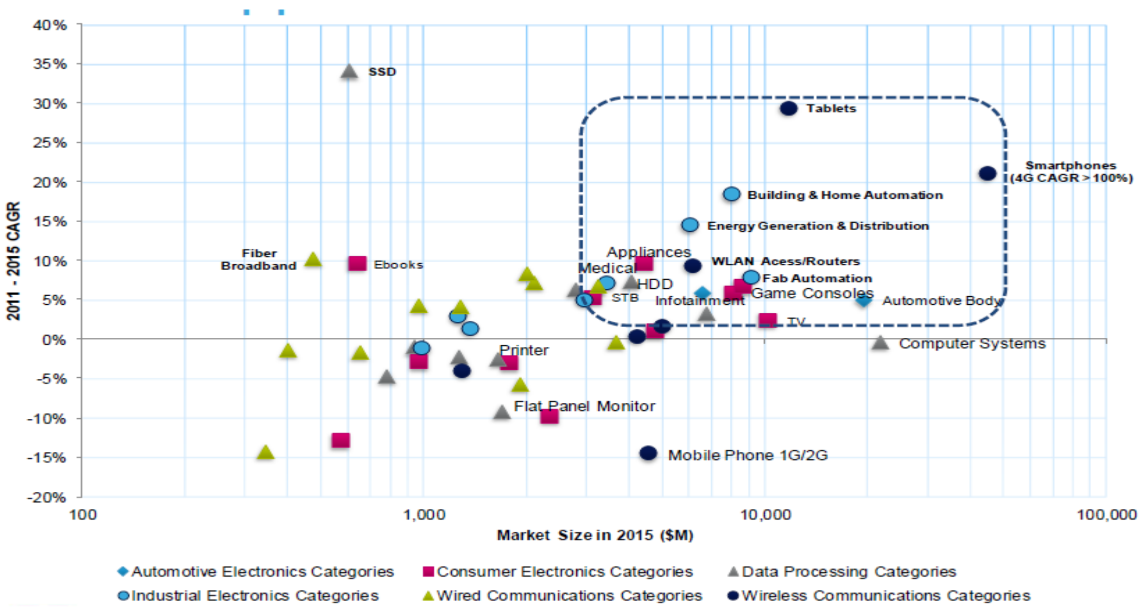



Figure 3: Growth areas of the semiconductor market.
Source: IHS iSupply 2014.

*Internet of Things*

IoT electronics is not a single market, but rather a heterogeneous collection of niche markets (that is a subset of the broader embedded electronics market). The common elements that hold it together are connectivity, sensors and processing. However, the collection sum of these markets will surpass the mobile market. The infrastructure build-up will not be as fragmented as the markets because the types of electronic equipment are relatively few in the infrastructure.

Since the IoT is nascent, there are no dominant ecosystems, yet. However, the heterogeneous nature of the IoT and all its aspects — be that the vertical industry focus, the complexity of the design (from the chip to the person), or the critical importance of the data and user experience in utilizing that data — means that ecosystems will be critical for the development of the IoT. Therefore semiconductor vendors should have flexible partnership strategies.

*Automotive*

Automotive ISP market is driven by the implementation of ADAS (Advanced Driver Assistance Systems) that will continue to grow in response to ever-present consumer demand for improved safety in their vehicles, combined with government mandates on safety systems intended to reduce road accident injury and fatality statistics.

*Micro-servers, Servers, High performance Computing*

There is a constant demand for improvements in online services, which means that the data centres that provide these services must continue to advance. This is a large target market, with over 500,000 data centres globally. Data centres consume up to 3% of all global electricity production. There are many reasons for this growth, not least of which are the rise of mobile, ubiquitous computing, social media sharing, and various other “Big Data” analytical systems. The amount of global, digital data is forecast to grow to 40 ZB in 2020 from 1.23 ZB in 2010. Such improvements are, however, limited by the technical and financial characteristics of current IT equipment, including their thermal-limited density, high capital cost, and excessive energy consumption. As the interests of the computing industry moves from a tight focus on performance towards energy-efficiency and total cost of ownership (TCO), the basic components of future servers and their integration into a full system must be reconsidered from the ground up.

*Advanced mobile*

Innovation in the smartphone space will bring more application development focused on making use of location and context information, such as augmented reality and broader context-aware computing. Reaching the full potential of these innovations will require further advances in sensing, processing, displays, connectivity technology and, especially, power efficiency. Estimates of emerging 5G systems in performance versus power demand a drastic reduce in power consumption, even orders of magnitude.

*Wearable electronics*

The consumer wearable electronics market for fitness and personal health will reach a $5 billion market opportunity for devices, apps and services by the end of 2016, increasing from an estimated $1.6 billion in 2013. The growth comes as the range of wearable device users continues to expand beyond fitness enthusiasts. In the wearable electronics market, the segments for fitness and personal health devices are among the first to gain traction. The apps and services for these wearable electronics are typically provided free for use with the devices.

*Augmented reality*

Augmented reality is also a heterogeneous market consisting of augmented awareness of environment, personal lifestyle, healthcare and entertainment, local navigation and social networking. Augmented reality is a strong growing market. The predicted growth is from $82M in 2012 to $5.2B in 2020.

## Players and European position

| Companies | IoT Processing | | IoT Sensors | IoT Wireless |
|---|---|---|---|---|
| | MPU/App Processor | MCU | | Cellular/Wi-Fi/BT/ GPS/NFC/ZigBee |
| Texas Instruments | Medium | Medium-Strong | Limited | Medium-Strong |
| Freescale | Medium | Medium-Strong | Medium | NA |
| STMicroelectronics | Limited | Medium | Medium-Strong | Limited |
| NXP Semiconductors | Limited | Medium | Limited | Medium |
| Atmel | Limited | Medium-Strong | NA | Medium |
| Renesas Electronics | Limited | Medium-Strong | NA | NA |
| Intel | Medium-Strong | NA | NA | Limited |
| Silicon Labs | NA | Medium | Limited | Limited |
| Qualcomm | Limited | NA | NA | Medium-Strong |
| MediaTek | Limited | NA | NA | Medium-Strong |

Key: Strong, Medium-Strong, Medium, Limited, NA

IoT = Internet of Things; MCU = microcontroller unit; MPU = microprocessing unit; NA = not applicable; NFC = Near Field Communication

Table 1: Ranking for Semiconductor Vendors' IoT offerings in production.
Source: Gartner Jan. 2014.

It is expected that 25 billion devices connected to the Internet by 2015 and 50 billion by 2020. IoT market(s) will surpass the mobile phone market. Innovation in traditional industries is driven by electronics. However, in IoT and related ("Internet of People") covering wearable electronics etc. will be driven as well by available ecosystems, services and application needs, electronics being a box of legos to build these. Table 1 shows Gartner's current ranking for the top 10 semiconductor companies based on their having products in production as well as go-to-market efforts on markets, software and ecosystems. This list excludes intellectual property (IP) and design firms, as it specifically focuses on companies with silicon products. At the moment, no company has any category classified as strong — because that would require a much richer portfolio of IoT solutions for specific niche markets.

Note that in such a rapidly changing market any comparative analysis is bound to fluctuate regularly.

In Europe, there is a strong embedded and low-power processor ecosystem. This includes many companies in hardware and software development for both the industrial and commercial sectors with several research organizations which are leading the development of semiconductor technology and the design of sophisticated devices. Moreover Europe is one of the biggest markets of the world and benefits from a very strong educational environment and a highly competitive undergraduate and graduate educational system. However, Europe suffers from a high degree of horizontal specialization, which leads to the absence of a global and consistent R&D approach and makes difficult for companies to amortize the costs of development across the product chain. There are no European agglomerations such as Silicon Valley or the Asian foundry companies or well-known economy drivers as kind of global "brand marks" that can act as job creation machines. As a representative indicator, the share of European papers in main conferences (ISSCC, ESSCIRC/DERC etc.) decreased considerably. In this context, the expansion of power efficient electronics to a wide range of new applications emerges as a unique opportunity for Europe, which holds a leading position in energy efficient computing and market prominent positions in embedded systems.

## The requested Research and Innovation effort

In the context of Horizon2020 Europe has setup several instruments to create significant opportunities for the computing systems industry in Europe. Future Emerging Technologies (FET), Joint Technology Initiative on 'Electronic Components and Systems for European Leadership' (ECSEL) and Leadership in enabling and industrial technologies (LEIT) are part of them. However, this funding framework is still suffering from a scattering of efforts not fully in line with the verticalization of upcoming challenges in the computing area such as energy efficiency and scalability. It could lead to inefficient use of public funding, duplication of work and lack of critical mass funds for developing breakthrough innovations. The Heterogeneous Technology Alliance ambition is to address these transverse challenges of energy efficiency and scalability for computing in a connected world. We cover core technologies, platforms and methodologies aiming a reduction of energy consumed by electronic devices by a factor 1000 in 10 years. This will be done through ultra-low power design methodologies for SoC, SiP and 3D Integrated Circuit including techniques such as: heterogeneous systems, dynamic throughput control, HW-SW interaction.

An application aware design poses new challenges to the design methods and tools itself. On the other hand, designing application-specific hardware and selecting key building blocks to integrate (e.g., processors, memory, analog, wireless, sensors, MEMS) will enable more optimized devices. However, as the development cost and mask cost for producing silicon chips is prohibitive for small product quantities, new techniques should be developed to enable our industrial partners to differentiate hardware with a reduced development cost. Solutions such as integration of heterogeneous dies on a silicon interposer might allow specialization while using the existing technological capabilities of the European semiconductor industry. The improvement and flexibilization of design methods starting at the system level are crucial for speeding up the design as well as to cope with the complexity of those systems and to fully take advantage of new technologies and, thus, to reduce costs further. The design of energy efficient computing nodes has to be embedded into intelligent platform concepts addressing the flexible combination of technologies, efficient system integration and a simple adaptation to specific applications to achieve global application aware energy optimization vertically across all levels from the cloud via the computing nodes and networks to sensors and MEMS.

The ambition of the HTA design platform is to enable the basis for energy efficient and scalable computing components for applications in a connected world.

# MEMS technologies: an opportunity for Europe

## Background

The MEMS field started in the 1980's in the academic field with the first conference on the subject (Transducers '81) held in 1981. Pressure sensors became the first industrial MEMS product in the late 1980's, but the packaging required for those sensors overshadowed the gains of batch fabrication of these sensors.

The MEMS sensors started their growth in earnest in the early 1990's with the legal requirement for airbags in newly produced cars. This proved to be a real impetus for the development of 50g accelerometers. Over time, the mastering of the design and technology led to the development of 1g accelerometers that found their use in ABS systems. The subsequently developed yaw rate sensors (gyrometers) found their way into electronic car stability control systems. With new techniques (DRIE) and SOI wafers becoming readily available the fabrication technology for these inertial sensors shifted from surface micromachining (1990's) to SOI-MEMS technologies (2000's).

The SOI-MEMS inertial sensors found their main market in automotive industry until, in 2007, Nintendo introduced the Wii game console that used accelerometers for the control of the games. This shift to the consumer market increased the volumes by an order of magnitude, which was repeated when inertial sensors were also introduced in mobile phones. As a result, tens of millions of SOI-MEMS inertial sensors are now produced each year, making the technology an extremely widely used. Its wide availability has led to the development of new MEMS devices using this technology. Two examples are MEMS resonators for time bases and for extremely sensitive temperature sensors.

In an independent development, the ink-jet printing heads used MEMS type fabrication techniques to define the required fine features. Today, only the mold for these heads is still fabricated with MEMS techniques: the heads themselves are produced by the millions with injection molding.

Another independent development was the micro-mirror array, developed by Texas Instruments in the 1990's. This independent development has allowed TI to become an almost unique player in the field of MEMS-based imaging devices for consumer applications.

Besides these main MEMS applications, a plethora of MEMS devices have been developed over the past 20 years, using an extremely wide variety of technologies. One notable example is the MEMS telecom fiber-optical switch which enjoyed a fantastic boom during the late 1990's and a dramatic bust during the telecom implosion of the early 2000's. It shows that the MEMS field has become mature, with some major large volume products and many niche products and a technology acceptance by the markets.

## Technology

MEMS fabrication employs mainly techniques issued from the microelectronics industry. It therefore takes advantages of the huge engineering efforts related to the deployment of this billion dollars industry. Such effort could not have been deployed for the MEMS market which is in comparison 40 times smaller.

Using microelectronics processes therefore allows re-using the processes, materials, equipments and fabrication infrastructure before dedicated to CMOS components. In that aspect, a number of MOS foundries that became obsolete with respect to high end electronics are now targeting MEMS applications.

MEMS fabrication is based at 80% on standard microelectronics processes: layer deposition, photolithography, and etching. However, dimensions are less critical for MEMS, the minimum lateral dimension being in the order of a micrometer, to compare with 14 nm for the most advanced node in micro-electronics. The last 20% are process steps that are specific to MEMS, and require particular know-how and equipment. These particular processes are:

- Deep silicon etching,
- Sacrificial layer techniques,
- Deposition of stress-free materials,
- Wafers bonding

The introduction of motion sensors in consumer products has recently dramatically increased the size of MEMS markets (see next paragraph). This change has raised a strong interest from big players and equipment supplier, and has increased the speed of standardization of MEMS process steps: One example is the now universal use of Vapor HF for the removal of sacrificial layers while several techniques were still competing in the 90's.

## Markets and Applications

The MEMS chip market is booming along with the high-profile consumer electronics devices using them. Cell phones dominate this growth, led by the phenomenal successes of Apple's iPhone and other smartphones which copy its sensor complement. MEMS accelerometers and gyroscopes are now widely used in phones, tablets, digital cameras, gaming controllers and automobiles.

According to Yole, the use of MEMS in consumer electronics is rising from $3 billion in 2009 to $10 billion in 2018. Overall, the MEMS will represent a market of nearly $23 billion in 2018 to compare with $7 billion in 2009. The average annual growth rate is above 13%, significantly higher compared to the IC industry.

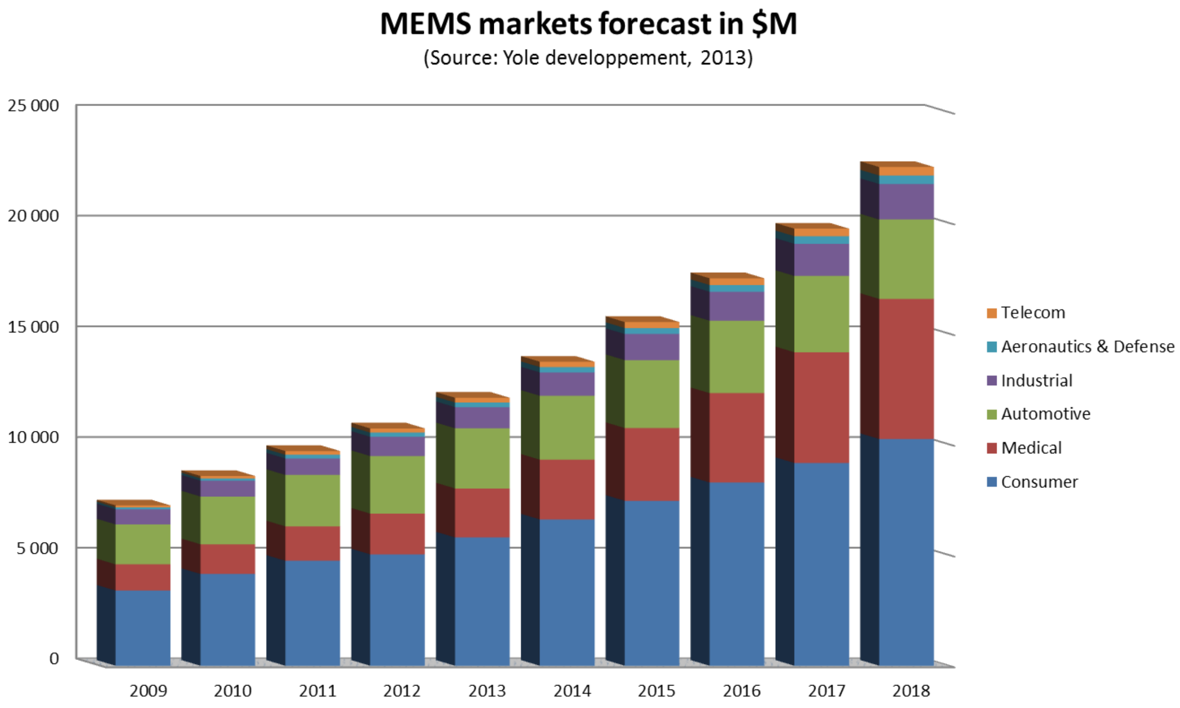



Figure 4: MEMS growth by application.
Source Yole développement, 2013.

Although big, the MEMS market is still highly fragmented. Only a limited number of applications have a market size above $200M. A lot of applications are indeed extremely different even for the same type of product (e.g. from barometric pressure in watch to pressure sensing in nuclear power plant…).

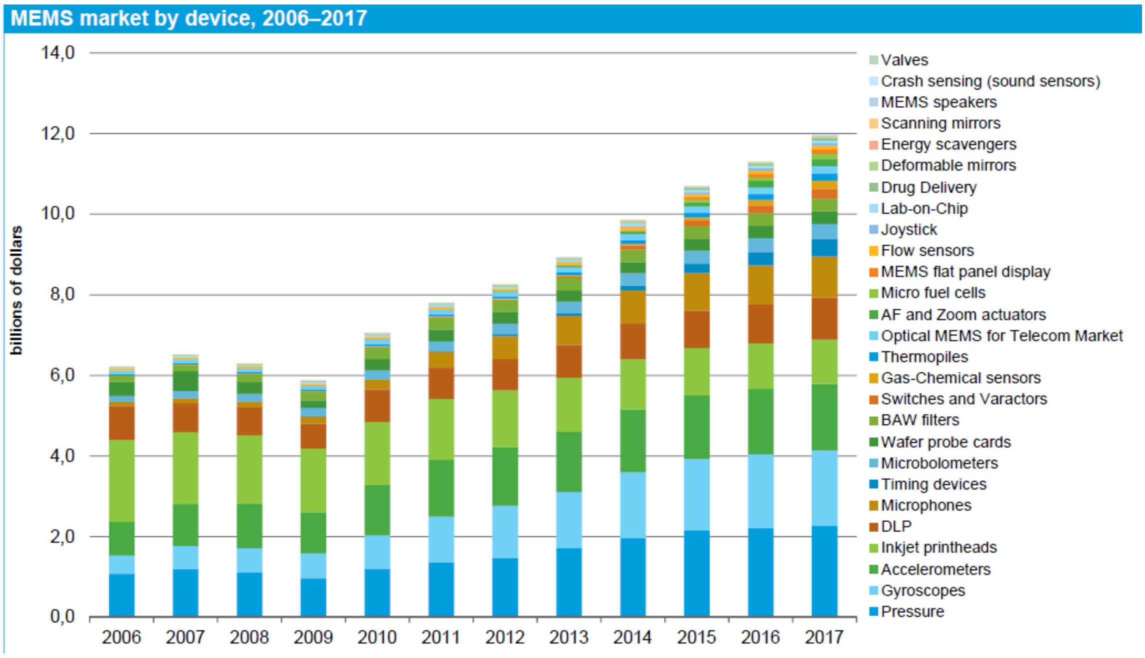



Figure 5: MEMS market by device, showing the product fragmentation.
Source IHS MEMS Market tracker, Q3 2013.

## Players and European position

Europe holds a strong position on the MEMS markets: The first two industrial players being European, ST Microelectronics and Bosch. This is notably thanks to the EC support that allowed the creation of European champions in this field, both as Integrated Devices Manufacturers and as equipment' suppliers (Suss microtec, EVG, SPTS…). Additionally, European companies are also well represented among wafer manufacturers for MEMS devices (e.g. Okmetic and Icemos).

European research organizations are world leaders in many fields of MEMS technology. The members of HTA alliance can be mentioned as an example. Funding instrument specifically targeted to lower the threshold of co-operation between the institutes would probably improve the situation even further.

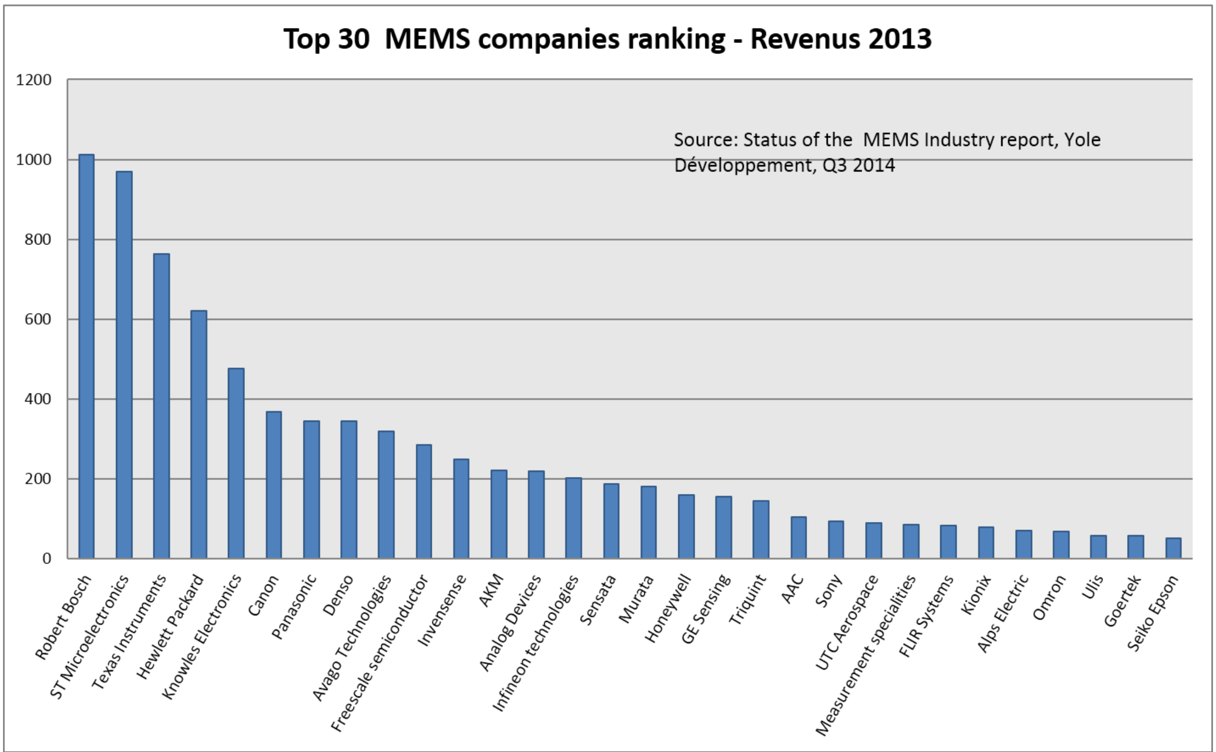


Figure 6: MEMS companies ranking; the first two companies are European.

## The requested Research and Innovation effort

Europe has endorsed the importance of MEMS which are an essential part of smart integrated or cyber physical systems. Such smart, interactive and sensitive systems with underlying data base and software are needed for the internet of things (smart grid, smart production, smart home …) and services. For example Bosch reported at Smart Systems Integration Conference 2014, that the third wave of MEMS proliferation is caused by internet of things and services.

Currently existing standard sensors and MEMS are not sufficient to increase the sensing capabilities of components and complex systems like cars, machines and other things or to open new application fields. So it is necessary to evolve new complex, multifunctional and miniaturized devices. This may be multi sensor modules or smart systems, combining different components like sensors and actuators with data processing as well interfaces for data (wireless communication) and power transfer.

It requires not only new materials (piezo, utilization of nanomaterials, amorphous metals, polymers …) for added functionalities like energy harvesting and chemical functions, but also continuous shrinking of size and power consumption. New methodologies like design for reliability, simulations and virtual prototyping are necessary to ensure shorter time to market of new innovative products. It is also recommended to foster the development of new MEMS devices fulfilling new applications: in the last ten years, only two new types of MEMs has emerged and reached the market successfully: microphones and time reference. Support to the development of new types of devices is somewhat missing.

Moreover, this development also leads to increasing demands on new technologies for MEMS, especially system integration technologies focusing on wafer scale packaging, cheap materials for bio compatibility and use of smart polymers as well as manufacturing technologies including 3D printing and reliability assessments.
Similar to the ongoing development MEMS foundries, the diversity of new emerging microsystems such as chemical sensors, silicon microfluidics, micro fuel cells, MEMS switches, touch screens, AOC MEMS, micro speakers and scanning mirrors requires the standardization of processes and technologies. Only by standardization and the establishment of design rules, the prototyping and production costs can be kept at a reasonable level.

In order to meet the challenges and to strengthen the European position, the HTA addresses especially SMEs. Based on the establishment of SIS² Facility which acts as a "one-stop-shop", a platform which provides generic technologies in fields of smart integrated systems is expected to benefit SMEs. The generic technologies include the creation of design rules for integrating different components, enhancement of generic process for prototyping and small volume production of heterogeneous system components by optimized use of existing process modules, potentially help niche markets by facilitating MPW project, finding cost effective solutions for integrating heterogeneous technologies into a single package, fully analyses and verification methodologies considering long term reliability, and seizing the cross link of societal challenges, i.e., health, and engineering communities to overcome the gap between user needs and SME capabilities.

Heterogeneous Technology Alliance HTA and the starting SIS² Facility will be a portal for SMEs targeting high-tech in a whole range of Smart Integrated System for a variety of applications as well as an aid to secure European industrial leadership in this domain.

# Photonics sensing and integration

## Background

Photonics is a **EU key enabling technology** with components, sensor and systems providing a large potential for the European photonics market. Large acceptance of optical components and subsystems in mainstream markets as telecommunications, smart phones or tablets exercises considerable pressure on prices, which in turn requires mass production. It is natural then, that the production and assembly of optical systems is moving to the far east due to reduced costs of personnel and expertise in low-cost mass manufacturing. Unfortunately this trend impoverishes Europe in terms of competent people and technologies. It is clear, however, that this kind of competence, i.e. production and assembly of high added value components, is essential for maintaining overall manufacturing capability in our continent. Optics and photonics is traditionally a European strength since centuries. SME networks, industrial culture and competences in Optics and Photonics have been built steadily in clusters such as in Germany (e.g. precision instrumentation and power lasers), UK (e.g. fiber-optics) or France (e.g. optoelectronics). Despite the beginning of deindustrialization during the last two decades the aforementioned long lasting elements (networks, culture and competences) persist and can be a healthy and stable basis for industrial regrowth.

The world photonics market is expected to grow from 350b€ in 2011 to 615b€ in 2020. Photonics is present in many segments in our life, spanning from telecommunications, displays, safety and security, lighting, medical devices and energy. As shown in Figure 7, the photonics industry growth rate is exceeding global GDP in all sectors.

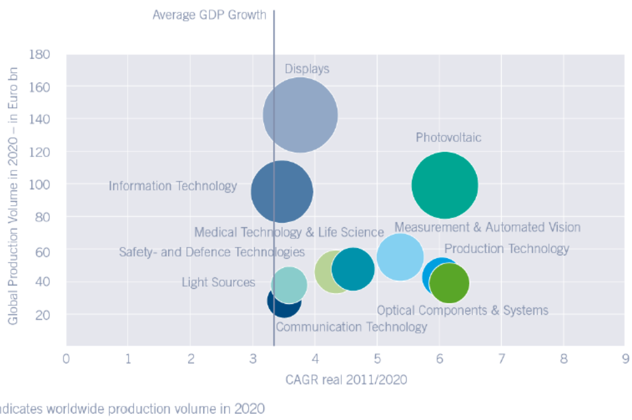



Figure 7: Expected growth rate of global photonics segments 2011-2020 compared to GDP growth.
Source: Industry Report Photonics 2013, Photonics21.

Today, in the worldwide competition, Europe has been able to stabilize a strong position with an overall total share of 20%, and as much as 40% in key sectors such as lighting. The European photonics industry employs more than 300,000 people, directly, many of these in over 5000 photonics SMEs. Photonics also has a substantial leverage effect on the European economy and workforce: 20-30% of the economy and 10% of the workforce depend on photonics, directly impacting around 30 million jobs *(source: Photonics21, EPIC)*.

As photonic components and systems are becoming smaller and smaller miniaturization integration solutions are essential and will require increased automated assembly. This leads to a reduction of the dependence on man-based assembly and opens the possibility of relocating and regrowing this industry back to Europe.

The concurrence of these factors, i.e. the need of specialized components and the possibility of engineering and producing them in a competitive manner, and the existence of the networks, culture and competences allows the opening of a window of opportunity for our industry in exploiting optics and photonics as a key pillar for a healthy economic growth. Industrial sectors that can strongly leverage and profit from such technologies include Medtech, Pharma, Automation, Energy generation, Consumer Goods, Environment and Security.

The needs for **adaptation** in particular areas such as flexible photonics as stand alone or with an interface to the traditional materials (glass or CMOS) are required. This could have an **impact on the industrial extension of a number of traditional SMEs** which could modernize their business. There is a need to demonstrate the potential of **new photonics applications** for the main current **societal challenges** (e.g. cleantech, medtech).

## Challenges

The **integration** of heterogeneous materials has to be considered as a higher level of integration (hybrid packaging of electronics and optics) and is becoming more and more important. This also means that the **design for assembly** needs to be included in the development of new devices and that a **variety of materials** (Si (CMOS), III-V semiconductors (lasers), glass,…) has to be taken care of. The **compatibility** of different design methodologies has to be ensured, e.g. for the optical design in new configurations. The trade-offs in terms of **costs, complexity and performance**, e.g. optical SiP versus optical SoC needs to be taken into account. Finally, **reliability and testing** continue to play a major role and are often a challenge given the variety of materials, processes, and devices in photonics. In general, the applications are manifold and also include image sensing, biosensing, 3D measurements of components and objects, fiber-optic sensors for harsh environment and medical applications, medical diagnostics, high-power lasers for marking, cutting and welding, and industrial process control.

There is a need to address **new fields** including biophotonics and medtech that have very high potential for innovation and breakthroughs. **Interdisciplinary** needs to be fostered to develop such innovative products. Integration of photonics in smart systems will produce high added value products. Photonics will be brought **to large area and low cost** leading to a potential paradigm shift: from the "rich-man photonics" (e.g. photonic crystals in semiconductors) to the "consumer photonics" (e.g. optical films/devices with interferential/diffractive/plasmonic effects).

**Disruptive technologies** emerge in a variety of fields. Quantum cryptography/communication technology is already entering the market. Plasmonics and new materials are appearing as an opportunity for bringing photonics to the daily-life. Technologies such as micro and nano-fluidics will provide an interface allowing photonic devices to communicate with the environment, thus opening more and more opportunities e.g. for biophotonics and medical applications. **Flexible photonic** devices, as standalone devices or interfaced with traditional CMOS or glass devices open up new routes towards cost-effective innovative photonic devices.

**Existing clusters** allow to let traditional technologies as lens making, high power lasers, or optical subassembly evolve and create a larger photonics industry based on both more traditional industrial sectors and the aforementioned disruptive technologies. Progress in **photonic integration**, less disruptive but also of great importance, is based on miniaturization, an increase of optical power output for light sources and automated assembly. For this, novel technologies dealing with heat removal, reduction of stress-induced failure during the assembly, and high-precision assembly of the different components are needed. Moreover, the technologies should be generic in such a way as to improve the current lack of standardization in many domains of photonics.

## HTA approach

As a step towards **new photonic solutions**, the Heterogeneous Technology Alliance (HTA) started to develop a **photonic sensing and integration platform**, by combining a variety of technologies available within the HTA. The HTA photonic sensing and integration platform will provide **many opportunities for the European photonics market** including i) the development of robust, reliable and low cost processes designed for devices/sensors and complete photonic systems, ii) precision robot systems for automation, and iii) manufacturing capabilities through the buildup and extension of an infrastructure for process development and pilot and small series. Key devices such as Silicon MEMS and high-brightness light sources will be combined with 3D integration technologies to allow **flexible manufacturing**.

## Technology Toolbox

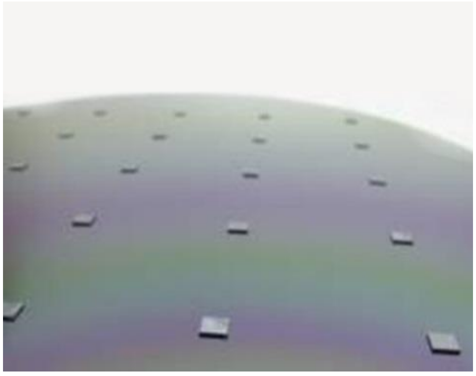


Figure 8: Lasers on 200mm silicon wafers by heterogeneous integration of III-V on silicon.

Photonics covers a broad range of applications. Related systems make use of various components suited for different wavelengths. So application oriented work is based on a technology toolbox of photonics components that can be subdivided into three classes. The following list summarizes the competence of HTA members within those fields. It focuses on applications in UV, VIS and IR and neglects developments for other wavelengths, like for example X-Ray related technologies.

## Light sources

Various types of sources have been developed and fully characterized (output power, optical farfield, modal gain, relative intensity noise (RIN), frequency response) by HTA partners including:

Inorganic light sources (NIR and UV) in a InP processing line. Applications include spectroscopic sensing, detection of hazardous substances, material processing, medical therapy and diagnostics as well as seeding and pumping of solid state lasers. Quantum Cascade Laser- (QCL) and Semiconductor Disk Lasers (SDL) based infrared laser modules in NIR (1.9 to 2.8 µm) and MIR (4 µm to 11 µm) are also available.

Compact laser sources covering the blue-to-ultraviolet spectral range (390-430 nm). CW output power with greater than 100 mW and peak powers exceeding 10 W in pulsed mode (10 ps). These lasers are used for optical spectroscopy, fluorescence based measurement techniques, fluorescence life time microscopy (FLIM) or general biophotonics.

Organic Light Emitting Diodes (OLEDs), focusing towards on large area light emitters typically for lighting and signage applications.

Tunable sources based upon MEMS monochromator for Fiber Bragg Grating (FBG) sensor in double stage configuration (from 400 nm to 800 nm or from 800 nm to 1600 nm).

High power optical sources, using new interconnection and integration technologies and adhoc material and system characterization tools to efficiently thermally manage such devices.

## Light processing

Optical components with feature sizes down to the micro- and nano-meter range are key components for systems and devices where small dimensions, compactness and light weight are demanded. In order to improve the efficiency of light sources or transform light in a predetermined way an entire toolbox of out-coupling structures has been developed. These include optical microlenses and diffractive optical elements (DOEs). Such elements are implemented in quartz glass, silica and silicon or polymer material fabricated by standard replication and step-and-repeat processes, applying large area techniques, like hot embossing or UV casting. Components include gratings (binary, multi-level, blazed gratings high frequency (down to 80 nm

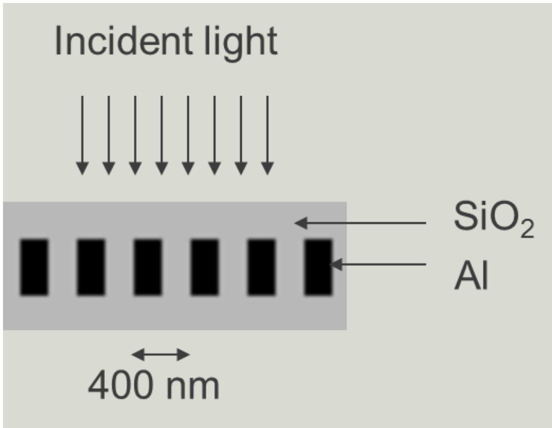


Figure 9: Nanostructured optical filters in CMOS.

line width, zero order gratings (ZOG)), lenses (refractive micro-lens arrays, on- and off-axis Fresnel zone lenses (FZLs), diffractive spherical, aspherical and cylindrical lenses, FZL arrays) and computer generated holograms (beam splitter, beam shaper, pattern generator). For modulation of optical signals especially in telecommunications InP based external modulators with a 3 dB bandwidth beyond 50 GHz based on travelling wave design have been developed as key components for metro and long haul fiber networks.

Spatial light modulators consist of arrays of micromirrors on semiconductor chips. The number of mirrors varies depending on the application, from a few hundred to several millions. In most cases this demands a highly integrated application specific electronic circuit (ASIC) as basis for the component architecture. High resolution tilting mirror arrays with up to 2.2 million individual mirrors are used as highly dynamic programmable masks for optical micro-lithography in the ultraviolet spectral range. The mirror dimensions are 10 μm or larger. Further fields of application are semiconductor inspection and measurement technology, microscopy and prospectively laser printing, marking and material processing. Piston micromirror arrays based on 240 × 200 individual mirrors (40 × 40 $\mu m^2$) can for example be used for wavefront control and correction in adaptive optical systems with applications in the fields of ophthalmology, astronomy and microscopy, as well as in spatial and temporal laser beam and pulse shaping.

Scanner mirrors, either resonantly or quasi-static operated, are the technology of choice to deflect light with extremely compact systems. To date, more than 50 different resonant scanners have been designed and manufactured. Scan frequencies from 0.1 kHz to 50 kHz have been successfully executed. Applications range from reading barcode and data code, through 3D metrology, and right up to laser projection and spectroscopy. Applications include Fourier Transform spectrometers, confocal microscopy, highly miniaturized displays, ultra-compact laser projection systems, endoscopic image acquisition as well as triangulation. Resonant scanners, quasi-static micro-scanners are also under development with applications such as laser beam positioning and switching.

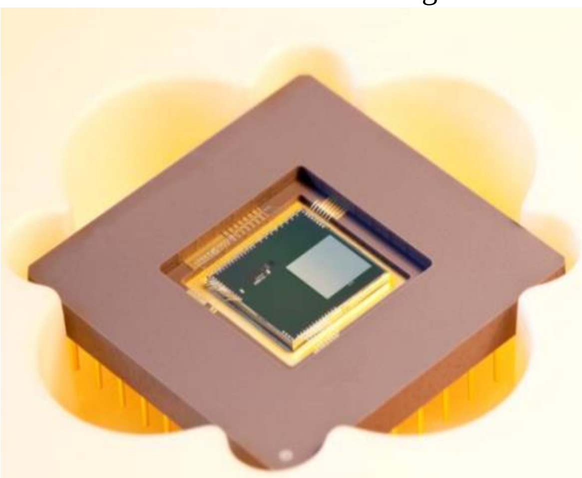


Figure 10: Micro-mirror arrays for light processing.

Thermotropic liquid crystals enable fast direct optical switching by using electro-optic Kerr effect. Electro-active organic materials are utilized for micro-lenses with an adjustable focus. Their functional principle is based on the displacement of liquids in etched silicon chambers. Applications include a zoom objective or autofocus system for a camera in a cell phone, medical and industrial imaging, optical systems for laser beam manipulation and lab-on-a-chip applications for cell manipulation and detection.

## Light detection (CMOS, wavelength range from UV to IR)

HTA members possess a long experience in CMOS photo detectors and imagers design, their processing and characterisation and CMOS post-processing (i.e. colour filters and microlenses deposition, stitching, wafer thinning, MEMS, or flipped-wafer techniques). R&D activities cover the spectra ranging from X-ray over EUV, UV, and the visible range up to near infrared. In addition, special detectors have been developed that offer more functionality than capturing a pure image. One example is a chip and camera designed to capture and measure the polarization state of light, pixel by pixel, for quality control through stress detection in transparent materials, carbon-fiber reinforced plastics or reflection suppression on non-metallic work pieces, tissue analysis for medical purposes and materials differentiation in general.

For analysis of wavelengths from the near up to the long-wave infrared (e.g. 3-5 µm and 8-12 µm), imagers, also referred to as focal plane arrays, are available. Typical features sizes of 288 x 384, 256 x 256 or 640 x 512 pixels and Noise equivalent temperature difference (NETD) of less than 10 mK. They are based on radiation-sensitive structures in silicon technology. Integrated on one chip with CMOS read-out circuits, complete imager chips have been developed. Possible applications are automotive industry (driver assistance, night vision and pedestrian detection), personal security, process monitoring, gas analysis, thermography in buildings or in medicine.

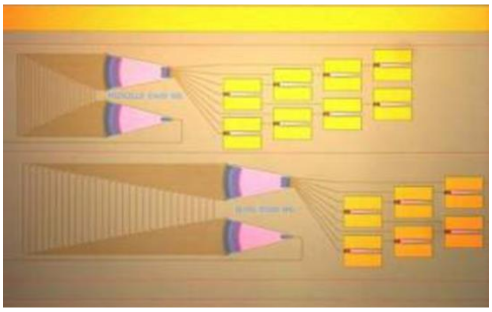


Figure 11: Ge-photodetectors on Silicon.

For application in telecommunications, high-speed photodetectors and photoreceivers on optoelectronic integrated circuits (OEICs) – typically based on InP – according to customer specifications, preferably for the 1.3 - 1.55 µm wavelength region with 1-150 GHz speed of operation are available. Other types of devices include waveguide-integrated detectors up to 150 GHz bandwidth.

## Assembly and integration

Assembly and integration covers a wide range of range of technologies. Electrical and thermal aspects have to be addressed as well as low loss optical interconnects and mechanical and hermetical housing. Electrical and thermal interconnection: Shrinking die size and increasing power result in a challenging heat flux density. Therefore heat dissipation and power delivery becomes much more critical. Beside standard processes like gluing and SAC soldering also forward looking technologies like sintering and transient liquid phase bonding are becoming important.

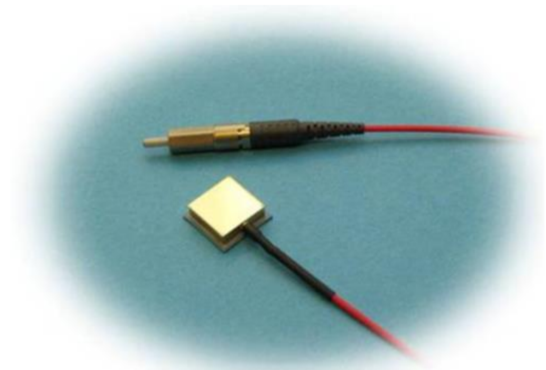


Figure 12: Fiber-optic assembly developed and tested for extreme environments.

RF, high-speed and optical interconnections: with higher bandwidth the design of high-speed signal interconnection paths without degrading signal integrity become more challenging and the demand on single mode instead of multimode solutions increases leading e.g. to an increased alignment accuracy of less than 0.3 µm. New packaging concepts consider also vertical coupling schemes.

Wafer Level Packaging has become the synonym of back-end processing of wafers with the focus on wafer bumping and redistribution with the trend towards system integration. Starting with the integration of passive elements like RLC the next step is the full 3-D integration. Using through silicon via technology CMOS - or MEMS-wafers can be used as active substrate i.e. a platform for further active functions. The reliability of modules and systems is analyzed under realistic or accelerated conditions (including temperature, humidity, shock, and vibration).

### The next layer: (sub) systems (optical sensing/diagnostics, spectrometers, atomic clocks…)

The assembly and integration technologies are used to build systems based on modules and sub-systems based on the System-in-Package (SiP) allowing functional testing and qualification.

Typical solutions have been found in the past and can be expected for future applications like:

- Large area assembly with very fine pitch and minimum distance between the chips for pixel detector modules (particle physics) and image sensor modules (from X-ray, visible to infra-red)
- Highly parallel optical interconnects for high performance computing and data communication (integration of CMOS and optical layer)
- Fully integrated transceiver modules with defined electrical, optical and thermal interfaces for high volume applications: Integration of Si photonics layer, optoelectronic components, driver and amplifier, lenses and filters on interposers and hermetical sealing
- Hermetical sealing of IR image sensor with Germanium windows, silicon cavity and activation of integrated getter material
- Intelligent, high resolution pixel LEDs for adaptive front head lamp

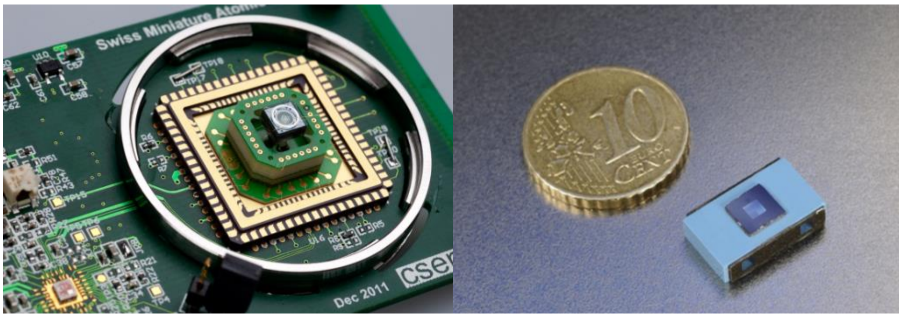



Figure 13: Left: Miniature atomic clock; right: Mini-photoacoustic gas sensor.

## HTA offer to Europe

HTA covers the full manufacturing value chain from materials and processes to devices, components and modules for photonic systems. Together with the European industry we are able to develop fully functional systems fulfilling the requirements of global customers. Therefore, the HTA is able to bring new business opportunities for European industry. In addition, it can leverage the establishment of new companies who are benefiting the photonics competences. Our strength is the capability to develop new devices, which are beneficial for applications such as process industry, optical connectivity, advanced lighting, life sciences, safety and security, and energy and environment. Our mission is to help European industry to find new business opportunities in these application fields. We can do this in collaboration between the HTA partners and their industrial collaborators.

Therefore, the HTA is targeting to reduce the dependence of European end users on critical technologies that are non-European origin and to build automated manufacturing capabilities in order to ensure that the manufacturing of photonic products such as sensors and instruments will be carried out in Europe. This can be realized due to novel integration concepts and automated manufacturing capabilities with the HTA Alliance.

# 3D advanced packaging: enabling smart systems for Europe

## Background

Our modern societies are strongly impacted by the emergence of smart electronic devices, which are expected to compute and to store more and more information, but also to sense and react to the environment and with the end-users, the human being (**Fehler! Verweisquelle konnte nicht gefunden werden.**4). Smart systems are now envisioned to bring new solutions to many current and future societal challenges, by mixing together different micro and nano-electronic technologies. This heterogeneous integration is seen as a smart way to extend Moore's law and CMOS possibilities by adding new functionalities in a same system, as illustrated in Figure 14.

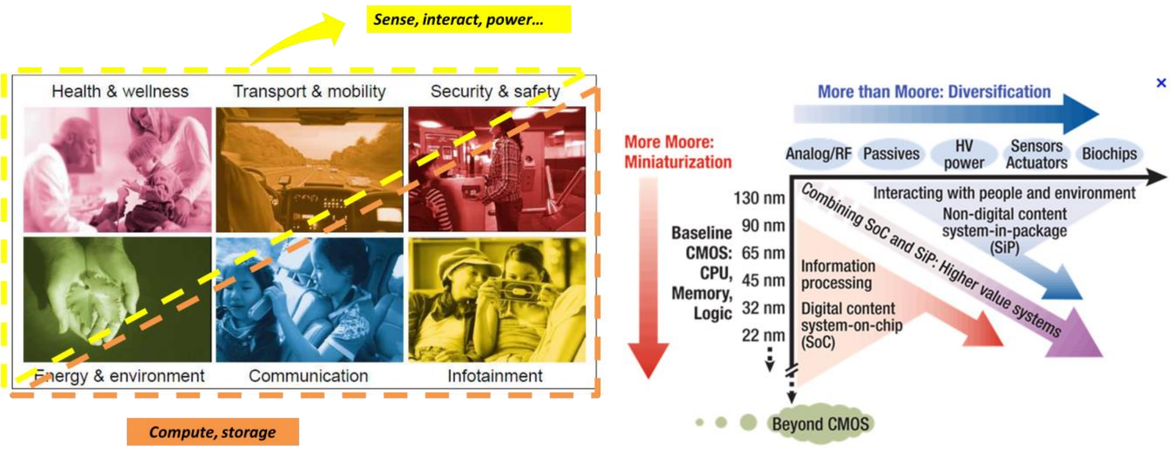



Figure 14: New societal needs (right) and More-than-Moore trend (left, from ITRS 2011).

In addition, these smart systems are expected to follow over the years major form factor and cost decrease, as well as performances improvement. Traditional packaging can no longer meet the requirements of the new advanced electronic components: conventional Printed-Circuits-Board (PCB) suffers from some strong limitations on the size and pitch of interconnects (~300-400 µm), no longer compatible with the very aggressive pitch of advanced CMOS die pads (down to 20µm). In the last 15 years, academics, technological institutes and semiconductor industry have put some effort to develop and improve new advanced electronic packaging, especially by considering the 3rd dimension. Instead of reporting individual heterogeneous components side by side on a board, it rapidly becomes very advantageous to stack the dies in 3D in one single package, as illustrated in **Fehler! Verweisquelle konnte nicht gefunden werden.**15.

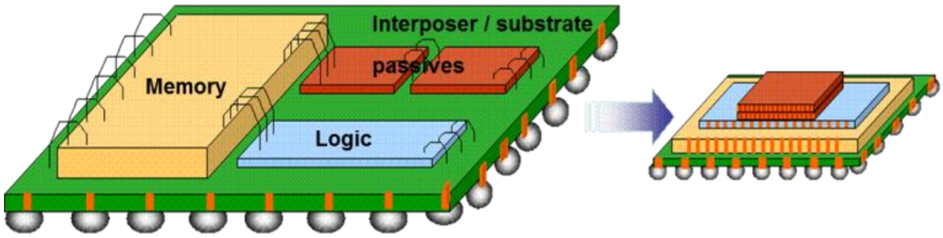



Figure 15: 3D advanced packaging principle.

Since its foundation, the Heterogeneous Technology Alliance (HTA) has clearly envisioned the new change in packaging paradigm for the new smart systems and all the associated related challenges. Mixing heterogeneous technologies in one miniaturized package cannot be straightforwardly done in the traditional packaging and assembly houses in Asia, and require some specific and cutting-edge research and developments from skilled engineers. New smart systems are seen as a great opportunity for Europe to bring back a part of the advanced electronic packaging activities, for specific and strategic markets such as medical, automotive, space or defense. The HTA alliance has been therefore fully involved in developing and promoting heterogeneous advanced packaging and 3D integration, together with several industrial partners' very complementary approaches.

## Advanced 3D packaging technology – key enabler for heterogeneous integration

Over the years, the electronic packages have evolved in more and more complex structure in order to gain both in interconnections density and number of functionalities. Initially based on organic compound (fan-out, e-WLB, embedded dies in PCB…), the packaging becomes today more and more complex. Wafer level packaging on silicon has been considered as a competing solution especially for high density, leading the 3D Integrated Components (3DIC) stacking, moving from pure back-end-of-line packaging to more and more front-end-of-line processing. The current different packages trends have been summarized in **Fehler! Verweisquelle konnte nicht gefunden werden.**16.

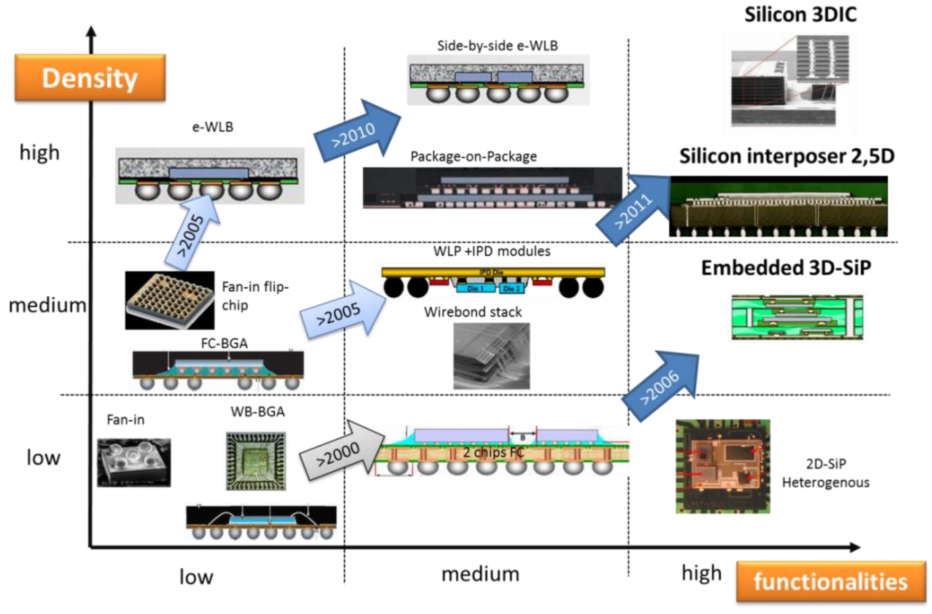



Figure 16: Illustration of advanced packaging and 3D integration for heterogeneous integration.

Beyond traditional packaging technologies (BGA package, stud bumps, wire bonding…), the members of the HTA have developed a wide wafer level3D and advanced packaging toolbox by their own basic technological research, together within collaborative programs (EU, Euripides, Catrene and ENIAC programs) or directly with key industrial partners. In particular, two large clean room facilities dedicated 3D integration and wafer level packaging have been recently set up and developed (All Silicon System Integration Dresden (ASSID) and 3D 300mm line at CEALETI). 3D integration on silicon relies on key modules such as: die-to-die and die-to-substrate interconnects, Through-Silicon-Vias (TSV), thin wafer (<50µm) handling systems and accurate, precise pick-and-place and wafer level molding. For each module, a large technology options panel is today available within the HTA to meet the requirements on the package in term on integration.

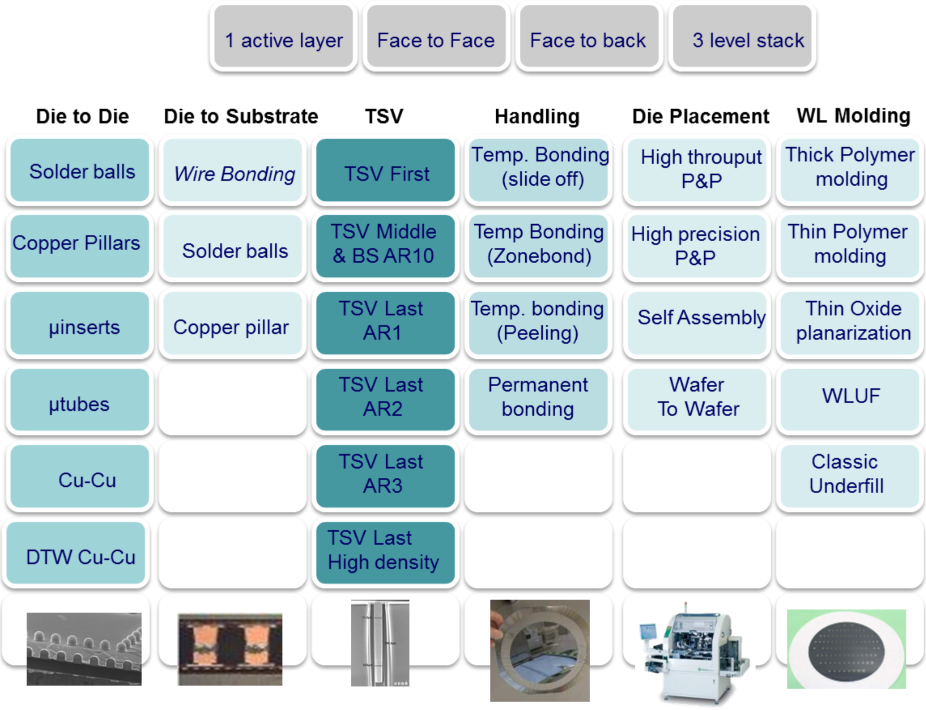
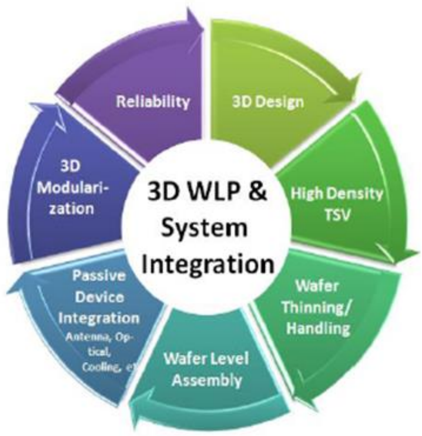



Figure 17: Examples of 3D tool box for 3D silicon integration.
Source: CEA LETI.

As an example, TSV are of primary importance in 3D integration in silicon wafer. They allow vertical and very dense connections within a silicon chip, which can be either a CMOS dies or an interposer. TSV require advanced knowledge and expertise of several process steps as described below:

- TSV Etching: DRIE
- TSV Isolation: $SiO_2$ (CVD)
- Barrier/Seed: PVD
- TSV Filling: Cu-ECD




State-of-the-art TSV (first, middle, last) with different size (from 100 µm down to 1 µm) and aspect ratio (1 to 20) are available within the HTA, enabling new type of architecture for smart systems. A wide range of interconnects solutions such as solder balls (800-250 µm), copper pillars capped with solder (50-20 µm), SLID (25-7 µm), Cu-Cu bonding (7-1 µm) and nano- interconnects (100-10 nm) are also thoroughly investigated within the HTA in order to propose the right solution for 3D flip-chip assembly.

Heterogeneous integration is made possible thank to new advanced 3D System in Package (SiP) architecture. System integration is much more than just assemble in 3D together different technologies. 3D design and test must be carefully addressed in order to optimize the package at system level. This results in complex procedures and advanced process flows as listed below and on Figure 18:

- Design - electrical, thermal, mechanical (DfT, DfM, DfR)
- TSV Formation (via first, middle, last (from BS)
- Interposer with TSV and multilayer RDL (FS/BS)
- Passive Device Integration
- Interconnect Formation (electrical, optical)
- Thin Wafer Handling
- Temporary and permanent Wafer Bonding
- Assembly & 3D Stack Formation
- Heterogeneous Device Integration (MEMS, sensor)
- Metrology, Analytic

In addition into traditional packages like BGA or PCB, HTA is currently fully involved in the hybrid integration in flexible substrates. Despites lower density interconnections, chip-on-foil bring another dimension or functionality to system design and packaging. New packaging supply chains are required as well as new business model. That is why HTA members are not only developing key technological process but are working on all the integration steps from 3D design until reliability tests in a global system approach.

## Markets and applications

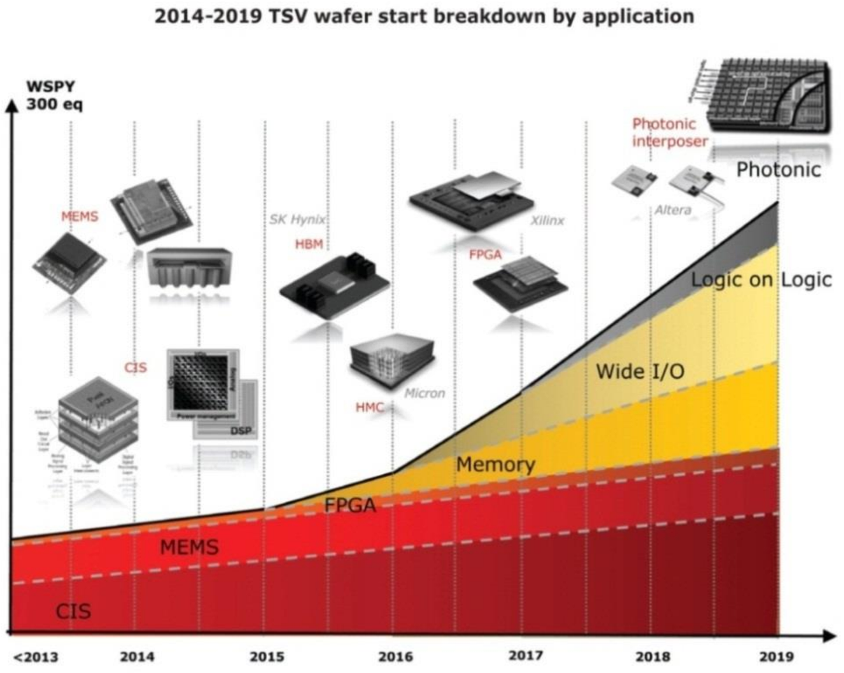



Figure 18: TSV production roadmap.
Source: Yole development 2014.

3D integration and advanced packaging are envisioned to profit many different market segments. The TSV production forecast represented in **Fehler! Verweisquelle konnte nicht**

**gefunden werden.**18 for the coming years illustrates the strong demand from the industry in different devices family.

Almost all kind of electronic components will be impacted or will profit from 3d advanced packaging in the coming years in different systems markets segments:

### High Performance Computing (HPC):

Deep sub-micron CMOS technologies face today low manufacturing yield for large multi core processor die. High density passive silicon interposers with fine pitch routing layer and TSV will enable to connect many smaller dies in one substrate, improve the performance and reducing the cost.

### CMOS imaging:

TSV fabrication originally took off with the emergence of CMOS image sensors for mobile phone (2008-2009). Today, back-side image (BSI) sensors are now moving into real 3D integration (ex: Sony BSI in iPhone 6) and involving very complex architecture and very small dimensions requiring new technologies (e.g. Cu-Cu bonding).

### Memory stacking:

Next generation of memories like wide I/O2, HBM and HMC will definitely be using 3D integration with TSV with several announcement from key plyers in the industry. Higher memory capacity and ultra large bandwidth are expected.

### Logic-on-logic:

Fine grain CMOS partitioning is seen as the next big step in CMOS integration, extending the Moore’s Law. Active interposers will enable data buffering as well as efficient power management (green IT) for both µ-servers and HPC applications. They will require very advanced 3D technology modules like 2-3µm diameter wide TSV.

### MEMS platform:

With the emergence of Internet-of-Thing (IoT), there is clear and strong demand for more integration of sensors and/or actuators inside the systems. First MEMS products recently show the 3D stacking of MEMS onto an ASIC with TSV via-middle (BOSCH Sensortec BMA355 3-axis accelerometer). Advanced and 3D integration will allow very miniaturized sensors platform, with hermetic 3D packages.

### Power, passives and RF:

3D advanced packaging is playing a major role for the ultra-miniaturization of analog, passives and RF components for kind of communication systems. It will in particular enable energy harvesting in smart systems by combining in one package all the power management components - systems-on-foil and printed electronics.

The current IoT vision forecast trillion sensors and will request low cost hybrid and flexible solution, with low to moderate number of interconnects. The packaging will have to be adapted with some overlap with 3D integration regarding the components ultra-thinning and handling. Probably, the flex itself will be smart and will embark some printed electronics.

## HTA and 3D advanced packaging in Europe

Today, HTA is actively supporting large industrial European IC and MEMS companies (like ST, Infineon, AMS, Bosch…) involved in both advance packaging and 3DIC by collaborative and bilateral programs. HTA is playing a key role in the development on improvement of the 3D technology thanks to close relationships with major European equipments' suppliers (like Suss microtec, EVG, SPTS…), within the frame of common labs or joint development programs. This allows to develop and to gain rapidly expertise on key 3D integration process steps (e.g. temporary bonding, lithography, deep-etching…), accelerating the transfer to the industry.

The HTA is also strongly involved with SME in heterogeneous integration. As an example, Advacam is a spin-off company found at early May 2012 to commercialize radiation detector technologies developed at VTT Technical Research Centre of Finland. During the first year and a half Advacam has offered silicon sensor fabrication and micro packaging services for more than 15 international customers. Since 2011, mature 3D technology modules like cu pillars and TSV last are available for SME and academics through the OPEN3D™ wafer service (Figure 19) from CEA LETI. New concepts and innovation are therefore made possible with 3D advanced packaging at industrial level.

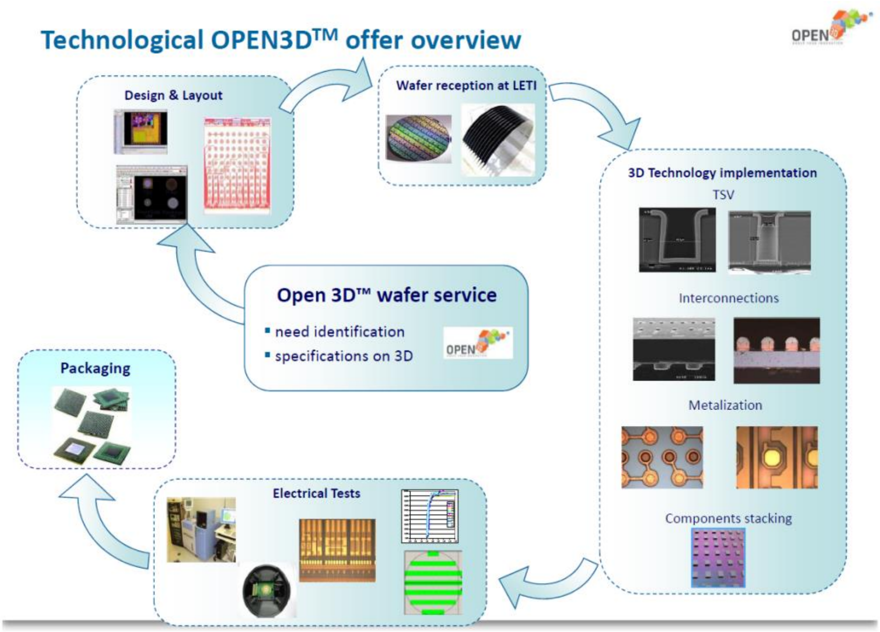



Figure 19: OPEN3DTM wafer service for 3D integration.
Source: CEA LETI.

In term of integration, the current EU-funded FP7 WiserBan (www.wiserban.eu, see **Fehler! Verweisquelle konnte nicht gefunden werden.**20) project led by CSEM, is a very good illustration of the fruitful collaboration of HTA members on 3d heterogeneous packaging up to the demonstration of smart systems. In this project, the four HTA institutes (Fraunhofer, CSEM, VTT and CEA LETI) bring their high level of expertise of System-in-Package (SiP) and 3D advanced technology to enable Wireless Body Area Networks (WBAN).

This is about improving personal sensing capabilities by using miniature, unobtrusive, long life sensors nodes. It will deliver innovative wearable and implantable 3D radio microsystems for healthcare, biomedical wellness and lifestyle. In this project, HTA supports key European industrial end-users (Sorin, Siemens, Debiotech, signal Generix) in the very strategic market of medical devices.

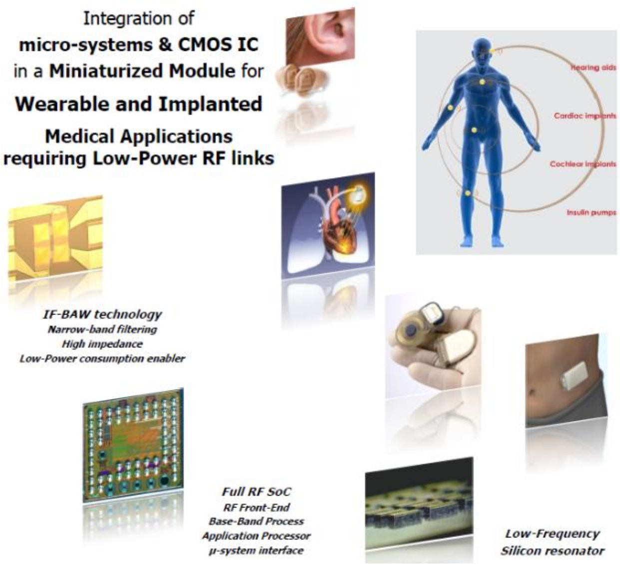



Figure 20: Overview of the Eu-FP7 WiserBAN project (from WiserBAN website) where the four institutes of HTA actively collaborates to make smarter and smaller medical systems.

At last but not least, the HTA sees some major opportunities in the field of hybrid integration for the short term needs of wearable and large area electronic applications. HTA members have been coordinating or participating together in many (15+) EU-funded collaborative projects (FP7: POLARIC, COSMIC, FLEXNET…) focused on flexible, bendable and stretchable substrates and electronic on foil. Chip integration in a thread is also investigated in for clothes applications (FP7 PASTA). These strong R&D developments are providing the key mature enabling technologies for new and promising type of industrial electronic packaging.

## Conclusions and upcoming challenges

3D advanced packaging is now present in almost every segment of the micro and nano-electronic devices. It represents a true change of paradigm for packaging, moving from a well-established packaging model, to very complex new 3D manufacturing models. Great opportunities for Europe are emerging from smart systems enabled by heterogeneous integration, but also in flexible substrates.

Many 3D technologies are available today. Some specific development challenges remains to be taken on enhanced design methods and tools, test of 3D integration, the reduction of global cost and the stabilization of supply chain in Europe for a large industrial take-off. At R&D level, next steps should focus on system integration for extreme application requirements (high Temperature, radiation resistance, moisture stability), on smart and efficient thermal management and on the link to ultimate integration in 3D of electronics and photonics. Concerning chip-on-foil packaging, improvements should be made in high temperature resistance, reliability and mechanical testing protocols.

HTA and its industrial partners are today well positioned with a very strong background to address these challenges and to develop innovation for smart systems integration within Europe.

# MEMS reliability: what is needed to make MEMS fit for space?

## Background

It is widely known that Micro Electro Mechanical Systems (MEMS) have shown high performance and reliability level in such application areas as automotive, displays, printing, biomedical and optical communications... However, in the future, it is expected that the function and performance of MEMS products will be increased and therefore, they will be used in even more applications areas due to the high ability to design and manufacture new MEMS products.

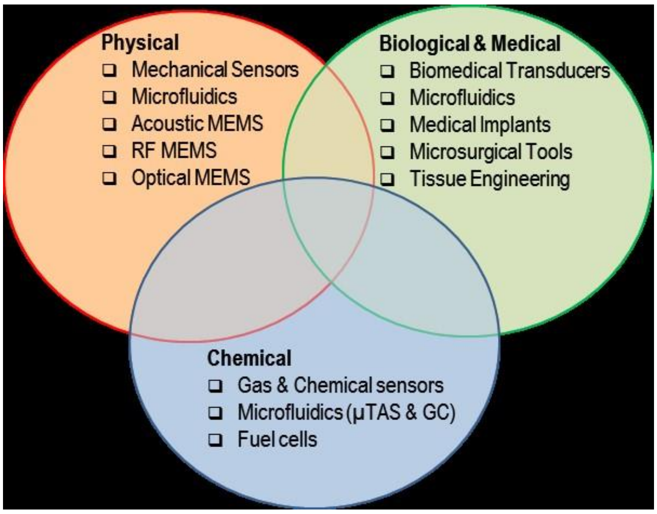



Figure 21:MEMS application.
Source Dr. Ramesh Ramadoss, Solid State Technology, 2013.

In the meantime, MEMS have a large potential in space applications like communication, navigation, Earth observation and scientific mission by:

- Fostering new types of scientific missions and instruments
- Reducing cost, size, mass and time from mission conception to launch
- Increasing performances, reliability and redundancy

In spite of the tremendous interest for MEMS technology, until now just quite a few MEMS components have been or are planned to be used in space applications. This can be explained by rather low TRL of the existing specific MEMS used for space. The key reason for this low TRL is the lack of appropriate standards for qualification of MEMS components. Therefore, MEMS reliability is one of the most key topics for integration of MEMS into space applications.

## Existing knowledge on MEMS Reliability Qualification

The increase of MEMS device performance, as well as the reduction of the volume, mass, and power has made MEMS very popular in the development of micro- and nano-spacecraft. Nevertheless, the real integration of MEMS into space applications requires deep understanding and standard qualification of MEMS reliability. Keeping this in mind, the NASA's Jet Propulsion Laboratory has made the "MEMS Reliability Assurance Guidelines for Space Applications". The aim of this review was to help the understanding of MEMS reliability and flight qualification of MEMS technologies. The main questions of failure mechanisms, device structures and packaging techniques common to MEMS are underlined in this guideline. However, several areas of failure modes and mechanisms have been defined and researched. By applying a test plan, the failure mode can be approached. This plan consists of at least a parameters overshoot (voltage, current) or environmental conditions, such as humidity, thermal cycling and thermal shocks, mechanical shock and radiation that could accelerate failures.

## MEMS Failure Modes

MEMS failure types can be divided between MEMS structural failures and package & assembly related failures. MEMS Structural Failures refer to failures of the MEMS device itself, and can be further divided into mechanical degradation, movement damage, electrical failures and material degradation. Package & assembly related failures may be divided into 3 types of failures: package integrity failures, assembly failures, and electric interconnection failures. Manufacturing failures can be also considered, however it's assumed that only fully functional MEMS devices go into a qualification process, and that manufacturing failures were detected and eliminated previously.

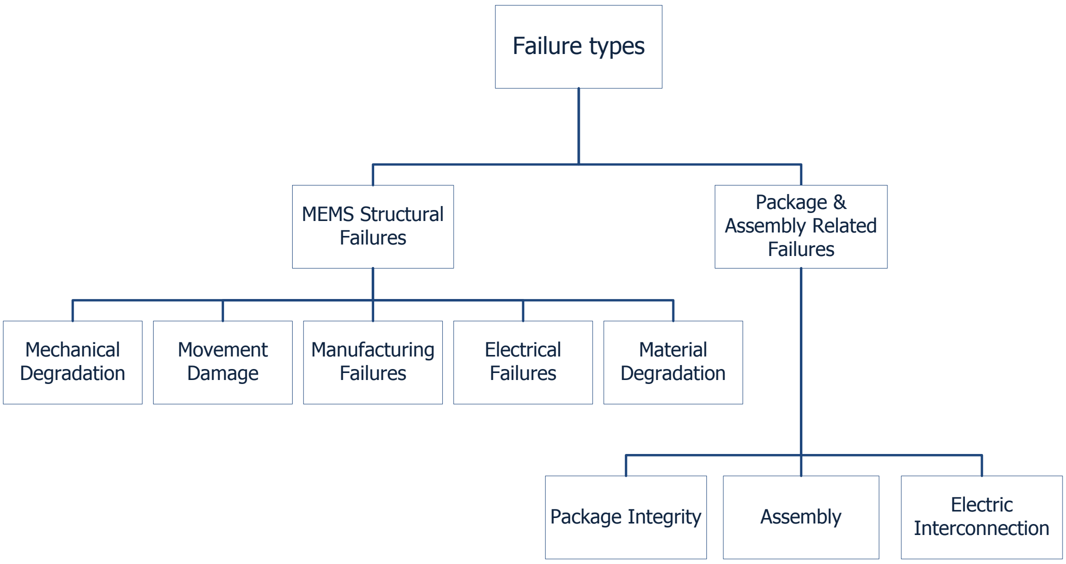



Figure 22: Failure types of MEMS devices.
Source: "MEMS-Qualification" project, 2013.

## MEMS Reliability Approach at HTA

To the best of our knowledge, there are no universal criteria that may be applicable to all existing and future MEMS devices. Currently existing standard qualifications of MEMS components for the space are not sufficient. Therefore, HTA consortium has proposed a qualification process containing a general test flow that is complemented with additional tests that are applicable depending on three different criteria: presence of hermetic package, presence of moving structure and the principle of electrical actuation/detection. Besides these three criteria also functional characteristics of the MEMS device can be used to define additional test procedures.

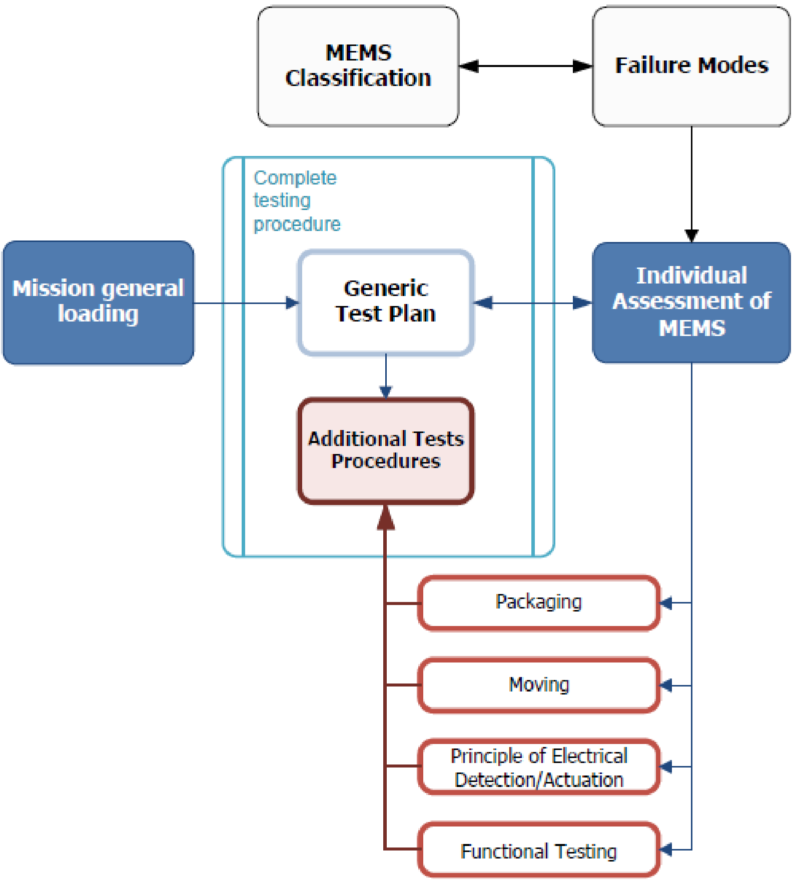



Figure 23: Schematic representation of the test plan concept showing a generic test plan and additional test procedures.
Source: “MEMS-Qualification” project, 2013.

Despite the fact that all space missions have different specifications, a general methodology to assess space qualification for all the incorporated components and subsystems on the spacecraft could be applied.

## HTA Competencies

The consortium competencies are graphically shown in the Figure 24 and the list of available equipments are summed up in the Table 2.

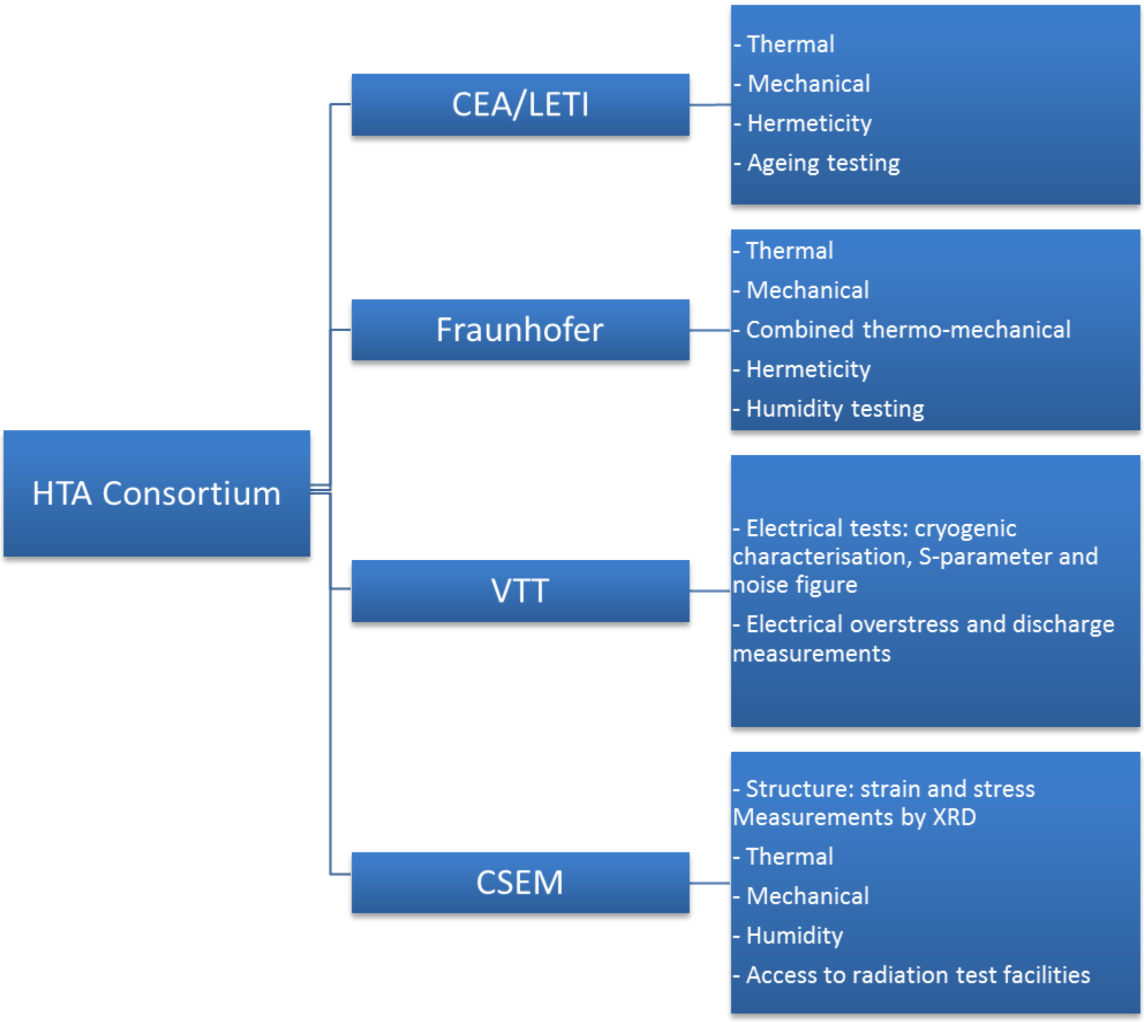



Figure 24: HTA qualification for the MEMS testing repartition.

| CEA-LETI | | CSEM | | Fraunhofer ENAS | | VTT | |
|---|---|---|---|---|---|---|---|
| **Testing equipment** | **Goal** | **Testing equipment** | **Goal** | **Testing equipment** | **Goal** | **Testing equipment** | **Goal** |
| Vacuum prober | Electrical performances<br><br>Measurement on a specific environment (T°C, pressure) | Vacuum prober | Electrical performances<br><br>Measurement on a specific environment (T°C, pressure) | Vacuum prober | Electrical performances<br><br>Measurement on a specific environment (T°C, pressure) | Vacuum prober | Electrical performances<br><br>Measurement on a specific environment (T°C, pressure) |
| Laser vibrometer | Optical measurement of the Q factor<br><br>MEMS motion behavior | X-Ray phase contrast and X-ray tomography | Non destructive inspection | X-Ray phase contrast and X-ray tomography | Non destructive inspection | Cryo chamber | Resistance ot cryo temperature |
| RGA | Composition measurement of package cavity | ESEM | Micrometer range inspection<br><br>Surface composition analysis<br><br>Specific environment analysis (T°C, pressure) | ESEM | Micrometer range inspection<br><br>Surface composition analysis<br><br>Specific environment analysis (T°C, pressure) | Optical profilometer | Inspection<br><br>Optical measurement of the Q factor<br><br>MEMS motion behavior |
| Nanoindentation | Hardness<br>Elastic modulus | TEM | Sub micrometer range inspection | Shaker | Mechanical resistance | Shaker | Mechanical resistance |
| | | HRXRD | Stress<br>Strain | Mechanical shock | Mechanical resistance | Mechanical shock | Mechanical resistance |
| Environmental chamber | Aging<br>MEMS behavior<br>on specific environment | Environ mental chamber | Aging<br>MEMS behavior<br>on specific environment | Environ mental chamber | Aging<br>MEMS behavior<br>on specific environment | Environ mental chamber | Aging<br>MEMS behavior<br>on specific environment |
| | | AFM | Surface roughness | Thermal shock | Aging | Corrosion testing chamber | Corrosion resistance evaluation |
| | | Optical profile meter | Inspection<br><br>Optical measurement of the Q factor<br><br>MEMS motion behavior | Scanning acoustic microscopy | Non destructive inspection | Scanning acoustic microscopy | Non destructive inspection |
| | | Pull test | Interface resistance evaluation | Helium leak test | Evaluation of small leak rate | Gross leak test | Evaluation of large leak rate |

Table 2: List of equipments available at each consortium member.

## Conclusion

Heterogeneous Technology Alliance (HTA) has endorsed the importance of MEMS reliability as it is an essential part of the lifetime of the smart integrated systems. One of the main tasks of the HTA consortium is focused on MEMS reliability issue as it continues to be a key point in the market-place acceptance and will help European industrial leadership bring to the market reliable systems. We believe it is necessary to carry on both: the development of MEMS reliability combined with the continuous advancement in reducing volume/mass, power and increasing in device performance.

A current focus of HTA research activities on MEMS reliability is set on cooperation with the European Space Agency (ESA):

- ESA contract No. 4000109903/13/NL/PA "MEMS Reliability Assessment".
- ESA contract No. 4000108095/12/NL/PA "Validation and experimental verification of ESA MEMS qualification methodology".
- ESA contract No. 4000107658/13/NL/PA "Wafer Level for encapsulation for Micro-Systems – PLUS".

# Integrated micro-nanotechnologies solutions for health: an opportunity for Europe

## Background

An aging population and an increasing prevalence of chronic diseases raise concerns globally about future health care costs and quality, driving the redefinition of health care systems and services in many countries. In this context, developing innovative and sustainable solutions to prevent the emergence of chronic diseases should be favored, as emphasized by the European Commission at the R&D level within its Horizon 2020 program.

New diagnostic opportunities are opened by systems biology research and 'omics' technologies. Biomarker candidates can be efficiently measured by new detection techniques providing the possibility for diagnostics of the health status already before disease onset.

However, molecular adaptation and resistance to targeted therapies are important pharmaceutical bottlenecks moderating the dream of universal targets and drug blockbusters. Prevention of diseases also faces important limitations due to the absence of validated strategies for early detection. These bottlenecks are very limiting in the field of neurology for example: brain functionality and inaccessibility impede the deciphering of disease mechanisms as well as drug therapies efficacy. Neurological diseases are a perfect example of the emergence of health technology solutions paving the way toward an alternative biomedical and industrial model, by swapping drug use to integrating active medical devices in the therapeutic process. Neurostimulation, for example, provided a major therapeutic effect in pharmacoresistant Parkinson's disease, epilepsy, psychiatric disorders and more recently Alzheimer's disease treatment by introducing microelectrodes and high frequency electrostimulation in the deep brain area. Similarly, brain-computer-interface with implanted neuroprostheses provides solutions to restore hand function in tetraplegic patients. Opposite to these invasive strategies, micro-nanotechnologies recently provided highly-efficient technologies for next-generation sequencing, opening a unique opportunity to access the individual genomic complexity with potential applications in disease prediction and prevention. Lab-on-chip miniaturization enables biomarker detection in emergency situation. New techniques in point-of-care settings will allow for more tailored treatments and more comprehensive predictions about health status. The technologies will also be used to develop preventive measuring devices for individuals based on their personal susceptibilities as dictated by the biomarkers, but also making better tools for toxicology supporting better development and understanding of drugs. Last but not least, the efficacy of pharmaceutics can be improved by using micro and nanotechnology to deliver the right portion of the drug to the exact site where it should take its effect.

Microelectromechanical systems (MEMS) were also recently introduced in efficient devices for movement tracking, defining a unique non-molecular strategy for early detection of diseases using wearable technologies. The link of these approaches to efficient and interoperative eHealth platforms will allow reaching and following patients in their natural environments.

These examples strongly emphasize the role of micro-nanotechnologies and electronics engineering to overcome important bottlenecks in the field of biotech, pharmaceutical, imaging and healthcare device industries. This prefigures the exponential emergence of a new industrial field moving electronics tools to the biomedical field.. To achieve this future vision for medicine, disruptive modifications of our current biomedical infrastructures and behavior are needed through hospital delocalization at home, disseminated in a biomedical informatics network, and coupled to prevention by using electronics tools, all of which could be integrated in the regular citizen everyday life. It also implements a new business model for medicine, using low-cost industrialized tools for a very large population. In brief, a movement from curative medicine to preventive medicine will be observed as a trend.

**We propose four axes of development** that HTA members find important to pursue, that are aligned with their core activities and that correspond to the full value chain of smart medical device development. These axes allow accelerating device development across the TRL (technology readiness level, see the Figure below) chain going from: (1) **microelectronics and component development**, to (2) **diagnostics method establishment for biomarker validation and toxicology assessment**, and relying on (3) an **integrated medical device platform organization** compatible with eventual uses linked to (4) **reliable and interoperative eHealth systems**.

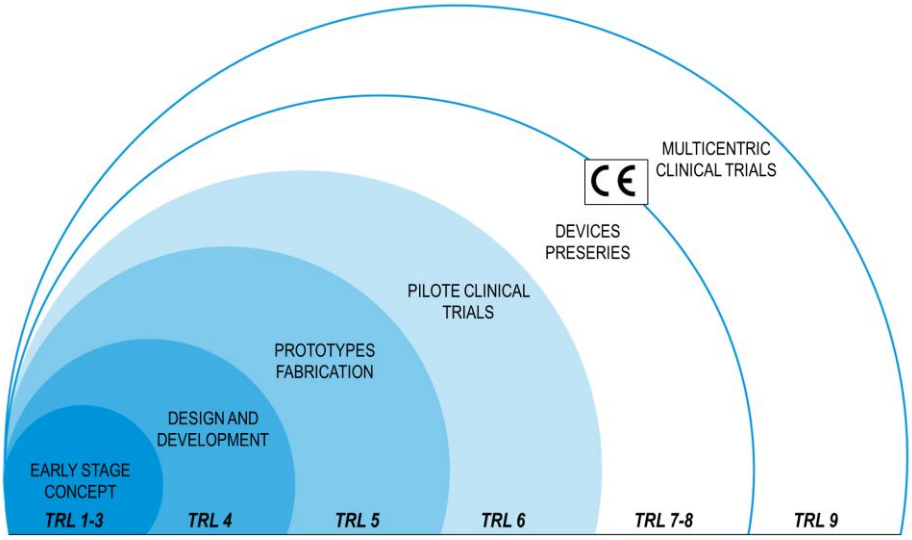



Figure 25: Medical device development technology readiness-level (TRL) scale: from clean-room to patient bedside.

## Microelectronic, micro- and nanotechnology components and the health revolution

Microelectronics and microsystems are key enablers in developing medical technologies, whether in terms of prevention, ambulatory, hospital, acute care or rehabilitation. At the intersections of these technologies, new opportunities for novel applications are often identified. These applications will further improve quality of life, and sometimes even with reduced costs, while keeping the same high level of security.

Wearable devices for lifestyle and health management are rather fashionable at the moment, boosted by the explosion of media interest around “smart” watches. These devices – initiated by Samsung, Garmin and recently also by Apple – enable the measurement of physiological parameters. At the same time, in Europe, a start-up called PulseOn, based on CSEM technologies, and has put on the market a highly reliable device for continuous measurement, focusing on multiple parameters such as pulse and blood oxygenation, measured directly at the wrist without the need for a chest belt. This success could not have been achieved without the initial market penetration of chest belts by companies such as Polar.

Today, multi-sensing smart shirts which provide measurement of full ECG (not only pulse) using smart electrodes as well as body core temperature, respiration rate and tidal volume, motion, fall and activity detection and classification are capturing market shares. Related developments e.g. at FhG-IIS additionally aim at full flexibility and washability of integrated ultra-low-power electronics with inductive loading of integrated batteries. The application of smart electrodes can involve between two and twenty or thirty miniaturized electrodes providing even more detailed information; for example, non-obtrusive blood pressure and the imaging of organs such as heart and lungs using electro impedance. In the first stages of this endeavor, CSEM’s spin-off Swisstom created a wearable system comprising multiple antennas on the chest to monitor and image patients’ lungs in acute care units. EMG measuring shirts benefitting from active electronics and wireless transmission have been demonstrated as well and recently, even EEG measuring in a wearable setting was shown to complement the measurement of the major neurophysiological signals which can be captured non-invasively. In the near future, this kind of technology will be used for the everyday monitoring of patients and sports people. Measuring physical parameters with wearable smart systems can also be an important factor in monitoring psychiatric conditions, such as bipolar schizophrenia and the monitoring of eating disorders and obesity in adolescents, augmenting traditional diagnostic routines. Wearable systems will in short continue to go beyond monitoring of physiological and physical parameters and include monitoring chemical and biochemical parameters as well as offering some therapeutic capabilities like applying vasopressure or delivering dermal drugs.

Implantable smart systems are an important complement to wearables in human care. Pacemakers were the first such devices. Deep Brain Stimulators (DBS), cochlear implants, stomach sphincters and insulin pumps are already well-established in the markets and are now leveraging microtechnologies. For example, the FhG-IMS develops active implants that measure vital parameters such as blood, intraocular and intercranial pressure. These implants have at their core a surface-micromachined pressure sensor that operates without battery – data communication and power transfer are achieved via an electromagnetic transponder technology. For Hydrocephalus patients, such a permanent implant to pressure intercranial pressure has recently been medically approved and is already on the market (commercialized by Miethke/Aesculap). Future development will include multi-parameter sensors measuring a variety of vital functions, and combining them with actuators (e.g. a shunt valve to release brain pressure). Such a combination has the potential to become a disruptive medical technology, combining diagnosis and therapy – so-called theranostic implants. Other developments aim at parallel measurement of neural activity and nerve stimulation to improve e.g. hand prostheses capabilities.

With smart miniaturized systems, the next level is now within reach: for example, using 100 implanted electrodes to read the brain, thus helping handicapped people. This has already been achieved experimentally. Ramping up from 100 to 1000 implants is the new challenge, where miniaturization, microelectronics and adapted biomedical packaging are absolutely essential. More exciting, beyond the "reading" function, is the "actuating", which – as an extension of DBS – can help paraplegic patients first to communicate with, and then perhaps to actuate, some of their paralyzed limbs. Tens, if not hundreds, of miniaturized sensors and actuators with wireless or contactless energy and information transmission will require large-scale use of microelectronics devices, implantable in the brain. Similarly, devices such as retinal implants or innovative hearing implants enable the leveraging of knowledge accumulated over decades on microelectronics and microtechnologies, for the benefit of our visually- or hearing-impaired fellow citizens. Aside from electrical stimuli, recent developments in optical stimulation of sensitive cell functions will open completely new, unprecedented fields of therapeutic applications.

## Diagnostics platform technologies / Point-of-care diagnostics tools

Decentralization in healthcare is a major trend increasing the need for point-of-care (PoC) testing providing more rapid test results, leading to improved patient care process. Due to increased health care costs, pressure in all market segments is to control the pricing. For PoC testing this means easy-to-use, low-cost disposable consumables and instrumentation. The current PoC technology development leans towards multiplexed simultaneous analysis of many different markers in miniaturized test cartridges with integrated reader solutions and IT data handling, storage, analysis and feedback guidance. PoC testing represents one of the fastest-growing segments of the in vitro diagnostic (IVD) market. New technical solutions in microfluidics, lab-on-a-chip methodologies, miniaturization of testing methods and improvements in detection technologies mark important development lines.

Consistently, approaches such as antibody engineering are providing excellent tools for the design of recombinant antibodies with higher affinity, specificity, sensitivity, labelling efficiency and oriented immobilization properties. These antibodies are important for the development of sensor platforms for PoC diagnostic applications that require high binding capacity of sensing surfaces, and sensitive analyte detection. Bioanalytics approaches often utilize recombinant antibodies for diagnostics, therapeutics as well for food safety and environmental applications.

Not only for diagnostic applications but also for applications such as drug development, or food and water quality monitoring, reliable handling and pre-treatment of samples and reagents is a key requirement. Samples need to be dosed for quantitative analysis and pre-treated for conditioning the species of interest for analysis. Specifically, the trend towards smaller volumes (faster results, less sample and reagents consumed) and highly integrated sample pre-treatment (more reproducible, less prone to mistakes) calls for new approaches to accommodate precise dosing of liquids, the integration of elements for filtration or concentration of analytes as well as process monitoring using integrated sensors. Thus, on-line verification during system operation and at every process step will be possible, pushing the state of art towards new technologies for integration of sensors or actuators very close to the point of action.

Microtechnologies and microfabrication have enabled the manufacturing of microfluidics devices that can finely control fluids in both time and space parameters. This precision is now sufficient to start mimicking biological functions, in order to create more authentic in vitro models that are closer to its in vivo counterpart and more accurate than traditional models. This development contributes to cancer research and toxicological studies, where animal-based models have shown limitations when compared to human studies. Microtechnology is therefore ready to assist the development of artificial organs, replacing more and more animal models, demonstrated already for skin, liver and cartilage. Furthermore, fluidic control enables the precise production of biocompatible tools such as microbeads for cell culture in bioreactors. This versatile method can be adjusted to handle various polymers and to address a variety of needs, from cell culture to sample preparation to sensors. Besides having the possibility to mimic some biological functions, there is an increasing need to monitor biological parameters on different scales.

Novel “lab on a chip” solutions can be applied using roll-to-roll hot-embossed polymer based microfluidics for life sciences applications, mainly for low cost point-of-care diagnostics. With pilot roll-to-roll (R2R) printing facilities and proven technological competencies, the use of this technology is brought to an industrially applicable level. A key asset in these approaches is to rely on a strong prototyping capability: for example in the VTT development chain the same foil materials and embossing tools can be used both for prototyping of a device concept and for mass manufacturing of the desired end product. In the same context, R2R integration of sensors and monitoring components can be performed without breaking the process flow, as demonstrated by FhG.

## Toxicology tools

The potential of micro- and nanotechnologies, as well as microelectronics, is obvious for Medtech; for the patient, the physician and in hospitals. However, these technologies can also bring enormous value to other life science domains, such as in the toxicological testing of chemicals and cosmetics, and efficacy tests in the development of new pharmaceuticals. In living tissue (in vivo), cells exist in 3D microenvironments with intricate cell–cell and cell–matrix interactions and complex transport dynamics for nutrients and cells. These microenvironments are key in determining cellular responses. Cells cultured in vitro – for example, in plastic petri dishes and multiwell plates – and lacking the appropriate microenvironment, differ in their responses to toxins and drugs, and sometimes significantly in their responses in vivo.

If cell cultures are to be used to speed up and reduce the costs of drug development and toxicity testing, a major challenge must be addressed: to replicate the in vivo cellular function and intercellular interactions. Therefore, the focus is on developing more authentic physiologically-relevant microenvironments (including the development of co-culture systems, structured surfaces, connected cultures, mechanical stimulation for bone and muscle cells, and cell culture supports In addition, there is a great need for new analytical tools in toxicology, to study the function of living cells and to understand how their function is affected by toxins. This gives more precise information than traditional toxicology, which studies only cell death and cell stress in the body. Moreover, tools are needed to monitor cell growth in the many novel 3D cell-culture formats now available. These new tools include miniature/integrated microscopes, tools for the rapid measurement of cell mechanical properties, electrical (TEER) systems, optical sensing layers, integrated sensing of local parameters such as oxygen partial pressure and concentrations of important ions such as calcium. Some of the newly-developed tools, instruments and surface technologies are already facilitating the pre-clinical research and clinical diagnostics.

## Medical device platforms

The development of comprehensive and potentially disseminated medical device development platforms is a must to facilitate the connection between technology development and clinical use. An early anticipation of translation at the bedside of innovative technologies, and early compliance to industrial norms and regulatory constraints are key to successfully bring medical device development beyond TRL 5, which is currently an observed bottleneck in Europe.

To address European and national medical device regulation requirements, adequate measures are required throughout the whole development, prototyping and production process. The development of early phase trial-pilot studies in the Medtech field should be a priority as adopted by Pharma with phase 0 pharmaceutical trials, by developing a multimodal investigation of the tested technology looking at both impact and side effects. Multimodal investigation is in our opinion the key conceptual strategy providing an opportunity to deliver strong “go/no go” checkpoints with only a small number of patients. This approach takes advantage of data fusion coming from clinical, multimodal imaging, molecular and electrophysiological investigations along with an integrated patient data mining. Similarly, individualized medicine will benefit from such approaches, leveraging modern clinical informatics tools, mapping of patient background information and precise diagnostics to match the therapy exactly to the patient’s needs.

Such an approach, developed for example at the translational platform CLINATEC involves an early-phase trial methodology using an integrated multimodal methodology associating clinical evaluation, multimodal imaging, computerized medicine, electrophysiology and molecular investigation in small cohort of patients or healthy subjects. The objective is to demonstrate safety and robustness with a small number of patients, using this cognitive multimodal approach. Such an approach provides a valid basis for CE-mark delivery, permitting dissemination with a technology whose biocompatibility, clinical operability and robustness have been positively assessed. The cost of this strategy is low compared to the failure of the large dissemination of devices following a non-relevant development that neglects applying strict biomedical methodologies.

To ensure a time- and cost-effective process, several steps are suggested that take patient needs and regulatory constraints into account very early in the development. This process should ensure:

1. Coupling between innovation and clinical operability by:

- Analyzing clinical and industrial needs, and designing the clinical trials.
- Submitting the clinical research protocol files to national agencies, as well as to patient protection committees through a dedicated clinical research team.
- Working in close relationship with the participating clinical research units.

2. Interfacing with a medical prototyping unit, ensuring that the medical device conception is realized in line with regulatory requirements, and follows the necessary steps for medical device release. Operating under the ISO13485 norm now offers guarantees for eventual industrial clients, and will become a must for research technology organizations interested in medical device full development.

Such organization is being deployed at LETI and is based on a distributed platform to benefit from all the technological bricks available onsite. For example, LETI’s Brain-Computer Interface program was conducted within this framework at CLINATEC that developed the first integrated electrocorticography implant for brain-computer interfaces (the WIMAGINE implant) designed for chronic uses. The system will be clinically tested with tetraplegic patients using a dedicated exoskeleton as actuator. At FhG, the EN ISO 13485-certified ‘Medical Technology Test And Demonstration Center’ METEAN provides related services particularly for SMEs including certification, market introduction and training support services.

Importantly, EC-supported initiatives with HTA members as central research partners to establish pilot fabrication lines targeting the medical device market are underlining the necessity to support innovative SME´s in their activities. Upcoming medical device development will benefit from this trained environment, and disseminate throughout HTA.

## eHealth and systems medicine

The technological approaches outlined are embedded in the ongoing global change of health system paradigms marked by terms like eHealth, m(obile)Health and p(ersonal)Health. Virtually unlimited communication capabilities and health-related information are becoming ubiquitously available using the Internet, wireless networks, personal computers and mobile devices – not only supporting health professionals, but noticeably fostering patient empowerment. The European eHealth Action Plan 2012-2020 defines eHealth as "the use of ICT in health products, services and processes combined with organizational change in healthcare systems and new skills, in order to improve health of citizens, efficiency and productivity in healthcare delivery, and the economic and social value of health. eHealth covers the interaction between patients and health-service providers, institution-to-institution transmission of data, or peer-to-peer communication between patients and/or health professionals." Utilizing this consumer technology in combination with miniaturized sensors enabled continuous telemonitoring of individual health-related parameters such as ECG, blood oxygen saturation, blood pressure, blood glucose level, pulse, weight, activity etc. Accordingly, eHealth platforms have not only to provide interoperability among professional stakeholders, but also to include patients in their home and mobile environments, enabling close-loop control of therapeutic efficacy and improving the overall outcome.

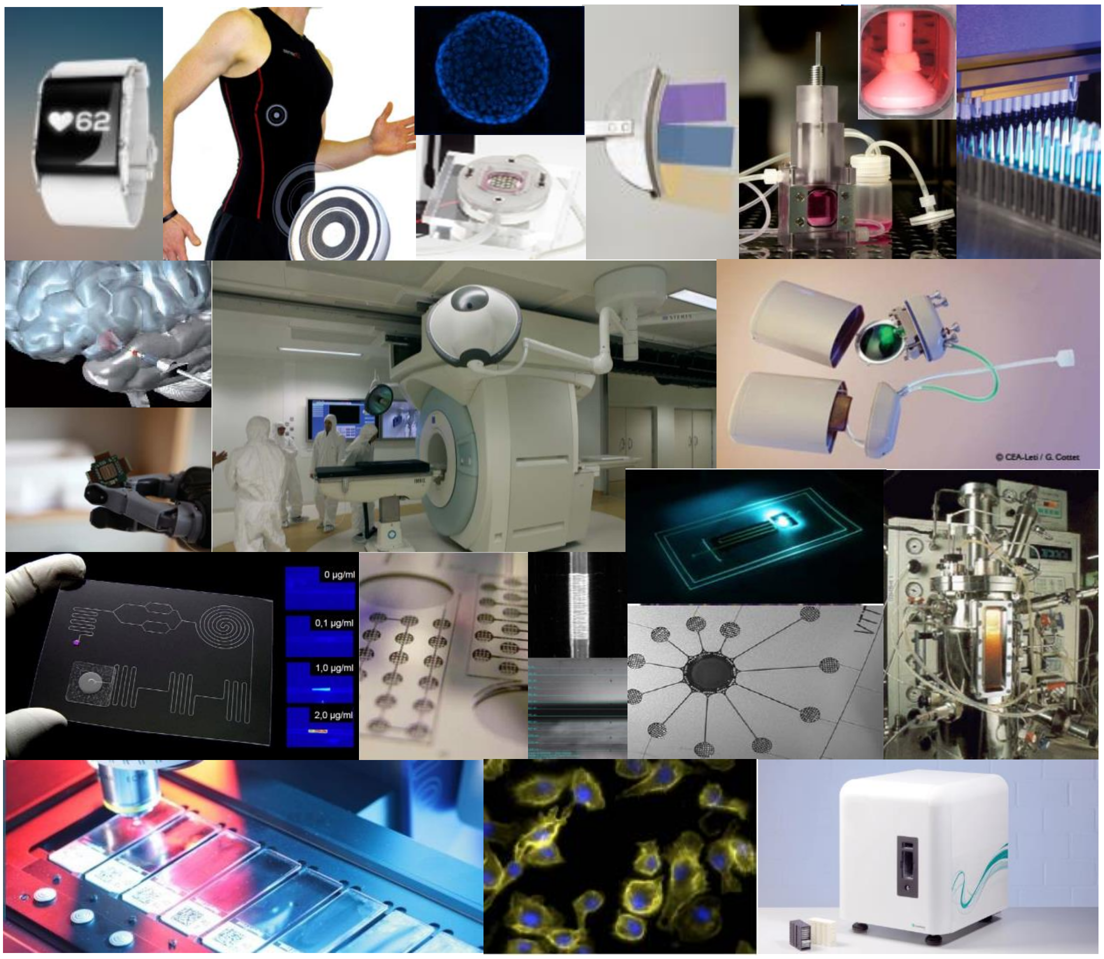
Digital health applications thus utilize the transformational power of ICT to address health challenges by aiming at a new care model: people as co-producers of health. In this context, R&D teams develop connected health contents providing solutions for the collection, interpretation and communication of personal health data. Digital health entails domain knowledge in areas such as wearable technology, sensor technologies, diagnostics, communications and printed electronics. A current line of research is the automatic assessment of physical activity using wearable sensor data, by exploiting dedicated softwares and algorithms based on several scientific studies, practical methods as well as large, realistic and annotated data libraries. Wellness index as a tool for holistic measure of personal wellbeing is another research example. Wellness index can be used for identifying individual and group-level factors contributing to suboptimal wellness state, enabling feedback to individuals and organizations.

The integration of systems medicine core competences within an eHealth approach will benefit patients, including the elderly. For example, VTT systems medicine team is utilizing effective methods for medical image-analysis: image segmentation, registration, morphometry, atrophy measurements, and statistical modeling of image data. The team has for example developed a computer-aided decision support tool for early detection of complex diseases like Alzheimer's disease enabeling an efficient, reliable and objective diagnosis of the disease at an early stage. Combining HTA expertise on multimodal mapping of images resulting from various sources and clinical expertise matching the findings with classification criteria, complements the holistic concept of the medical intitiative driven by HTA.

The patient or individual is an important part of the equation, the other being the therapeutic part, which includes the hospital, the medical doctor and the equipment. Here, smart systems can be used in a myriad of key components of the system and benefit medical practice. An important aspect for ensuring clinical utility of eHealth, mHealth, and pHealth solutions will be their systematic scientific and clinical validation similar to any other medical device validation scheme, and consistent with FDA position regarding prescription-modifying mHealth applications. Such a rigorous approach will ultimately benefit patients by providing a normative framework which is still under construction in Europe.

## Conclusion

The medical and industrial perspectives of micro-nano-technologies approaches in health R&D are a unique opportunity to solve key bottlenecks in the pharmaceutical, biotechnology and imaging industry. These industrial sectors will have to communicate and interact strongly in order to define new combined strategies for the benefit of both patients and industry. Societal acceptance and ethical issues will have to be rigorously explored to ensure a wide adoption of novel medical technology solutions. The Heterogeneous Technology Alliance HTA and its starting Health Platform will be a portal for SMEs, as well as Medtech and pharmaceutical groups interested in developing micro-nanotechnologies and medical devices in health to secure a durable European industrial leadership in this domain.



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