Executive summary

The ITRS roadmap is very successful in setting technological challenges and in driving the progress in the digital technologies supporting the microelectronics industry. It helps providing guidance to the research community and to the associated funding agencies worldwide. It synchronizes the technology development and the timely availability of manufacturing tools and methods. And more generally speaking it increases the resource efficiency through focus and it fuels the growth of the microelectronic market in giving confidence in the capability of the microelectronic community to fulfill “Moore’s Law” for the decade to come.

“More-than-Moore” (or MtM) is the other facet of the microelectronic products complementing the digital part of the integrated systems. More specifically the “More-than-Moore” approach allows for the non-digital functionalities of a product – which do not necessarily scale according to “Moore's Law”, but provide additional value in different ways – to migrate from the system board-level into the package (SiP) or onto the chip (SoC). This report issued by a Working Group of the CATRENE Scientific Committee is aimed to stimulate a broad roadmapping effort in the “More-than-Moore” domain as successfully as it is done in the ITRS for its digital counterpart.

In a first chapter, following the ITRS White Paper on “More-than-Moore” in which the Working Group participated, we try to understand why the ITRS was so successful in the digital domain. Through this analysis we are able to outline what are the prerequisites for a potentially successful technology roadmap and what are the specificities of the “More-than-Moore” domain. The resulting methodology stresses the importance of defining generic functionalities needed by many “More-than-Moore” applications as well as of the underlying devices and technologies which are able to fulfill such functions.

The rest of the document selects few applications and devices which outline the potential and issues of such a methodology.

The selected application domains – energy, automotive, healthcare, security and safety – require advanced “More-than-Moore” functionalities. Further segmentation is needed to identify generic functions prone to roadmapping: this was partially achieved in this report along with the identification of some underlying technologies which are central to these applications.

In a second part of this report a tentative taxonomy of potential MtM devices is first established. Then specific MtM devices are selected owing to their perceived potential for technological roadmapping, namely integrated power devices, lighting, image sensors, biochips and MEMS. Finally we consider some emerging research devices having a potential for future use in the “More-than-Moore” domain.

Some general conclusions can be drawn from this report:

1. There will not be a single roadmap of the “More-than-Moore” domain, but many dedicated roadmaps for those applications or technologies which fits the prerequisites (as defined by the ITRS White Paper) for a successful roadmapping effort.

2. The identification of generic / basic “More-than-Moore” functionalities and of the applications which will drive the progress of these functionalities is a central part of any “More-than-Moore” roadmap. It requires a huge effort to reach meaningful conclusions which could be only partially achieved owing to the limited resources of the Working Group.
More specific conclusions and recommendations can be drawn for each selected application domain and “More-than-Moore” devices and technologies:

3. The **automotive** sector is driven by safety, energy efficiency and/or impact on the environment, which translate into the need of better transducers and integrated power. It is suggested to focus on the requirements of the **electrical car** which will be addressed by the newly launched European project ICT4FEV. Further activity in this domain could also be pursued within the EPoSS frame.

4. **Energy** as such is a too broad field but few associated device roadmaps are meaningful:
   a. The field of **integrated power** is clearly worth further investigation, more specifically in the medium power domain. This activity will take place within the CATRENE Scientific Committee, through the roadmapping activity of the ECPE organization and/or within the EPoSS frame.
   b. In **lighting** some international and European roadmaps exist for devices. A system-level roadmap could benefit from the update of the section of the ENIAC Strategic Research Agenda dedicated to lighting.

5. A MtM roadmap on **healthcare** should focus on diagnostics rather than therapeutics. However owing to the breadth and diversity of this field it is suggested to postpone a major roadmapping effort covering the entirety of this application domain. On the other hand focused roadmapping effort can be envisaged in fields like **wearable healthcare** or **biosensors** (focusing on molecular / cellular diagnostics and **in-vivo** devices).

6. Some devices and technologies are driven by the **security and safety** application domain, especially infrared image sensors, THz spectroscopy and imaging, and secure hardware. Further work in this direction is recommended.

7. The field of **image sensors** – in the visible range – is very competitive and it is thus unlikely that a roadmap in that domain will emerge. In any case the ITRS frame is best suited to address this field.

8. **MEMS** is a very limited market and a fragmented field which addresses many critical applications, but without showing clear common long-term trends and drivers. As an international effort was started within iNEMI and will be also pursued from 2011 in the ITRS: it is suggested that Europe play a significant role in these international initiatives.

9. The **analog front end** is one of the main building blocks that any transducer system shares and which would be worthy addressing as a stand-alone section. This could take place within the ITRS frame, e.g., in its “**System Drivers**” chapter.

10. The long-term opportunities of **emerging research devices** in the “**More-than-Moore**” domain are mostly in the fields of photonics, energy and (bio)chemical sensors. From 2011 on, the ITRS will add a section on “**More-than-Moore**” initially focused on wireless applications and it is suggested joining this international effort.
Table of content

Executive summary ................................................................................................. 2
Acknowledgements .................................................................................................... 6
Disclaimer ................................................................................................................ 6
Copyright .................................................................................................................. 6
1. Introduction .......................................................................................................... 7
2. Methodology ........................................................................................................ 9
   2.1. Introduction ...................................................................................................... 9
   2.2. Preconditions for an industry-wide technical roadmap ................................... 15
   2.3. Lessons learned from “More Moore” ............................................................ 16
       2.3.1. Meeting the preconditions for industry-wide roadmapping ................. 16
       2.3.2. Combining focus and variety ................................................................. 17
   2.4. Proposed methodology for “More-than-Moore” ........................................... 18
   2.5. Applying the proposed methodology .......................................................... 19
       2.5.1. From societal needs to markets .............................................................. 19
       2.5.2. From markets and needs to functions .................................................. 22
       2.5.3. MtM devices ......................................................................................... 24
       2.5.4. MtM technologies .............................................................................. 26
       2.5.5. Existing roadmaps .............................................................................. 26
       2.5.6. Assessing selected MtM devices and technologies with respect to roadmapping ................................................................. 26
   2.6. Conclusion ..................................................................................................... 27
3. Application domains ........................................................................................... 28
   3.1. Automotive .................................................................................................... 28
       3.1.1. Scope & taxonomy ................................................................................ 28
       3.1.2. Eligible technologies for roadmapping .................................................. 30
       3.1.3. Available roadmaps ............................................................................. 30
       3.1.4. Technical Challenges .......................................................................... 35
       3.1.5. Conclusions ......................................................................................... 36
   3.2. Wearable Healthcare ..................................................................................... 37
       3.2.1. Scope and Taxonomy ............................................................................ 37
       3.2.2. Eligibility for Technology Roadmapping ............................................. 41
       3.2.3. Existing Roadmaps ............................................................................. 46
       3.2.4. Technical Challenges .......................................................................... 52
       3.2.5. Potential Solutions ............................................................................... 54
       3.2.6. Conclusions ......................................................................................... 55
   3.3. Safety & security .......................................................................................... 56
       3.3.1. Scope & taxonomy .............................................................................. 57
       3.3.2. Existing roadmaps .............................................................................. 61
       3.3.3. Why it is eligible for technology roadmapping? ................................... 62
       3.3.4. Technical challenges and potential solutions ....................................... 63
       3.3.5. Conclusions ......................................................................................... 64
4. Devices ................................................................................................................ 65
   4.1. Taxonomy of “More-than-Moore” devices ...................................................... 65
       4.1.1. Transducers .......................................................................................... 65
       4.1.2. Power devices ....................................................................................... 66
   4.2. Integrated Power ............................................................................................ 67
       4.2.1. Scope & taxonomy ............................................................................... 67
       4.2.2. Why it is eligible for technology roadmapping? ................................... 68
Acknowledgements

We would like to thank:

- the members of the Working Group on More-than-Moore roadmap (Wolfgang Arden, Michel Brillouët, Patrick Cogez, Mart Graef, Bert Huizing, Reinhard Mahnkopf, Jose Millan, Joachim Pelka, André Rouzaud, Anton Sauer, Marco Tartagni, Chris Van Hoof) for their dedication to this MtM roadmap challenge in spite of their limited available time for this task

- the persons who supported this effort (Michel Burle, Adrian Ionescu, Werner Mohr, Peter van Staa) and provided useful guidance to this work

- the participants to the topical meetings and to the concluding workshop this Working Group organized

- and many other contributors, who brought very valuable inputs to this work

Disclaimer

The information in the current document is provided "as is" and does not contain any guarantee, either express or implied, and this in the broadest sense possible. The opinions expressed do not bind in any way either the CATRENE organization and its representatives or the respective employers of the CATRENE Scientific Committee members and of its Working Group members.

Copyright

The entire content of this publication and the publication itself are protected by copyright. All rights reserved. No part of this publication may be reproduced, stored in a retrieval system or transmitted in any form or by any means – electronic, mechanical, photocopying, recording or otherwise – without the prior permission of the CATRENE Scientific Committee.

Contact person: Michel Brillouët (tel.: +33 4 38 78 43 02).
Towards a “More-than-Moore” roadmap

1. Introduction

The term “More-than-Moore” (MtM in short) was invented by Europe in the early 2000’s to stress the fact that the value of a packaged system doesn’t rely only on the performance of the CMOS technology for the digital information processing, but also on diversified technologies which doesn’t necessarily perform better through a dimensional scaling.

The very nature of this domain which is defined as diversified and complementary to the digital domain makes it difficult to characterize by few headlines – like a switch or a memory cell – or to define trends comparable to the ubiquitous “Moore’s Law” of the logic technologies. However as stressed in the mid-00’s¹ “the world of “More-than-Moore” can only become as successful as Si [digital] microelectronics if we also succeed in defining shared roadmaps with modular and platform solutions, common modeling, simulation, and design tools, and shared testing strategies”.

While the need for roadmaps is there, few attempts of covering this MtM field were really successful. Many documents tried to describe potential evolutions of present and emerging markets rather than sketching technical trends of the underlying technologies. The CATRENE Scientific Committee started a Working Group on a “More-than-Moore” roadmap in 2009. This report and the associated work within the ITRS context aimed to propose actions for a more successful roadmap of some of the MtM technology fields.

In a first chapter we tried to understand why the ITRS was so successful in the digital domain. Through this analysis we were able to outline the main beneficiaries of such a roadmapping effort and – more important – what are the prerequisites for a potentially successful technology roadmap and what are the specificities of the MtM domain. The resulting methodology stresses the importance of defining generic functionalities needed by many MtM applications as well as of the underlying devices and technologies which are able to fulfill such functions. This work was done by the European representatives in the ITRS, discussed within the CATRENE Working Group and led to an ITRS White Paper which was made public in December 2010.

The rest of the document selects few applications and devices which will outline the potential and issues of such a methodology.

The selected application domains are at the core of many strategic papers in microelectronics. Automotive, healthcare, security and safety are societal needs which are put high in the European political agenda and require advanced MtM functionalities. However it was clear from the beginning that such fields were way too broad to lead to the identification of generic functions which would characterize the technological progress in these domains. Further segmentation was needed and partially achieved in this report; in some cases underlying technologies which were central to these applications were also identified.

It should be outlined that some other application domains were not selected, either because they were already more or less covered by the ITRS Technology Working Groups (this is the case for the wireless communications), because some societal changes will not benefit primarily and directly from the progress of the microelectronic industry (e.g., shortage in water or other natural resources), because the field was not familiar to the participants of the Working Group or simply by lack of time (e.g., the energy domain).

---

In a second part of this report a tentative taxonomy of potential MtM devices is first established. Then specific MtM devices were selected owing to their perceived potential for technological roadmapping. Integrated power devices, lighting, image sensors, biochips and MEMS were among the selected devices whose potential in the selected application domains of this report is rather clear. This selection is by many respects arbitrary, but the aim of this report is to explore the validity of the proposed methodology rather than to propose an exhaustive catalog of MtM devices which would be worth roadmapping.²

Finally, in the same way as the ITRS screen long-term technology options whose potential is not firmly established, we considered potential emerging research devices for the MtM domain.

The report concludes in summarizing the findings of this study and in proposing paths for further work.

As a general disclaimer the authors would like to stress some issues in performing this work:

- The field to be covered is extremely large and would have required extensive studies and full time work by many experts over many months to achieve significant results comparable to what is presently obtained in the ITRS for the digital domain: this was clearly not possible with the limited resources of the present CATRENE Working Group.

- The authors used their limited knowledge and time in trying to cover the areas which are addressed in this report. This could thus induce some bias in the way the different fields were covered.

- This work wasn’t financially supported. It was thus very difficult to motivate potential additional contributors – from their own entity or from other organizations – to dedicate a significant amount of time in a roadmapping effort which would have required an extended work and whose immediate return was not clear to them.

Some readers may thus have expected more insights in their field of expertise from this report than it was actually able to deliver. The authors still believe that the proposed methodology and some of the conclusions reached paves the way for further progress in roadmapping the “More-than-Moore” domain.

---

² This later goal would have been anyhow unrealistic owing to the very limited resources dedicated to this work.
2. Methodology

**Note:** This section is based on the ITRS “More-than-Moore” White Paper published in December 2010: most parts of this section are a reproduction of the original text of this White Paper.  

### 2.1. Introduction

The idea of a technology roadmap for semiconductors can be traced back to a paper by Gordon Moore in 1965, in which he stated that the number of components that could be incorporated per integrated circuit would increase exponentially over time. This would result in a reduction of the relative manufacturing cost per function, enabling the production of more complex circuits on a single semiconductor substrate. Since 1970, the number of components per chip has doubled every two years on emblematic products like microprocessors and memories. This historical trend has become known as “Moore’s Law”.

As the number of components (i.e., transistors, bits) per chip increases, the total chip size has to be contained within practical and affordable limits (typical chip sizes should be <145 mm$^2$ for DRAM devices and <310 mm$^2$ for microprocessor units (MPUs)). This can be achieved by a continuous downscaling of the critical dimensions in the integrated circuit, which can be expressed in terms of “Moore’s Law” as a linear shrink by a factor of $0.7^5$ every 2 years, where “critical dimension” is understood as “half pitch”, as defined in the International Technology Roadmap for Semiconductors” (ITRS).

As a consequence of this trend, the miniaturization of circuits by scaling down the transistor has been the principal driver for the semiconductor technology roadmap, for more than forty years. Thanks to its ability to dramatically decrease the cost per elementary function (e.g., cost per bit for memory devices, or cost per MIPS for computing devices), the semiconductor industry has almost reached by the year 2010 the $300 billion mark, displacing alternative system solutions (e.g., in telecommunication, radios, TVs…) or enabling the emergence of entirely new markets (PCs).

The wide applicability of semiconductor technology has a widespread impact on many other industries because of its considerable reduction in cost per function. This long-term deflationary effect of semiconductors has never been fully accounted for in statistics and economics. For example, the decline in price per bit has been stunning. In 1954, five years before the integrated circuit was invented, the average selling price of a transistor was $5.52. Fifty years later, in 2004, this had dropped to a billionth of a dollar. A year later in 2005 the cost per bit of dynamic random access memory (DRAM) is an astounding one nanodollar (one billionth of a dollar).

In a nutshell, the industry ability to follow “Moore’s Law” has been the engine of a virtuous cycle (see Fig. 1): through transistor scaling one obtains a better performance-to-cost ratio of products which induces an exponential growth of the semiconductor market. This in turn allows further investments in new technologies which will fuel further scaling. Technical progress was of course a key ingredient of this industry ability, but it was not the only one:

---


5. A linear shrink of $0.7 = 1/\sqrt{2}$ results into a doubling of the integration density.

another key factor was the high degree of confidence, shared by the industry players, that achieving “Moore’s Law” was possible AND would bring the expected benefits. This consensus on the technical trends was and is a distinctive characteristic of the microelectronics community.

Fig. 1 – The virtuous circle of the semiconductor industry

The ITRS is based on this industry-wide shared confidence of both the technical feasibility and the economic validity of this virtuous cycle, as it is clearly stated in the introduction to the ITRS executive summary: “a basic premise of the Roadmap has been that continued scaling of electronics would further reduce the cost per function […] and promote market growth for integrated circuits”.

Of course the ITRS is not the only mechanism that has been at work to achieve that virtuous cycle. Nevertheless, it has had a strong prescriptive effect: not a single PhD thesis in the field is written without positioning its research vs. the ITRS acknowledged “roadblocks”. Likewise, funding agencies are also referring to the roadmap. The ITRS has therefore been able to provide research guidance for the many actors of the semiconductor ecosystem (semiconductor companies, equipment and material providers, public and private research laboratories and institutes, and funding agencies), thereby significantly contributing to technology exploration and at the same time increase resource efficiency in the very fast technological development of the industry. It should also be stressed that the ITRS helped to synchronize the technology development and the timely availability of manufacturing equipments and methods.

The literature on innovation management supports this view of the key role of a global roadmapping process for the industry innovation capabilities. This literature stresses that the success of an individual company depends critically on the “collective health of the organizations that influence the creation and delivery” of the firm product – in short, the ecosystem of the firm –. It also documents the attempt of individual firms to foster – and not only benefit from – that ecosystem health. The next logical step is a situation where competitors, which in theory could collectively benefit from the same healthy ecosystem, cooperate to sustain that ecosystem. In fact, the Roadmap can be viewed as a common good

---

pursued and collectively managed by the ecosystem players \(^8,9\) (see also Table 1). The perceived benefit of sharing their vision of the future in setting common technical targets and identifying showstoppers of generic devices and technologies while competing on the final products was instrumental in the success of the ITRS roadmap among the microelectronics players.

Table 1 – Potential benefits of an industry-wide technical roadmapping effort \(^10\)

<table>
<thead>
<tr>
<th>Benefit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>guide the research effort worldwide</td>
</tr>
<tr>
<td>2.</td>
<td>synchronize the technology development and the timely availability of manufacturing tools and methods</td>
</tr>
<tr>
<td>3.</td>
<td>increase the resource efficiency through focus</td>
</tr>
<tr>
<td>4.</td>
<td>promote market growth and job creation</td>
</tr>
</tbody>
</table>

From a technology perspective, the continuous increase in the integration density proposed by “Moore's Law” was made possible by a dimensional scaling whose benefits in performance were conceptualized by R. Dennard \(^11\): in reducing the critical dimensions while keeping the electrical field constant, one obtained at the same time a higher speed and a reduced power consumption of a digital MOS circuit (see Fig. 2): these two parameters became driving forces of the microelectronics industry along with the integration density.

**Fig. 2** – The constant field scaling theory predicts an increased speed and a lower power consumption of digital MOS circuits when the critical dimensions are scaled down.


\(^10\) In the specific case of the semiconductor industry, it can be argued that growth and job creation benefits go beyond the boundaries of this industrial sector, due to its impact as a key enabling technology on other economic activities.

The MOS transistor is the basic building block for logic devices (e.g., MPU), which – along with storage components – represent the digital content of an integrated circuit. However, many microelectronic products will have non-digital functionalities as well, as they should operate in a user environment. The typical embodiment of these more complex products is realized as an assembly of various components (ICs, passive components, etc.) on a printed circuit board (PCB). However, the present progress in both process technology and design is enhancing the compatibility of CMOS and non-digital technologies, which enables the migration of non-digital components from the PCB into the package containing the integrated circuit, or even into the chip itself. This combined need for digital and non-digital functionalities in a product is depicted in Fig. 3.

**Fig. 3 – The combined need for digital and non-digital functionalities in an integrated system is translated as a dual trend in the International Technology Roadmap for Semiconductors: miniaturization of the digital functions (“More Moore”) and functional diversification (“More-than-Moore”).**

The International Technology Roadmap for Semiconductors has emphasized in its early editions the “miniaturization” and its associated benefits in terms of performances, the traditional parameters in “Moore’s Law”. This trend for increased performances will continue, while performance can always be traded against power depending on the individual application, sustained by the incorporation into devices of new materials, and the application of new transistor concepts. Maintaining the increase of performances by other means than just scaling the dimensions is called “equivalent scaling”.

---

12 The resulting implementation is called “System-in-Package” or SiP
13 In this case it is referred as a “System-on-Chip” or SoC
14 Maintaining the increase of performances by other means than just scaling the dimensions is called “equivalent scaling”.
Towards a “More-than-Moore” roadmap

systems, although they do not necessarily scale at the same rate as the one that describes the development of digital functionality, but provide additional value in different ways and allow for the non-digital functionalities to migrate from the system board-level into the package (SiP) or onto the chip (SoC). Consequently, in view of added functionality, this trend may be designated “More-than-Moore” (MtM).

Functional diversification may be regarded as the complement of digital signal and data processing in a product (see Fig. 4). This includes the interaction with the outside world through an appropriate transduction (sensors and actuators) and the subsystem for powering the product. These functions may imply analog and mixed signal processing, the incorporation of passive components, high-voltage components, micro-mechanical devices, sensors and actuators, and micro-fluidic devices enabling biological functionalities. It should be emphasized that “More-than-Moore” technologies do not constitute an alternative or even competitor to the digital trend as described by “Moore’s Law”. In fact, it is the heterogeneous integration of digital and non-digital functionalities into compact systems that will be the key driver for a wide variety of application fields, such as communication, automotive, environmental control, healthcare, security and entertainment. Whereas “More Moore” may be viewed as the brain of an intelligent compact system, “More-than-Moore” refers to its capabilities to interact with the outside world and the users.

Fig. 4 – “More-than-Moore” technologies complement the digital processing and storage elements of an integrated system in allowing the interaction with the outside world and in powering the system.

Fig. 5 illustrates this architecture using the imager example: combination of both “More Moore” (image signal processing) and “More-than-Moore” (image sensor, through silicon via) technologies result into a compact camera, including smart and/or (ultra-fast) pixel electronics, and exhibiting low power consumption and small footprint, fit for integration within a portable device such as a mobile phone.

“More-than-Moore” based technologies have already made a considerable contribution to the worldwide microelectronics market, and the opportunities are huge. Since it is expected that the relative weight of the “More-than-Moore” component in the industry evolution will increase over time, a new “virtuous cycle” must be established to relay the industry expansion, based no longer just on device scaling but on many innovations, at the system, technology, device and circuit levels. Those innovations will have to address not just frontend technologies but backend/packaging technologies as well recognizing an increasing importance of the interaction between frontend and backend technologies for SoC and SiP systems (see Fig. 6).

While opportunities are huge, so are the challenges. The pervasion of “More-than-Moore” technologies will impact the development of integration platforms, of innovative technologies (e.g., for 3D integration of multiple chips), manufacturing techniques (e.g., for test and reliability assessment of compact systems), and design & modeling tools capable of handling multifunctional heterogeneous subsystems.

This leads to a growing diversity of the scientific fields that must be covered by multidisciplinary research programs in order to sustain the pace of innovation, while the financial constraints are becoming more critical. The question of providing guidance to the research efforts in this new field is therefore crucial. Given the benefits of the roadmapping process experienced in the “More Moore” domain, it seems highly desirable to develop and sustain a similar process in the “More-than-Moore” domain.
It is an opportunity for the microelectronic community to extend its technology roadmap in including part of the “More-than-Moore” domain, in conjunction with the digital domain which will continue in compliance with “Moore’s Law”. The purpose of this report is to analyze the conditions that made the “More Moore” roadmapping possible, and to deduce from that whether a similar roadmapping exercise is feasible for selected “More-than-Moore” domains, and, if yes, show some examples on how to develop such a roadmap.

2.2. Preconditions for an industry-wide technical roadmap

In spite of the advantages listed previously of developing and managing a roadmap as a common good for the industry, it seems that the ITRS is a fairly unique industry-wide roadmapping exercise. This might be due to the set of conditions that must be met to make an industry-wide roadmapping effort possible (see Table 2).

First of all, it must be possible to abstract some generic feature which characterizes the progress in the underlying technology: this has to be summarized through a restricted set of figures of merits (FOM: Figures Of Merit) whose value continuously increases or decreases over a long period of time. One of the difficulties faced today in the “More-than-Moore” domain is the multiplicity of such figures of merit depending on the type of devices and applications. The increase in performances of an image sensor, for example, is not judged according to the same criteria than a BAW filter! Once these figures of merit have been identified, a consensus on the methods by which to measure them needs to be achieved and translated into appropriate standards.

Secondly, it might be that a given technology has a large potential for roadmapping, but that the industrial players using that technology don’t recognize themselves as an industrial community sharing the same needs of developing that technology in the same direction (this might be the case when a technology addresses disjoint markets, the actors of which do not know each other). A prerequisite for a roadmapping effort is therefore the existence of a community (ECO: Existing Community).

Third, the different players in a given technology must be convinced that they will gain, rather than loose, in sharing their vision of the technical development of a given technology and in participating in the roadmapping process (SHR: willingness to SHaRe).

Fourth, the potential market for a technology for which one wants to build a roadmap must be large enough to justify a pre-competitive joint effort (WAT: Wide Applicability of the Technology). The expected profits must be sufficient to support a critical mass effort devoted to roadmapping a given area of the “More-than-Moore” domain with a reasonable probability of a useful return on investment.

Finally, there must be a convergence of opinion among a majority of the key players on the technical trends of the selected figures of merit, in other words, there must be an agreement on the “law” of progress that these figures are expected to follow (LEP: “Law” of Expected Progress).

This roadmap will be easier achieved if these figures and trends are not directly linked to a specific application in which the technology will be used or for which the technology will be

---

16 The term “law” can lead to the misleading perception that the technology trends follow a scientifically proven law of progress. In practice – and as experienced with the so-called “Moore’s Law” – making the trends explicit as “laws” of expected progress can lead to a self-fulfilling prophecy of continuous progress.
developed. If the old idea referred as “MEMS Law” \(^{17}\) (“one product = one process”) applies it may be difficult to come to a common description of the technical trends for the future.

| 1. **FOM** | restricted set of figures of merits |
| 2. **ECO** | existence of a community of players |
| 3. **SHR** | willingness to share information |
| 4. **WAT** | potential market of significant size inducing a wide applicability of the roadmap |
| 5. **LEP** | convergence of opinion among a majority of the key players on the progress trends (“Law” of Expected Progress) that these figures of merit are expected to follow |

*Table 2 – Necessary conditions for an industry-wide technical roadmap effort*

### 2.3. Lessons learned from “More Moore”

#### 2.3.1. Meeting the preconditions for industry-wide roadmapping

The CMOS planar technology has given birth to an industry and clearly meets the preconditions listed above:

− **FOM**: in fact, one might argue that there is only one figure of merit, at least in the digital domain: the achievable transistor density (sometimes summed up through the transistor gate length, or the metal 1 or poly half pitch) which has doubled every two to three years since the seventies and is expected to continue along that trend over the next decade. In the constant field scaling paradigm, not only a smaller transistor meant lower cost (due to a smaller silicon area for a given function), but it also meant higher performance and lower power per device (see Fig. 2).

− **ECO**: The digital microelectronic industry emerges in the 70’s as a community sharing the same vision of scaling down the logic switch and the memory cell while improving the performances. The ITRS effort was first initiated at the US level as the NTRS, which in turn can be considered as a child of the 1985 SRC summer study, which was intending to “construct a roadmap which would help to secure […] the future of the US semiconductor industry” \(^{18}\). So there was, as early as 1985, an industrial community sharing a collective conscience of its existence.

− **SHR**: The performance benefit resulting from scaling also allowed solving the issue of competition: all semiconductor companies involved in ITRS could agree on a common target for the evolution of the technological characteristics, namely a constant “shrinking” of semiconductors dimensions; but they maintained competition on the use of the

---

\(^{17}\) “one product = one process” meaning that each product needs the dedicated development of a unique technology. It should be stressed that the MEMS industry strives to develop generic technologies.

“shrinking” capacity to develop “shrunk” products. Hence the “shrinking” principle is a “decoupling” principle between common interest and competition. Finally, since the roadmap was defining which performances were to be reached over the years (e.g., the value of the dielectric constant for the gate oxide), but not how to achieve it (detailed process step recipes and process flows remain trade secrets for technology providers), competitive issues were avoided.

- **WAT**: through the pervasion of the digital information processing which was enabled by the CMOS technology and its cost effectiveness, many markets were covered by the same technological trend, independently of the applications, meeting the precondition of wide applicability of the technology.

- **LEP**: Obviously there is a large agreement among the expert community that the integration density as a figure of merit is expected to follow “Moore’s Law”.

The combination of the two previous criteria played a critical role in the roadmap success; since technical and financial decision makers shared confidence that progress would continue (LEP), and thanks to WAT, high returns were expected and thus significant investments were done in R&D to make the expected progress happen.

### 2.3.2. Combining focus and variety

As mentioned earlier, one goal of the ITRS is to provide research guidance for the semiconductor ecosystem, and it has achieved a strong prescriptive effect. This has had a very effective focusing effect for the scarce research resources. The question is: wasn’t this achieved at the expense of innovative ideas?

However, in fact, the ITRS managed to combine focus and variety. This point can be illustrated by taking the example of the various venues followed by the industry so far, and the ones listed as possible solutions, in the photolithography domain (see Appendix B for a detailed discussion).

So, far from quenching innovative ideas, the semiconductor industry roadmapping in the “More Moore” direction has managed to focus resources while leaving ample room for disruptive concepts. Whatever methodology is applied in the “More-than-Moore” domain will need to allow for the same balance.
2.4. **Proposed methodology for “More-than-Moore”**

In this chapter a methodology will be described for encompassing “More-than-Moore” technologies in the ITRS roadmap in the future.

This methodology is somewhat different from what we are used to in past and present ITRS roadmap releases for “More Moore” technologies. The reason for this is the following: the future development of “More Moore” technologies can be quite accurately described with a high confidence level by extrapolating “Moore's Law” from trends observed in the past based on the availability and commercialization of products in those technologies in the recent years. Scaling requirements can be derived from extrapolating those trends into the future. This doesn't require visions of future markets and applications, the underlying technologies are “transparent” to applications and products to a large extent and have a broad spectrum of applicability for many market segments.

This is different for MtM technologies. There is no “natural” roadmap existing per se, technology needs and company internal roadmaps are usually defined based on short term market requirements. In addition there is a much closer link between process technologies on the one hand and product implementations on the other hand. The following methodology for deriving roadmaps for MtM technologies is thus proposed to take into account the specificities of the MtM domain.

Based on **societal needs** and **market trends** visible today and based on visions for future markets and products some **application scenarios** are sketched. For those different scenarios one derives required **functionalities** and then **related building blocks** (this key link is further discussed below). Technology building blocks (devices or elementary functions) are then analyzed and described based on a restricted **set of figures of merit**. The expectation is that those technology building blocks will – to a large extent – not depend on the scenario, or in other words, many different scenarios will hopefully lead to same or similar technology building blocks: as done in the “More Moore” arena, **requirements** on these building blocks will be derived from the needs of the most demanding applications. In other words the identified building blocks should enable functionalities which are enabling several applications and markets. They should be “robust” or versatile enough against potential scenario changes. (see **Fig. 7**)

This methodology should lower the barriers for all stakeholders in the process to openly share information during the roadmap discussions to come up to a commonly accepted MtM roadmap.

The MtM building blocks which would be amenable for inclusion within ITRS should be selected through the following process:

1) assess the technologies with respect to the prerequisites for a successful technical roadmapping, namely:

   a. technically describe the technologies with a restricted set of parameters or **Figures-Of-Merit (FOM)**
   
   b. check whether the potential providers of those technologies know each other well enough to engage in a cooperative roadmapping effort (**ECO**)
   
   c. define precompetitive domains where contributing parties are willing to share the respective information (**SHR**)
Towards a “More-than-Moore” roadmap

2.5. Applying the proposed methodology

2.5.1. From societal needs to markets

Underlying the evolution of markets and applications, and therefore their economic potential, is their potential in addressing societal trends and challenges for the next decades. Societal trends can be grouped as energy & environment, transport & mobility, health & wellness, security & safety, communication and digital lifestyle (this latter term including

Fig. 7 – In order to identify relevant MtM devices and technologies to be roadmapped, one may start in looking for suitable needs, markets and applications, derive then underlying functionalities and devices. A set of associated parameters and processes will be derived

MtM topics which are outside of any scope of the present Technology Working Groups (TWGs) of the ITRS, could require the creation of a new TWG, or a specific cross-functional coordination of existing TWGs
infotainment). Many other names may be used but all cover more or less the same fields. These trends create significant opportunities in the markets of consumer electronics, automotive electronics, medical applications, communication, etc. Examples of applications linking societal trends and markets are given in the figure below (Fig. 8).

**Fig. 8** – Example of an application matrix linking some societal needs and market segments.

Note that the above figure is somewhat simplifying things: for example, “connected car” is relevant to many trends beyond e-society, e.g.:

1. cars synchronizing their speed can act as virtual “train on the roads”, reducing the overall energy consumption;
2. communication with traffic lights could increase safety;
3. the car-to-car links could be used by *ad-hoc* communication networks

Another way of linking societal needs and markets (or systems) is to look at the entire “food chain” from production to consumption for a given good (in the most general sense, for example, entertainment, or travel). **Fig. 9** below is illustrating this chain for power.
Many applications will target an increase of the functionality of existing functions, e.g., cars will become even more intelligent and further enhance comfort and safety of driver and passengers. Other applications will open new or non-existing markets, e.g., bio-medical chips may well revolutionize healthcare. A commonality however, is that applications in these markets become increasingly sophisticated and often demand optimized and tailored solutions which will be able to sense and actuate, store and manipulate data, and transmit information.

As sketched in the following figure (Fig. 10), some domains tend to be more digital-intensive and some require more MtM technologies.

---

**Fig. 9** – Entire energy “food chain” from generation via distribution to consumption, in all segments semiconductor power technology devices are required (Source: Infineon)

**Fig. 10** – Some societal needs favor the digital domain ("More Moore") or the interaction with the outside world ("More-than-Moore"). (from T. Claasen, MEDEA+ Forum, 2007).
2.5.2. From markets and needs to functions

This step can be visualized in the following figure (Fig. 11)

Fig. 11 – Relationship between markets and relevant devices.

This diagram is established by looking at the various markets segments and sub-segments identified in the previous steps, notably while building the application matrix represented in Fig. 8. The segmentation of course needs further refinement and will evolve over time (it can’t be exhaustive).

For example, electronic modules addressing automotive electronics systems could be segmented into the following major categories (see Chap. 3.1 below):

- **Powertrain Electronics**, such as engine controllers, transmission controllers, voltage regulators, and any other systems that control the engine or driveline of the vehicle
- **Entertainment Electronics**, ranging from standard AM/FM radios to on-board video entertainment systems, satellite radio receivers
- **Safety and Convenience Systems**, such as airbag sensors, climate controls, security and access controls, anti-lock braking systems
- **Vehicle and Body Controls** that manage specific vehicle functions, such as suspension, traction, power steering
- **In-Cabin Information Systems**, such as instrument clusters, trip computers, telematic products
- **Non-Embedded Sensors**, such as speed sensors, temperature sensors, fluid level sensors, and many others

In turn, any of the functions listed above can be further decomposed into the devices required to fulfill that function (e.g., gas / chemical sensors for in-cabin air quality or for monitoring exhaust gas composition and oil quality)
The instantiation of the diagram represented in Fig. 11 will evolve over time, as new markets are considered or as new innovative approaches are proposed. However, an exhaustive list is fortunately not required to start the roadmapping process. Quite likely, with only a few markets, devices common to several markets, or crucial for the development of an important market, will rapidly be identified. The next step will be to assess the potential for roadmapping of the various devices which will emerge from the diagram.

In Fig. 11, device $d_1$ is required for function $f_1$, which is required by markets $M_1$ and $M_4$. If market $M_1$ and $M_4$ rely on similar evolution trends for the performances of function $f_1$, then this functional performance trend will lead to a common definition of the figures of merit by which this device should be measured (FOM) and to a convergence on the “law” of expected progress (LEP) of the $d_1$ device. Knowledge of markets $M_1$ and $M_4$ also allows to assess the existence of a community between these actors (ECO) and to estimate the readiness of the market actors to share (SHR). Finally, the device or technology applicability (WAT) will depend on the predictable evolution of markets $M_1$ and $M_4$, the pervasion of function $f_1$ in these two markets, and the number of devices $d_1$ required to fulfill function $f_1$.

In general, if function $f_j$ requires $d_{ij}$ devices $d_i$, and market $M_k$ requires $f_{jk}$ implementations of function $f_j$, the estimated number of devices $d_i$ required for all markets will be

$$N(d_i) = \sum_k \sum_j f_{jk}(M_k) \ast d_{ij}$$

$f_{jk}$ depends on the characteristics of the market $M_k$ and will vary over time. Furthermore, since it is a forecast, rather than taking a single number for a given year, the methodology will be more robust if different scenarios are established. If the applicability of a device proves to be large across a variety of scenarios, it can be awarded a high mark for the WAT criteria. For our purpose, exact numbers are not needed: qualitative estimates (“very large”, “fairly low”) will be quite enough to determine whether a given device or technology is a good candidate for roadmapping, based on the criteria identified earlier.

For example, we can estimate that high speed bipolar devices will be required to build millimeter wave imaging systems, which in turn can appear in many markets: industrial (production control), healthcare (medical imaging), transportation (obstacle detection), security... It is likely that in many combinations of the possible evolution scenarios for these various markets, the applicability of this technology will be wide.
2.5.3. MtM devices

2.5.3.a. Interacting with the outside world

As the digital information processing is expected to use electrons for the years to come the elementary MtM components will have to transduce a physico-chemical parameter into an electrical signal or vice versa.

It should however be stressed that to build a specific function (e.g., sensing the concentration of specific gases) one may need many “elementary” sensors and actuators (in the proposed example an IR light source, either broadband or single wavelength, one or many photodetectors). The macro-function \( F \) will have thus to be build through the combination of many elementary functions \( f_i \) and devices.\(^{20}\)

\[
F = f_1 \circ f_2 \circ ...\]

Many physical parameters can be considered. However for the sake of simplicity, we list here some illustrative examples of inputs / outputs to the system:

1. electromagnetic wave distinguishing:
   a. the radio-frequency domain up to the THz range
   b. the “optical” domain from the infrared to the near ultraviolet
   c. the “hard” radiation (EUV, X-ray, \( \gamma \)-ray)\(^{21}\)

2. mechanical parameters (position, speed, acceleration, rotation, pressure, stress, etc.) for which MEMS (and more recently NEMS) are the emblematic MtM devices

3. chemical composition

4. biological parameters\(^{22}\)

This list is by no means limitative and will be most likely expanded in the future. It should be also stressed that a given parameter can be expressed:

- as a single measure (sensing) or action (actuation)
- as a two dimensional representation (e.g., image sensor for sensing or display for actuation)
- in including a temporal component (e.g., as a movie for an image evolving over time)
- more generally in a multidimensional approach (e.g., imaging multiple parameters of a single object in 3D dimensions over time)

This further segmentation can induce specific characteristics of the MtM device and technology under consideration.

\(^{20}\) This approach is not different of what happens in building an integrated circuit: using n and p-MOS transistors in assembling standard cells (gates, memory cells, etc.) one is able to build more complex functions (e.g. addition).

\(^{21}\) The cross-over between the optical domain and the hard radiation (ca. \( \lambda = 0.1 \) \( \mu \)m) can be loosely defined as the wavelength at which no refractive material exist for deflecting the electromagnetic wave.

\(^{22}\) There may be some overlaps between chemical and biological MtM devices. The present differentiation resides in the sample to be analyzed or to be acted upon: biological transducers are interacting with living objects while chemical transducers are with inert species.
The following table (Table 3) summarizes the proposed taxonomy of MtM devices providing an interaction between the digital domain of the integrated device and the outside world. It gives also some examples of relevant devices.

<table>
<thead>
<tr>
<th>Physical parameter</th>
<th># dim.</th>
<th>Sensing</th>
<th>Actuating</th>
</tr>
</thead>
<tbody>
<tr>
<td>electromagnetic</td>
<td>1</td>
<td>filter, demodulator, antenna</td>
<td>modulator, antenna</td>
</tr>
<tr>
<td>– rf (up to THz)</td>
<td></td>
<td>photodiode</td>
<td>LED</td>
</tr>
<tr>
<td>– optical</td>
<td></td>
<td>photon counter</td>
<td>laser</td>
</tr>
<tr>
<td>• incoherent</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• coherent</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>– “hard” radiations</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>mechanical</td>
<td>MEMS, NEMS</td>
<td>MEMS</td>
<td></td>
</tr>
<tr>
<td>chemical</td>
<td>electrical nose</td>
<td></td>
<td></td>
</tr>
<tr>
<td>biological</td>
<td>DNA chip, glucose meter</td>
<td>pacemaker, brain-computer interface</td>
<td></td>
</tr>
<tr>
<td>e.g., optical…</td>
<td>2</td>
<td>image sensor</td>
<td>micro-display</td>
</tr>
<tr>
<td>2 + t</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>…</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>…</td>
<td>n</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3 – Potential taxonomy of MtM devices and technologies for sensing/actuating.

2.5.3.b. Powering

All systems need to be powered in order to perform some information processing. It does translate into the fact that many dedicated components need to be developed and integrated in order to:

- condition the energy or power supply in an usable form for the electronic circuit (e.g., dc-dc or ac-dc conversion)
- store energy (e.g., capacitors) which is critical in case of intermittent energy or power supply
- scavenge any outside source of energy or power for supplying or complementing the supply of the integrated system, especially in the case of nomadic or autonomous systems
- possibly supply energy or power through sources integrated in the SoC or SiP (e.g., micro-battery or integrated fuel cell)

To avoid any misunderstanding, low-power design techniques and low-power digital components are not considered as MtM technologies and devices, although “More-than-Moore” devices are very often found in systems that will require low power “More Moore” components.
2.5.4. MtM technologies

It should be outlined that up to now only devices were considered. The supporting processes and techniques need also to be addressed. As an example, looking at MEMS devices one may expect that deep RIE and release processes will play a significant and specific role, while dedicated considerations have to be made regarding design techniques, modeling, test, manufacturing techniques and the like. Likewise, nanoscale contacts and interconnects will represent significant challenges for the MtM domain.

In addition, as represented by Fig. 3, in most cases “More-than-Moore” devices will take benefit from the “More Moore” progress. Technical enablers will be needed to allow the integration between the “More-than-Moore” and the “More Moore” devices, and roadmaps for these technical devices will also be needed – for example, 3D integration, RF signal transmission methods or optical IO to reach high throughput data rates, power dissipation methods and other technical enablers.

2.5.5. Existing roadmaps

As indicated in Table 4, the “Radio Frequency and Analog-Mixed Signal Technologies for Wireless Communications” TWG has been roadmapping many devices in the RF space since its inception, in effect pioneering the methodology delineated in this methodology section, and its excellent work should be recognized here.

It is also important to identify domains where it may be more efficient to rely on existing roadmaps rather than to have the ITRS community duplicating this effort. ITRS has a strong interaction with iNEMI for the system drivers and has started interacting with this community in the MEMS domain. As a general conclusion it may not be appropriate to develop a specific effort where publicly available roadmaps exist.

2.5.6. Assessing selected MtM devices and technologies with respect to roadmapping

The last step before entering a full-scale roadmapping exercise would be to assess the MtM devices and technologies described in the previous paragraphs with respect to their potential for roadmapping. The following figure is an example of what should be the ideal outcome of the present exercise.

<table>
<thead>
<tr>
<th></th>
<th>FOM</th>
<th>ECO</th>
<th>SHR</th>
<th>WAT</th>
<th>LEP</th>
<th>Public roadmaps?</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF</td>
<td>++</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>++</td>
<td>yes</td>
</tr>
<tr>
<td>Integrated power</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>?</td>
<td>on-going</td>
</tr>
<tr>
<td>...</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4 – Example of a template matrix in assessing the potential of some MtM devices for roadmapping.

---

23 Some publicly available roadmaps will be mentioned in this report.
It should be stressed that this table is very preliminary and is here only to show the structure. Filling it is an on-going work and this report is a first attempt to pursue that goal.

2.6. Conclusion

ITRS is very successful in roadmapping the digital domain of the microelectronics, offering guidance to the microelectronic ecosystem, and allowing synchronization between the technological progress and the timely availability of manufacturing techniques. It is expected that the non-digital / non-memory part of integrated systems will play an increasing role in the future putting more emphasis on the MtM domain. The challenge of the microelectronic community is to assess to which extend the success of the ITRS roadmapping effort can be extended further to the MtM technologies.

The ITRS community, i.e., the Technology Working Groups and the International Roadmap Committee, is willing to include more significant parts of the “More-than-Moore” domain in the future releases of its roadmap. This is an opportunity for Europe to take a leading role in this trend. It should also be stressed that building the link between societal needs, markets and technologies goes well beyond the ITRS current practice, and is likely to require the involvement of many actors beyond the ITRS historical membership. For example, roadmapping efforts in healthcare for clinical and commercial success will require the inclusion of physicians, clinicians, and health regulators from the beginning.

The purpose of this section was to analyze the conditions that made the “More Moore” roadmapping possible, and to deduce from that whether a similar roadmapping exercise is feasible for selected “More-than-Moore” domains, and, if yes, derive some indications on how to develop such a roadmap. The next sections will apply parts of this methodology to specific MtM domains.
3. Application domains

3.1. Automotive

Joachim Pelka, Fraunhofer Gesellschaft – Group Microelectronics

3.1.1. Scope & taxonomy

The automotive electronics industry was approximately 6% of global electronics production in 2007 and growth is expected to increase continuously due to an increase in average electronic content per vehicle. Main drivers for this development are safety and security features, rules for protection of the environment and the development hybrid and fully electrical cars.

The automotive sector is therefore one of the most important application areas for “More-than-Moore” electronics. Vehicles today are using up to 80 microcontrollers which create a complex data network. One of the trends in the development of automotive electronics drives into more centralized architecture reducing the number of “general purpose processors”. Simultaneously, smart sensors with integrated controllers will create more decentralization of data processing. This will lead towards completely new architectures using buses for data communication and power distribution on a single wire.

For the decentralized part more distributed intelligence is needed. A typical example for this is the Tire Pressure Monitoring System (TPMS). It combines the pressure sensor with microcontroller and RF transceiver.

Based on such concepts the major trends driving the demand for increased electronics penetration in automobiles include:

- Stricter fuel economy and emissions mandates
- Legislated requirements for advanced safety systems, such as advanced airbags, onboard tire pressure monitoring, RADARs, intelligent headlights, and driver assistance like parking assistant or adaptive cruise control
- Consumer demand for greater vehicle efficiencies driven by escalating global crude oil prices
- Consumer demand for greater safety, comfort, and convenience features
- Consumer demand for luxury features

Electronic modules addressing these issues as well as other automotive electronics systems can be segmented into six major categories:

- **Powertrain Electronics**, such as engine controllers, transmission controllers, voltage regulators, and any other systems that control the engine or driveline of the vehicle
- **Entertainment Electronics**, ranging from standard AM/FM radios to on-board video entertainment systems and satellite radio receivers

---

24 Automotive Product Emulator Group (PEG) Chapter, 2009 iNEMI Technology Roadmap

- Safety and Convenience Systems, such as airbag sensors, climate controls, security and access controls, anti-lock braking systems
- Vehicle and Body Controls that manage specific vehicle functions, such as suspension, traction, power steering
- In-Cabin Information Systems, such as instrument clusters, trip computers, telematic products
- Non-Embedded Sensors, such as speed sensors, temperature sensors, fluid level sensors, and many others

Today the further development is mainly driven by the rapid emergence of new technologies and by the increasing integration of sensors with electronics which has overcome a lot of restrictions. However, the resulting technology push can only be successful if the costs can be kept low. Price pressure is immense in the automotive business. Besides costs, reliability is a main issue. Therefore vehicle manufacturers are demanding systems solutions instead of components.

For the future it is expected that the level of monolithic integration will be increase in the next future, and that multiple sensors will be integrated in a package or on a chip. Moreover microwave, infrared and optical technologies will be used in a wider range of applications.

**Fig. 12 – Power electronic key systems for the cars of tomorrow.**

MEMS (Micro-ElectroMechanical Systems) are finding increased applications for automotive sensor products (accelerometers, yaw rate, pressure, etc.) and the Hybrid Electric Vehicle (HEV) initiatives have accelerated the development of new packaging materials and processes designed to enhance thermal management. This has also spurred on much activity to develop automotive grade power electronics components for high current (100A to 1000A) and high voltage (42V to 1000V) applications.

---

The general trends which can be seen today are expecting an increased functional content, an enhanced integration of electronics with mechanical components (“embedded electronics”) and the increased use of electronics (“X by wire”).

### 3.1.2. Eligible technologies for roadmapping

Roadmapping from a “More-than-Moore” point of view requires a breakdown of the above mentioned application oriented topics into components and technologies. On a component level one has to address topics like

- **Integrated sensors** for pressure (Manifold Air Pressure, Fuel, Occupant Detection, Tire, Airbags), acceleration, non contact temperature, airflow, fuel flow and angular rate (Airbags, Electronic Stability Control, Roll Over) sensors
- **Gas / chemical sensors** for in-cabin air quality, monitoring exhaust gas composition and oil quality
- **Actuators / valves** for fuel injection
- **Optical / Infra-Red sensors** for in-car Local Area Networks, Heating, Ventilation, & Air Conditioning control, occupant sensing, night-vision and in-vehicle displays
- **Polymer based sensors** for humidity detection
- **Radar based sensors** for back-up aid, blind spot detection, and adaptive cruise control

Adding the respective technologies like bulk and surface micromachining, SOI-technologies, power semiconductors (Si, SiC, GaN), polymers, and RF, one will end up with quite a complex matrix which will make it difficult to define suitable figures of merit and to choose the right representatives for roadmapping. The upcoming hybrid and fully electrical technologies will introduce even more technologies. For the hybrid car it is expected to have higher voltages (batteries 150- 400V, step up converters 500-700V), 42V technologies will be used only for subsystems (Antilock Braking System (ABS), power steering, valve-train control …).

Again costs and reliability will be major issues. Cost factors will be: power devices & packaging, capacitors, connectors, EMI filters and cooling. Reliability aspects concern printed circuit boards, modules, and packages in harsh environments (temperature, humidity, ESD …)

### 3.1.3. Available roadmaps

A good starting point for an automotive roadmap initiative can be found in the iNEMI Technology Roadmaps. The latest version (January 2009) gives some key figures for the technical development until 2019, but this approach does not yet describe technological details from a “More-than Moore” point of view.
### Table 5 – Some key figures for the automotive sector until 2019

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Metric</th>
<th>2009</th>
<th>2011</th>
<th>2013</th>
<th>2019</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PMIC Costs (FAB)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6-layer conventional</td>
<td>$ pm^2</td>
<td>0.02</td>
<td>0.019</td>
<td>0.018</td>
<td>0.015</td>
</tr>
<tr>
<td><strong>Package Costs</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IC Package Cost</td>
<td>$ /UO</td>
<td>0.5</td>
<td>0.5</td>
<td>0.4</td>
<td>0.3</td>
</tr>
<tr>
<td>Connector Cost</td>
<td>$ /UO</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.4</td>
</tr>
<tr>
<td><strong>Cycle Time</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time to add EMS</td>
<td>Weeks</td>
<td>22</td>
<td>18</td>
<td>16</td>
<td>8</td>
</tr>
<tr>
<td>NPI Cycle Time</td>
<td>Weeks</td>
<td>78</td>
<td>72</td>
<td>66</td>
<td>60</td>
</tr>
<tr>
<td><strong>Reliability</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature Range</td>
<td>Deg C</td>
<td>-40 to 115</td>
<td>-40 to 115</td>
<td>-40 to 125</td>
<td>-40 to 125</td>
</tr>
<tr>
<td>Number of Cycles</td>
<td>Cycles to Pass</td>
<td>10k</td>
<td>10k</td>
<td>12k</td>
<td>13k</td>
</tr>
<tr>
<td><strong>Display</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Resolution</td>
<td>Type</td>
<td>800 X 480</td>
<td>800 X 480</td>
<td>800 X 480</td>
<td>920 X 1060</td>
</tr>
<tr>
<td>Technology</td>
<td></td>
<td>AMLCD</td>
<td>AMLCD</td>
<td>AMLCD</td>
<td>AMOLED</td>
</tr>
<tr>
<td>Color</td>
<td>Type</td>
<td>8 bit RGB</td>
<td>8 bit RGB</td>
<td>8 bit RGB</td>
<td>8 bit RGB</td>
</tr>
<tr>
<td>Cost</td>
<td>$ /unit</td>
<td>75</td>
<td>60</td>
<td>110</td>
<td>110</td>
</tr>
<tr>
<td>Average Display Size</td>
<td></td>
<td>8 inch</td>
<td>8 inch</td>
<td>12.3 inch</td>
<td>14.16 inch</td>
</tr>
<tr>
<td><strong>Memory</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Main Memory Type</td>
<td>Type</td>
<td>Flash</td>
<td>Flash</td>
<td>Flash</td>
<td>Flash</td>
</tr>
<tr>
<td>Main Memory Size</td>
<td>MB</td>
<td>2</td>
<td>32</td>
<td>32</td>
<td>64</td>
</tr>
<tr>
<td>Storage Memory Type</td>
<td>Type</td>
<td>None</td>
<td>Hard Drive</td>
<td>Hard Drive</td>
<td>Hard Drive</td>
</tr>
<tr>
<td>Storage Memory Size</td>
<td>MB</td>
<td>N/A</td>
<td>40000</td>
<td>40000</td>
<td>60000</td>
</tr>
</tbody>
</table>
Table 6 – The iNEMI Roadmap deals with more general aspects like number of I/Os, board size etc. but not with “More-than-Moore” technologies.\(^ nation
Towards a “More-than-Moore” roadmap

Table 7 – iNEMI covers also other technologies like batteries which are not real “More-than-Moore” technologies, but cannot be neglected from an application point of view.\(^{24}\)

The also publicly available Freedom Car Roadmap (2010)\(^{27}\) is written from the car manufacturers’ point of view and has a focus on the system aspects. It gives some guidance into the future but no information on “More-than-Moore” technologies. Again there is a focus on cost aspects.

More detailed roadmapping activities are with the car manufacturers (Fig. 13) and their suppliers and are not publicly available. The willingness to share this strategic information seems not to be high.

However, a first approach from a “Smart Systems” point of view is given by the EPoSS Strategic Research Agenda (SRA)\textsuperscript{29}. This SRA paper has a focus on the system level and addresses safety, driver assistance and convenience, energy efficiency and environment friendly smart power trains. Additionally, it deals with the enabling technologies for fully electrical vehicles (FEVs) as well as cross-over technologies. The EPoSS automotive SRA is set to be a reference for advanced micro- and nano-technology development in general.

In the present version (March 2009) the EPoSS SRA gives the major R&D objectives for the next 10 to 15 years:

**Safety** – including active and passive vehicle systems to protect the driver and the passengers as well as other road users –:
- driver information on vehicle dynamic limitations
- adaptive human machine interface systems
- personalized safety systems
- monitoring systems to sense and predict dangerous drivers situations
- road safety in cities
- pedestrian protection systems
- collision mitigation systems
- emergency braking systems
- vision enhancement systems
- vehicle interaction systems

**Driver assistance**
- vehicle guidance systems
- semi-autonomous driving
- personalized driving
- active load management systems
- adaptive human machine interface systems

\textsuperscript{28} after Chan, C.C.; Wong, Y. S.; Bouscayrol A.; Chen A.; Powering Sustainable Mobility: Roadmaps of Electric, Hybrid, and Fuel Cell Vehicles; *Proceedings of the IEEE*, Vol. 97, No. 4, April 2009, pp. 603 – 607
Towards a “More-than-Moore” roadmap

- adaptive light projection systems

Convenience
- non fogging windscreens
- anti-dazzle systems
- automated light and wipers
- user identification systems
- adaptive control elements and human machine interfaces
- personalized environment
- advanced multimedia systems

Smart Power Train
- clean power train
- smart energy strategies
- alternative fuel concepts
- adaptive power train solutions
- comprehensive energy management
- active wheels

Fully Electrical Vehicle
- Smart systems for the management of energy storage systems
- Intelligent power electronic devices
- Active control units for electric motors & wheels
- Smart integration of range extenders
- Advanced vehicle to grid connection systems

Because the research agenda is still quite general, additional work has to be done. Moreover, the fully electrical car will face industry with new challenges. Within Europe a so-called Coordination Action “Information and Communication Technologies for the Full Electric Vehicle (ICT4FEV)” of the European Green Cars Initiative\(^\text{30}\) was initiated by the technology platform EPoSS and has been started May 1\(^{st}\), 2010.

The focus of the project is on enabling the full electric vehicle (FEV) by opening new technology paths towards energy efficiency, functionality and usability that are complementary to future advances in performance of battery cell technology. The objectives of the project include: to build a R&D community, to edit a European roadmap, to recommend standards, regulations, business cases and R&D priorities, and to establish a European Organization / Think Tank for the FEV.

The consortium is lead by VDI/VDE-IT and includes as members CRF (I), Siemens (D), NXP (NL), and EADS (F), as well as AVL List (A).

The results of these discussions shall be integrated across the involved sectors into a “European FEV roadmap”. It will be the basis for a strategy process that makes suggestions for regulations and standards related to ICT for the FEV that may serve both involved industries and public authorities as a guideline for the move towards full electric mobility in Europe.

3.1.4. Technical Challenges

Major challenges from an application point of view are low cost packaging, manufacturing and assembly. Meeting harsh environmental conditions, maintaining quality and reductions of costs are the main drivers. The infrastructure for low-cost, high-density substrates (i.e.,

\(^\text{30}\) Information and Communication Technologies for the Full Electric Vehicle (ICT4FEV), www.ict4fev.eu
module level) is regarded as critical. Up to now IC- or microsystem-specific challenges are not discussed in publicly available roadmaps.

On a component level only low cost built-in IC self test and real time process control for the assembly processes are regarded as critical issues to reduce the dependence on final functional tests.

Another issue is the convergence of automotive and consumer electronics because the different life cycles of automotive electronics products and the higher reliability requirements compared to consumer electronics often hamper a utilization of consumer products in vehicles.

### 3.1.5. Conclusions

Is “Automotive” as a whole a suitable topic for roadmapping? Using the scheme from the basic considerations about roadmapping this question can be clearly denied. On the other hand focused roadmaps on dedicated subfields have to be considered.

<table>
<thead>
<tr>
<th></th>
<th>FOM</th>
<th>ECO</th>
<th>SHR</th>
<th>WAT</th>
<th>LEP</th>
<th>Public technology roadmaps?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Automotive</td>
<td>−</td>
<td>+</td>
<td>−</td>
<td>+</td>
<td>?</td>
<td>few</td>
</tr>
</tbody>
</table>

*FOM = Figure Of Merit  
ECO = Existing Community  
SHR = Willingness to Share information  
WAT = Wide Applicability of Technology  
LEP = “Law” of Expected Progress

**Table 8 – Assessment scheme for the application field “automotive”**

Today existing roadmaps are only partially public. They give a sketch of the general requirements for the next years, but these publicly available roadmaps do not cover the semiconductor viewpoint. Starting a “More-than-Moore” roadmapping process from an application point of view will be therefore as complex as trying to start it from a mere technological basis. Due to the complexity of “More-than-Moore” applications and the variety of different technologies to implement these applications it will be a tough task to work out such a matrix and to identify the best suited technologies for roadmapping. Suitable figures of merit still have to be defined and an accepted “law” of expected progress is not yet known. The willingness to share information as a basis for roadmapping outside the existing (industrial) initiatives seems to be low, although a community already exists. Since the “More-than Moore” technologies used in the automotive area are usually not restricted to the automotive sector, widespread application of these technologies is guaranteed. However, a proper selection of the eligible technologies requires a combination of the results for several application domains.

An additional roadmapping activity would compete not only with the car manufacturers’ efforts, but will also interfere with other initiatives, like the EPoSS SRA and the EPoSS triggered ICT4FEV initiative.

Therefore a close cooperation with EPoSS and ICT4FEV is recommended to get
- the necessary electronics-related information
- to get access to the car manufacturers
3.2. Wearable Healthcare

Chris Van Hoof, IMEC

3.2.1. Scope and Taxonomy

Recent efforts on medical device development have focused on providing solutions for wearable health monitoring systems, to allow physiological monitoring and interpretation in daily life environments. To provide these solutions, devices must be smaller and more comfortable to wear, be robust against motion artifact, be power efficient, intelligent, and be able to communicate with the user. Microelectronic advancements are therefore paramount to ensuring the new devices are capable of these requirements.

In wearable health monitoring systems, the important microelectronic advancements can be grouped into the following components:

- **Sensors and circuitry**: sensitive sensors appropriate to the application, for accurately monitoring the relevant signals, while being miniaturized and low power

- **Digital Signal Processing and Digital Signal Processors**: to allow intelligence to be embedded in the wearable health system while maintaining reduced overall power consumption

- **Integration technologies**: to be able to provide a wearable device suitable for continuous wear in daily life, the electronics components must be suitably integrated together. This includes ensuring flexibility and stretchability of the device.

- **Memory**: some applications use local storage of data, and therefore rely on the availability of memory. This storage can also be done on an external device, in which case the data must be transmitted wirelessly.

- **Power management**: autonomous devices providing long use times with less user interaction add to the wearability of the device, and overall compliance with using the device. Therefore power management, both from ultra-low power consumption and from energy harvesting technologies are necessary.

- **Radio technologies**: for real time monitoring and alerting, a message must be transmitted from the device to the user. In addition, to achieve wearability, this transmission must be wireless.

- **Body/electronics interface**: necessary to capture the relevant body signals at the required quality. In case of electrical measurements, this can be electrodes with or without contact gel. It also includes the means of attachment.

Wearable health monitoring devices can be divided according to their application domains. For each application domain, the importance of a particular enabling technology can be rated. The applications surround health monitoring using a wearable patch device such as ECG patch, wearable EEG device, or subcutaneous devices. Four major application domains are identified:

- **Monitoring**: long-term, diagnostically relevant monitoring of the full data, with all data recorded and allowing the medical professional to make diagnosis. Analysis will typically be made off-line. For example, measuring ECG for a longer period of time (Holter system).
- **Prevention**: continuous monitoring of a known disorder in order to provide an alarm to detect and/or prevent the onset of the disorder. For example, in epilepsy monitoring, to monitor the patient and alert them to the onset of an epileptic seizure. Prevention can also be used to assist in preventing the development of a disorder such as obesity, by monitoring the risk factors.

- **Closed loop**: automatic detection of an adverse event, and automatically provide output to overcome the adverse event. For example, in diabetes monitoring, to detect the blood glucose level and automatically provide insulin as necessary.

- **Spot-check**: whenever desired, the user can measure a body function. For example, when a heart patient feels a bit dizzy, he grabs his phone with two hands, after which his ECG is analyzed.

Generic technology requirements can be defined for each of these application domains. For example, monitoring devices typically do not have onboard intelligence for decision making; therefore digital signal processing and processor technologies are less important than storage capability (memory). Monitoring devices may require efficient, medical grade, radio communications in case the physician needs on-line access to the data. To the contrary, prevention and closed-loop devices require advanced intelligence and the ability to provide an alert to the user or automatic feedback, requiring enhanced digital signal processing capabilities. Depending on the implementation as a Body Area Network or as a single-unit device, wireless technology can be added as required technology. Spot-check devices have less stringent power consumption requirements in comparison to the three other domains. Table 9 provides an estimation of the importance of enabling technologies for the four application domains considered here.

<table>
<thead>
<tr>
<th>Application domain</th>
<th>Sensors and circuitry</th>
<th>DSP (Artifact reduction)</th>
<th>DSP (Event detection)</th>
<th>Integration Technologies</th>
<th>Memory</th>
<th>Power consumption</th>
<th>Radio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monitoring</td>
<td>+++</td>
<td>+++</td>
<td>+</td>
<td>+++</td>
<td>+++</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>Prevention</td>
<td>++</td>
<td>+++</td>
<td>++</td>
<td>+++</td>
<td>++</td>
<td>+++</td>
<td>+++</td>
</tr>
<tr>
<td>Closed-loop</td>
<td>++</td>
<td>+++</td>
<td>+++</td>
<td>+++</td>
<td>+</td>
<td>+++</td>
<td>+</td>
</tr>
<tr>
<td>Spot-check</td>
<td>++</td>
<td>+</td>
<td>+++</td>
<td>+</td>
<td>++</td>
<td>+</td>
<td>+++</td>
</tr>
</tbody>
</table>

**Table 9** – Relevance of enabling technologies for four wearable healthcare application domains

Wearable healthcare devices can also be grouped in terms of the medical field they address: a particular disease, disorder or conditions. Specific technology requirements can then be defined for a particular medical field in a certain application domain. A few examples are given here:
Cardiac (Holter). A patient with known heart problems attaches the wearable device by sticking gel electrodes to his chest. The device records and locally stores the raw ECG on a micro-SD card for a long period of time. The recorded data is manually evaluated by a cardiologist.

Epilepsy. A patient with regular epileptic seizures always wears his EEG cap when going out. The electrodes in the cap comfortably touch his skull and ensure a reasonable signal quality without the need for gel. Intelligent algorithms are processing the brainwaves continuously, in order to predict epileptic seizures 5 minutes before they actually happen. Signal processing algorithms clean up the signals, as to make sure that the intelligence is not confused by motion artifacts and other forms of interference. In case of a predicted epileptic event, the user is warned by means of a message that appears on his watch, combined with haptic and audible feedback.

Stress. A manager starts the day by putting on a sticky chest patch and his stress watch. The heart rate, breathing rate and skin conductance can be measured this way. Combined with other sensors, that provide information about the manager’s state of physical activity, the algorithms embedded in the watch can estimate the level of mental stress. Haptic feedback is provided if the stress level is elevated too long, after which the manager can go for a short break.

COPD. A patient diagnosed with the lung disease COPD (Chronic Obstructive Pulmonary Disease) needs therapy in order to manage the disease and reduce symptoms. This requires a strict control over the amount of daily physical activity. Therefore, the patient is wearing sensors (accelerometers and gyroscopes) that can be used to estimate the level of physical activity. On top of that, the bodily response to the physical activity is monitored by a sticky chest patch, which captures heart rate and respiration rate. All sensors work together in a Body Area Network, which takes care of integrating all data into an advice to the patient.

etc.

From the definitions above, we can derive typical requirements for these applications, as summarized in Table 10.
<table>
<thead>
<tr>
<th>Medical field</th>
<th>Application domain</th>
<th>Sensors</th>
<th>DSP</th>
<th>Form factor</th>
<th>Memory</th>
<th>Autonomy</th>
<th>Radio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cardiac (Holter)</td>
<td>Monitoring</td>
<td>Multi-lead ECG, accelerometers</td>
<td>Artifact reduction</td>
<td>Patch type</td>
<td>GB</td>
<td>7 days to 1 month</td>
<td>On-request for remote data inspection</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EEG</td>
<td>Artifact reduction</td>
<td>Certain level of obtrusiveness ok to start with</td>
<td>MB</td>
<td>7 days</td>
<td>Event-based</td>
</tr>
<tr>
<td>Epilepsy</td>
<td>Prevention</td>
<td>Multi-sensors: ECG, respiration, GSR EMG, ACC</td>
<td>Artifact reduction Seizure detection</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stress</td>
<td>Prevention</td>
<td>Multi-sensors: ANS, bio-chemical sensors</td>
<td>Artifact reduction Stress measurement</td>
<td>Extremely non-obtrusive</td>
<td>MB</td>
<td>1 month</td>
<td>On-demand</td>
</tr>
<tr>
<td>COPD</td>
<td>Prevention</td>
<td>Multi-sensors: ECG, respiration</td>
<td>Artifact reduction Patch type or belt</td>
<td>MB</td>
<td>7 days</td>
<td>Event-based</td>
<td></td>
</tr>
<tr>
<td>Stroke</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Parkinson</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Asthma</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weight management</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diabetes</td>
<td></td>
<td>Closed-loop</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sleep apneas</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 10 – Typical technology requirements per medical field and application domain
3.2.2. Eligibility for Technology Roadmapping

3.2.2.a. Figures of merit

Today’s available components and technologies need to be improved on several aspects to make a wearable health sensor that will find its way to potential end-users. Several Figures of Merit (FoM) can be defined, depending on which technology aspects are most important for a certain application.

- Autonomy (how long the device can be used before it needs re-charging)
- Wearability (small size, flexible, non obtrusive)
- Performance (quality of diagnosis in terms of Positive predictivity and False negatives)
- Robustness to daily life activities (i.e., movement)
- Reasonable cost

Generic figures of merit can impossibly be given, which is why it will be done here on application basis. As reference, the 4 categories as defined above will be re-used. The results can be seen in Table 11, where the most difficult requirement is indicated in bold.

<table>
<thead>
<tr>
<th>Purpose</th>
<th>Autonomy</th>
<th>Wearability</th>
<th>Performance</th>
<th>Robustness</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monitoring</td>
<td>7 days</td>
<td>15 cm³</td>
<td>99.9%</td>
<td>ADL</td>
<td>€500</td>
</tr>
<tr>
<td>Prevention</td>
<td>7 days</td>
<td>1 cm³</td>
<td>80%³²</td>
<td>Sports</td>
<td>€200</td>
</tr>
<tr>
<td>Closed-loop</td>
<td>2 days</td>
<td>5 cm³</td>
<td>100%</td>
<td>Sports</td>
<td>€1000</td>
</tr>
<tr>
<td>Spot-check</td>
<td>100x</td>
<td>10 cm³</td>
<td>90%</td>
<td>Quiet</td>
<td>€20</td>
</tr>
</tbody>
</table>

注释：
³¹ Robustness categories: Sports (extreme movement), ADL (Activities of Daily Life, in-house activities, moderate movement), Quiet (no movement)
³² Performance is defined here as the average Sensitivity and Positive predictivity of the analyzing algorithm.
³³ Please note that higher levels of intelligence/reasoning can be used to prevent false alarms

In this case, being portable is more important than wearable

Table 11 – Figures of Merit as a function of application category

This overview is a generalization and therefore, exceptions will exist in which it cannot be applied. The applications, as defined in Table 10, can also be used to make similar table, in order to obtain a higher level of detail.

3.2.2.b. Drivers of wearable healthcare

1. The present

There is a wide consensus about the necessity of Wireless Sensor Networks (WSN) as means to deliver higher quality health monitoring at lower cost. This general opinion is backed by many data, related to the high prevalence of certain chronic diseases and the ageing population in western countries.
For example, Table 12 shows that a large percentage of the total expenditure on health costs in Europe is spent on a few chronic diseases. If the use of WSN could result in more prevention and more on-line monitoring (i.e., less visits to the doctor), this could rapidly reduce healthcare costs.

<table>
<thead>
<tr>
<th>Diseases</th>
<th>Prevalence</th>
<th>Costs</th>
</tr>
</thead>
</table>
| Diabetes (IDF Diabetes Atlas, plus several sources) | - 6.6% of total population  
- 2.2 million DALYs lost yearly | - Type II: € 29 billion per year in 8 countries (Jönsson and Jönsson 2002), |
| COPD (Several sources)                    | - Range from 4% to 11%  
- 2 million DALY lost yearly | - No aggregate data found  
- cost per patient per year: from € 400 up to € 2,100 (several studies) |
| CVD in general (S. Allender, ed. 2008)    | - 12 million DALYs lost yearly                                            | - EU27 € 109 billion direct costs= 10% of expenditure  
- Indirect costs: € 83 billion (41 of lost productivity and 42 for informal care) |
| CHF (several sources, OECD 2009 Health Data) | - Between 1% and 3% of general population  
- 10% among the very elderly | - Up to 2% of total health expenditure (23 Billion €)  
- Up to 5% of all hospital admissions  
- CHF patients average bed occupancy: 10.2 days  
- Up to 45% re-hospitalisation after 6 months of discharge  
- Mortality rate at one year 25%-40% (at 5 year up to 75%)

Table 12 – Prevalence and costs involved in most common chronic diseases (source: ITPS: Strategic Intelligent Monitor of Personalized Health Systems – SIMPHS (2009-2011))

The Continua alliance has gathered statistics on the present status of fitness and chronic diseases. The main trends are summarized as follows:

- There are more than 1 billion overweight adults worldwide and at least 300 million who are clinically obese (WHO World Health Report, 2002). Researchers associate obesity with more than 30 medical conditions. Annual healthcare costs associated with obesity are approximately $100 billion.

- About 21% of coronary heart disease globally is attributable to body mass index (BMI) above 21 kg/m² (WHO World Health Report, 2002). About 22% of coronary heart disease globally is caused by physical inactivity (WHO World Health Report, 2002)

- 860 million people worldwide have one or more chronic diseases

- 1.3 billion people worldwide smoke

- In Europe, cardiovascular disease causes more than 4.35 million deaths (49% of all deaths) each year (European Cardiovascular Disease Statistics, 2005 edition, Dept. of Public Health, University of Oxford)

- It is estimated that over 48 million adults in Europe (including Eastern Europe and Russia) aged 20–79 years are living with diabetes — an overall prevalence of 7.8%. (The International Diabetes Federation’s Diabetes Atlas)

- 15–37% of the global adult population has hypertension. In those older than age 60, as many as one-half in some populations are hypertensive. (Integrated Management of Cardiovascular Risk. Report of a WHO Meeting, Geneva, July 2002). WHO estimates that 600 million people with hypertension are at risk of
heart attack, stroke and cardiac failure (Cardiovascular Diseases – Prevention and Control. WHO CVD Strategy, 2001-2002)

- The number of healthcare providers is decreasing: according to the World Health Organization’s World Health Report, 2006, there is a global shortage of 4.3 million doctors, midwives, nurses, and support workers

2. The future

It is well known that the expenditure on healthcare will grow in the near future, because of an ageing population, as shown in Fig. 14 (source: Uwe Reinhardt, economist at Princeton University and EuroStat, 2004-based population projections, trend scenario, baseline variant (2010-2050)).

![Fig. 14](image)

**Fig. 14** – Projected for the percentage of the total population aged 65 and over

Fig. 15 shows how this growing population of elderly will change the cost of healthcare, and hence the financial burden on society (source: Uwe Reinhardt, economist at Princeton University).

![Fig. 15](image)

**Fig. 15** – Relative healthcare spending by age category. Age group 35-44 set to 1.
The Continua Alliance also makes projection for the evolution of the prevalence and costs of major diseases in the next decades. The main projections are summarized here.

- Heart disease and stroke will become the leading cause of both death and disability worldwide, with the number of fatalities projected to increase to more than 20 million a year by 2020 and to more than 24 million a year by 2030. (Atlas of Heart Disease and Stroke, WHO, Sept. 2004)


- By 2020, tobacco is expected to be the single greatest cause of death and disability worldwide, accounting for about 10 million deaths per year. (World No-Tobacco Day, WHO website, Jan. 2004)

- Obesity among children has reached epidemic proportions. WHO estimates that about 22 million children worldwide under age 5 are overweight. In the United States in the last 30 years, the prevalence of overweight children ages 5-14 has increased from 15% to 32%. One of four U.S. children is overweight, while 11% are obese. In Beijing, 20% of school children are obese. 16% of Saudi schoolboys are considered obese. (World Heart Federation Fact-Sheet, 2002.)

- There are 600 million people in the world over 60. By 2025, there will be 1 billion. By 2050, the number will be 2 billion.

### 3.2.2.c. Wearable healthcare eco-system

Wearable healthcare is addressing these issues by offering high quality and person-centric health services at affordable cost. The goal is to bring cost of medical service down through prevention, monitoring and e-health (i.e., online consults).

However, as the medical care paradigm shifts towards patient-centered care, the need for interoperable and low cost devices and services increases. Not only do the wearable health sensors need to incorporate increasing functionality and intelligence into an ever-shrinking, comfortable form factor, but they need to communicate with other devices and wider health services. Therefore development of these new health monitoring mechanisms require integration of multiple components:

- Wearable health sensors
- Communications network infrastructure for data communications
- Infrastructure for data centralization (storage and processing)
- Medical service provider network for expert medical assistance

Typically, these components will be developed and manufactured by many different players, which makes co-operation and sharing of information a necessary condition for successfully creating a functional eco-system. Furthermore, sharing of information will be a prerequisite for creating affordable healthcare solutions. Nowadays, we see several alliances in which big
players join forces (Continua, West Wireless Health). This shows that the willingness to share information exists, although still many activities are deployed by entities that are not part of such alliances.

An eco-system would consist of companies and bodies that realize the aspects given in the list above (wearable sensors, communications infrastructure, centralized data storage and processing infrastructure and medical service providers). A more detailed breakdown of such eco-system is given in Fig. 16.

![Fig. 16 – Eco-system for wearable health systems](image)

The large number of players requires a large degree of standardization to ensure interoperability. Such a close community exists today in the Continua alliance.
3.2.3. Existing Roadmaps

In order to observe trends and convergence in the field of wearable healthcare, roadmaps from the participants in the entire eco-system need to be investigated. Taking from Fig. 16, the ecosystem can be grouped into 3 lines, with various industries and bodies involved at different levels.

- Regulatory bodies
  - European Union
  - FDA
  - Standardization bodies

- Industries active in the wearable health value chain
  - Semiconductor industry (chips from large manufacturers, sensors)
  - Mobile and IT industry (Enhanced Data Rate, network infrastructure)
  - Pharmaceuticals
  - Medical Devices

- Enabling stakeholders
  - Medical professionals
  - Medical insurance agencies
  - Application research centers

Each participant in the ecosystem comes with its own vision and roadmap. Some of them are reviewed here.

3.2.3.a. Regulatory Bodies

Regulatory bodies provide the guidelines for safe and effective development, implementation and use of technology. They include government bodies such as the FDA that work with lawmakers, through to technical bodies such as the IEEE that regulate technology specifications to ensure seamless system integration and operation.

1. European Commission: PHS2020 project

The PHS2020 project, a European Commission FP7 funded project, aimed to produce

a policy-oriented Research and Technology Development roadmap for future ICT-supported Personal Health Systems, focusing on technological developments and applications, but also taking into consideration broader societal trends and issues.

The results of the project are summarized in the book “PHS2020 – Reconstructing the Whole: Present and Future of Personal Health Systems presents the vision of future Personal Health Systems”. The main focus is on filling the gaps in the current technologies towards fully functional personal health systems of the future. In order to fill these technology gaps, some key actions are defined:

- Infuse biomedicine into technology
- More intelligent data processing: from personal to personalized

---

34 “PHS2020 – Reconstructing the Whole: Present and Future of Personal Health Systems presents the vision of future Personal Health Systems; available on the website”

- New generation sensors: self-calibrating, with on-board processing, multi-signs/multi-diseases, non invasive, energy efficient, plug and play into Body Area Networks
- More inclusive and user-friendly interfaces and interaction channels
- Move from remote monitoring to diagnosis, treatment and prevention

The future wearable health system is sketched as follows:

- it will capture the very peculiar characteristics of individuals (vital and physiological signs, but also their genetic outlook, as well as their clinical history, and their socio-demographic and socio-economic conditions)
- it ensures awareness of very punctual contextual conditions (location, activity being performed, emotional status, physical and chemical conditions in the environment, etc.)
- it intelligently processes such information to support traditional action and automatic actuation, thus enabling new applications and services going beyond monitoring
- it uses devices as minimally invasive and constraining of normal life as possible, adaptable to the very personal specificities and needs of each single individual.

The result is a roadmap (Fig. 17) that aims to bring the next generation of personal health systems to a state where they can be widely deployed in every-day health monitoring.

Fig. 17 – PHS2020 roadmap, supported by the European Commission

2. **Continua Health Alliance**

One of the bodies working on standardizing the entire value-chain of body area network-based wireless health monitoring systems is the Continua Health Alliance. Continua is an open industry group comprising some 240 medical providers and networking and medical
 device companies, aimed to develop interoperable tele-health devices and services towards chronic disease management, independently aging and health and fitness monitoring. Towards these goals, Continua provide guidelines for device implementation to meet industry standards such as ZigBee and Bluetooth for wireless communications. The resulting products are given the Continua Certified certificate, indicating the device is interoperable with other certified devices. Other activities include reimbursement tactics and strategies with insurance companies, and work towards a centralized database collection for remote patient monitoring.

3. Wireless communication standard: example of Bluetooth

Several wireless standards are under development that will facilitate wearable sensor networks, specifically targeting the requirements of low-power, privacy, quality of service, co-existence (both with other wireless equipments as well as with medical equipments) and compatibility. Specifically for wireless health monitoring, Bluetooth, Zigbee and IEEE 802.15 communications are most commonly used.

The goal of Bluetooth has always been to provide a flexible cable replacement technology at low cost, insensitive to interference, compatible among different products from different brands (interoperability) while still consuming low-power. Bluetooth development has followed two streams: one towards higher data rates to facilitate streaming music, video and transfer of large files; the other towards low-power (and low-bandwidth) communication. This resulted in several possible different physical layers for Bluetooth.

Interoperability is ensured through the use of profiles, and one of the profiles currently under definition is the medical devices profile, which will most likely be targeting (among others) low power communication (expected in 2010).

Chips with Bluetooth Low Energy are becoming available now, such as the Nordic nRF8001 from the mBlue series.

3.2.3.b. Industry

In order to manufacture and implement the wireless health concepts, many key industries are required. Exploring their own roadmaps, it is evident that little coherence occurs across the industries, highlighting the need for a focused wearable healthcare roadmap which incorporates the input from these industries.
4. **Semiconductor industry**

Several companies are active in the field of low-power integrated circuitry, such as Texas Instruments, Atmel, NEC/Renesas, NXP, Nordic, Broadcom and Qualcomm to name a few. In line with “Moore’s Law”, these chips benefit from ongoing shrinkage of chip processes, and hence improved performance at less power. However, in addition to “Moore’s Law”, we see increasing activity in the “More-than-Moore” paradigm, where multiple technologies are integrated into the one chip, resulting in lower power consumption and enhanced functionality.

As example, the following figure shows the current TI MSP430 microprocessor family together with the future versions. We can clearly see a trend towards higher integration with more performance. The power consumption of these new chips is projected to go even smaller than the current generation.

![Figure 19](image-url)  
**Fig. 19** – MSP430 roadmap: higher performance, lower power, low price (F5xx)

5. **Mobile and IT industry**

One of the main requirements for wireless health monitors is connectivity, to either a remote patient monitoring system, personal data storage system, or other network service. Therefore the infrastructure is as necessary as the monitoring devices. Further, mobile phones can act as gateway between the Personal Area Network and the outside world. This will create data traffic, and hence the interest of cellular network operators in wireless health is explained.

However, the mobile operators are not very open in disclosing their roadmaps. One interesting press release from 2009 was made by Philips and Vodafone in which a new division is announced to provide mobile solutions to governments and pharmaceutical companies for mobile health services. At this year’s Mobile Health Industry Summit 2010, Qualcomm’s Vice President of Healthcare Don Jones stated: “It’s clear now that operators (as we saw in an earlier presentation by Thierry Zylberbery from Orange) are going to form part of a new distribution channel for some of the important developments in the healthcare”.

---


Towards the necessary back-end network infrastructure, a group of companies and institutions joined forces to draft a roadmap on IT developments to facilitate long-term and post acute care. However, it does not come up with very concrete, tangible items. A more concrete but rather old roadmap is the “roadmap for the adoption of health information technology in rural communities” (August 2006). It gives some examples of well-suited applications for IT, among which:

- **Remote psychiatric evaluation/monitoring**
  Through videoconferencing, remote psychiatric evaluation and treatment can improve access to mental healthcare for patients without providers nearby.

- **Remote fetal monitoring of high risk pregnancies**
  For women with high-risk pregnancies, remote fetal monitoring would allow doctors to more closely track the fetus’s condition and respond quickly to any change, without necessarily relying on long hospital stays.

- **Remote home healthcare assistance**
  Remote home healthcare assistance will improve the quality of care patients are able to receive in their own homes with the help of telemedicine and remote monitoring technology.

- **Remote chronic disease monitoring and management**
  Remote home healthcare assistance will improve the quality of care patients are able to receive in their own homes with the help of telemedicine and remote monitoring technology.

### 3.2.3.c. Enabling Stakeholders

With the support of the key involved industries to provide manufacturability, and the adherence to the regulatory requirements, the final piece of the eco-system involves the presence of the enabling stakeholders. These are the people, institutes and centers, and companies who contribute to the development and realization of the new wearable health concepts, both pulling from the application side and pushing from the technology development side. Above all, without the support of the medical professionals themselves and the ability to fund devices through medical insurance rebates, wearable health devices could not be accepted as standard devices.

### 6. VTT Technical Research Centre of Finland

In 2007, VTT published a roadmap, in which the landscape for wireless sensor networks was sketched, and possible topics for further exploration are pointed out.

Some technical solutions for long-term health and wellness monitoring are described here: “Development of viable methods for long-term monitoring of health and wellness in real life settings. This includes easy wearability and management of personal wireless sensor networks, mobile phone-centric data collection, signal processing, wellness history presentation for self care, and integration of wellness data with patient information databases. Easy WSN management includes maintenance-free units requiring energy scavenging and...

---

37 A roadmap for Health IT (HIT) in Long Term and Post Acute Care (LTPAC) 2010-2012 (http://www.ahima.org/advocacy/ltpachit.aspx)
38 http://www.norc.uchicago.edu/NR/rdonlyres/6A09114C-1B4D-4834-A942-8D6E0EDB799B/0/HIT_Paper_Final.pdf
low-power wireless sensors and sensor platforms. The focus is on stress and weight management, and monitoring of wellbeing of the elderly.

Development of low-power wireless (RFID) sensors with memory capacity capable of storing several measurements.”

On the medium term, they foresee “mobile phone-centric field trials with embedded or external sensors. Construction of a gateway to integrate sensor network protocols with mobile phone.”

On the longer term “wellness monitoring carried out by a wearable system that includes an easily portable UI unit/gateway device (wrist unit, pendant), which may communicate with a mobile device online, and process and store data. Development of sensor tags capable of storing a series of measurements. Physical selection should be included as a means to manage the configuration and measurements of peripheral devices.”

7. Holst Centre (Netherlands)

The Holst Centre in the Netherlands follows a roadmap (Fig. 20) in which 4 axis are defined based on the particular embodiment of the technology, and the application it targets.

- Health patch for monitoring, prevention and closed-loop system
- Headset for brain-computer interfaces
- Subcutaneous implants
- Stress and emotion monitoring, combining several of these embodiments

The main technical challenge is the design of ultra-low power components to make such systems. Also challenges on sensor technology, integration technology and validation are foreseen.
3.2.4. Technical Challenges

The challenges towards wearable health monitors can be categorized into 6 categories.

3.2.4.a. Longer autonomy

To reach maximum autonomy, it is required to develop wireless sensor nodes that are ultra-power efficient, through developing alternative strategies for various technologies.

One could think of specific data processing units, targeting a functional domain (one example being a DSP specifically suited for biomedical processing). This can well be combined with forms of analog (pre-) processing. The technical challenge is to find the architecture that is specific enough to match the low-power requirements but still broad enough to be commercially interesting.

When in use, the radio is one of the major power consumers on a wearable health device, thus it is necessary to improve power efficiency of the radio (including the used protocols for wireless transmission). The technical challenge will be to find a reasonable trade-off between flexibility (in terms of latency, data throughput, packet error rate) and yet simplicity and the possibility to go to very low-power sleep modes. This trade-off also needs to be flexible in its application, as the use of the radio will be application-dependent:

- **Monitoring**: the radio will either not be used at all, as in the case of a holter-like device where data storage is on the sensing device, or the wireless transmission quality needs to be very high to ensure data is transmitted in real time and maintain data integrity, in which case the demands on the radio are very high.

- **Detection and Prevention**: when used in combination with on-board signal processing, and through implementing an effective duty cycling scheme, the power consumption of the radio would be low on detection and prevention devices, as the data rate would be minimized. In fully closed-loop systems, the radio can become again important, especially when low latency is required.

On system level, smart strategies of using the available power can be found in distributed and adaptive processing (for example, the computational complexity of an algorithm might vary with the context or the situation). Hybrid strategies where analog and digital processing interchange depending on the situation, or where even the dynamic range of the analog to digital converter (ADC) is adapted as conditions change are largely unexplored. One related field is compressive sampling, where sampling is optimized with respect to signal information content. In general, low-power design at this level is a paradigm shift in a world where processing power is ever increasing, which forms one of the biggest challenges.

In addition, battery technology and energy harvesting technologies can be improved to provide power efficiently to the device. In this respect, thin film batteries are good candidates, providing good capacity at small and flexible form factors.

3.2.4.b. Wearability

Wearability shall be improved on through component miniaturization, development of systems-on-chip and systems-in-package, and integration into flexible and stretchable electronics and substrates. Many technical challenges still persist in this field, such as stability of the tracks and mounted components when bending a flexible PCB with a small radius. Miniaturization poses problems with electromagnetic compatibility when sensitive analog amplifiers have to work next to digital components and radio waves are transmitted.
Another wearability aspect is the use of sticky electrodes with gel. They are generally considered undesirable, which calls for more comfortable electrodes that do not need gel. However, these electrodes typically degrade the signal quality, which calls for better automated signal analysis methods.

### 3.2.4.c. Reliability and Trust

One of the worst things that could happen with the use of wearable health technology is that medical personnel are overloaded with false alarms. On the other hand, a missed event is just as bad. In either case, the trust in wearable health technology will diminish. Reliability and Trust is a true system challenge, which impacts the development of wearable sensors, and the entire infrastructure for health delivery. The technical challenge is to have excellent signal quality and very robust signal interpretation algorithms. Improvement of signal quality can be obtained by sensor research and by the use of amplifiers very close to the sensor (active front-ends). Of course, such active front-end needs to be ultra-low power.

Signal interpretation algorithms can be improved for example through multi-modality and personalization. The latter will require adaptive algorithms that can also learn from the user. The challenge is to have stable algorithms that will not drift to extremes. Pre-processing steps to remove undesired components from the signal can help in improving the performance of signal interpretation algorithms.

The network infrastructure shall also conform to the QoS requirements for a given application.

### 3.2.4.d. Monitoring ‘on-the-go’

Related to the previous point, but very important to note, is the notion of robustness in daily life activities. Typically, these activities will cause a degradation of the signal quality, and hence an increased likelihood of false alarms and missed events. Today, the general approach is to detect the artifacts, and discard the signals during the corresponding period. This is, however, not sufficient to enable use of wearable sensors in every-day life situations. This can only be overcome with very good sensors and signal interpretation algorithms, which shall be aware of the daily life activity and the possible artifacts that are introduced in the signal as a result of these activities. Methods to predict the impact of daily life activities on the signal and signal integrity are required for noise reduction techniques and prevention of false alarms. A potential correlate to such artifacts is the electrical impedance between the electrode and the skin.

A secondary source of awareness of the daily life activities could come from context awareness and multi-modality. Context awareness can be used to increase robustness if the daily life activity creates particular patterns in the observed parameter (for example, if the subject is practicing sports, then the heart rate typically goes up, which is in that case not a sign for a cardiac problem). Multi-modality can be used to increase robustness by looking at several signs for an observed condition, and only raise an alarm if all signs make the observed event very likely. For example, if the observed event is an epilepsy attack and the person starts shaking, it is gives only an alarm if the heart rate also shows a rapid increase. If not, then the person might just be biking on a very bumpy road.

### 3.2.4.e. Multi-sensory

As mentioned above, in some cases a multi-modal approach seems to help in increasing robustness of the wireless health system. However, the design of multi-sensory algorithms to interpret the all incoming data in a holistic manner requires knowledge about the co-variation of these parameters under all given conditions. This knowledge is, in many cases, not
available nowadays. There is a huge demand for such multi-sensory data, which can be used by the artificial intelligence community for the development of pattern recognition techniques to monitor body parameters.

If such parameters are measured at several parts of the body, they can form a body area network. A second challenge with multi-sensory data is how to process the data in such a way that the total system is optimized with respect to power consumption. Data fusion can be done on the raw sensory data, on classified data or anywhere in between – the choice might heavily impact the overall power budget. Possibly it can even be made dependent on the amount of energy available on a particular sensor node or on other conditions.

### 3.2.4.f. General

In general we can observe here a tension between simplicity for low-power and complexity for robustness. Along these lines, smart solutions on many aspects will make the difference between success and failure.

### 3.2.5. Potential Solutions

While there are many comfortable wireless health monitoring products available today, these generally measure only 1 or 2 parameters, are still bulky, have autonomy up to just a few days. Interoperability and interconnectivity of these devices is non-existent, resulting in limited monitoring functionality and limited intelligence achieved. Through development of platform technologies towards wearable health monitors, today’s limitations can be overcome.

In the field of wearable health patches, the leading products currently available are 1-lead ECG patches with embedded beat detection and arrhythmia detection algorithms, and aimed at continuous monitoring for prevention of adverse events (e.g., Corventis Piix). These systems are bulky, obtrusive and require regular recharging. Using microelectronic technologies, not only is the number and type of sensors increased, but so too is the intelligence available, the integration and the autonomy.

In comparison, few wearable headsets are available, and those that are (e.g., Neurosky, Emotiv) provide limited scope for use in daily environment. By miniaturizing the sensors and technologies, and enhancing their performance, new devices will allow continuous monitoring of disorders such as epilepsy in daily life.

Not only do sensors on the body benefit from the advances in microelectronic technology, but also subcutaneous sensors. Through miniaturization of the sensor, they are more suitable for implantation. Once implanted, they can be used for closed-loop monitoring of diseases such as diabetes, cardiac diseases and defibrillation, epilepsy via vagal nerve stimulation, hormone detection and delivery, muscle fiber activity and activation, and Parkinson’s disease via brain stimulation. Autonomy becomes a critical factor, as removing the sensor daily is no longer possible, as is intelligence and sensing and actuating components.
3.2.6. Conclusions

It seems rather difficult to envisage a roadmap effort on the whole healthcare application domain. On the other hand in focusing on dedicated markets some trends may be made more explicit and roadmaps could be envisioned. In this chapter we concentrate on wearable healthcare where further roadmapping efforts could make sense.

<table>
<thead>
<tr>
<th></th>
<th>FOM</th>
<th>ECO</th>
<th>SHR</th>
<th>WAT</th>
<th>LEP</th>
<th>Public technology roadmaps?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wearable healthcare</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>=</td>
<td>?</td>
<td>few</td>
</tr>
</tbody>
</table>

FOM = Figure Of Merit  
ECO = Existing Community  
SHR = Willingness to Share information  
WAT = Wide Applicability of Technology  
LEP = “Law” of Expected Progress

Table 13 – Assessment scheme for the application field “wearable healthcare”
3.3. Safety & security

Michel Brillouët, CEA-Leti

The Merriam-Webster on-line dictionary\(^\text{40}\) defines:

- **safety** as “the condition of being safe from undergoing or causing hurt, injury, or loss” or “a device designed to prevent inadvertent or hazardous operation”
- **security** as “the quality or state of being free from danger, fear, anxiety or risk of loss, or of being safe”, as “something that is secure (synonym of protection), trustworthy or dependable”, or as “measures taken to guard against espionage or sabotage, crime, attack, or escape”.

Wikipedia\(^\text{41}\) proposes similar definitions in adding more details:

- **safety** is “the state of being safe […], the condition of being protected against [any] types or consequences of failure, damage, error, accidents, harm or any other event which could be considered non-desirable. Safety can also be defined to be the control of recognized hazards to achieve an acceptable level of risk. This can take the form of being protected from the event or from exposure to something that causes [damages]. It can include protection of people or of possessions.”
- **security** is “the degree of protection against danger, damage, loss, and criminal activity. Security as a form of protection is structures and processes that provide or improve security as a condition. […]. Security [can be defined] as a form of protection where a separation is created between the assets and the threat. This includes but is not limited to the elimination of either the asset or the threat. […] The key difference between security and reliability is that security must take into account the actions of people attempting to cause destruction.”

It should be stressed that the perception of safety is rather subjective and any “objective” analysis and engineering response or regulation may not be felt appropriate enough. The “perception of security can […] increase [or decrease the] objective security” depending on how far the measures in place will “affect or deter malicious behavior”\(^\text{42}\).

In summary this domain covers all measures intended to prevent the consequences of non-desirable and harmful events. It combines:

- an event or **threat** (and in some cases the probability of occurrence)\(^\text{43}\)
- what is impacted by this event (the **assets**)
- the **vulnerability** of the asset to the threat\(^\text{44}\)
- the **severity** of the impact (which will contribute to define the “acceptable level of risk”)
- systems to **detect** the threat
- reliable **measures** put in place (which involves some cause – effect analysis):
  - to prevent or reduce the likelihood of the event

\(^\text{43}\) In most cases the system under attack / thread is not used / working in the way it was designed for.
\(^\text{44}\) It is often referred to critical infrastructures without giving a way to assess the criticality of this asset.
to avoid, mitigate or dilute (risk sharing) the impact of that event
- to transfer the impact on less harmful assets
e.g., in creating a tight separation between the assets and the threat
- the cost of such measures with respect to the benefit and efficiency of the prevention

Any roadmap or strategic document is structured along these lines. The way this field can be analyzed is reminiscent of techniques like quality insurance, risk management, root cause analysis, FMEA… and the like.

### 3.3.1. Scope & taxonomy

One way to classify technologies for Safety and Security is to build application scenarios from the combination of threats (see Table 14), assets (see Table 15) and measures (see Table 16). While this approach may lead to the definition of products / applications and an assessment of markets, it hardly brings any clue about which technologies or generic functions need to be specifically developed.

<table>
<thead>
<tr>
<th>Events external to the asset</th>
</tr>
</thead>
<tbody>
<tr>
<td>- environment-related</td>
</tr>
<tr>
<td>- natural disasters (weather, earthquake…)</td>
</tr>
<tr>
<td>- pollution…</td>
</tr>
<tr>
<td>- hardware-related</td>
</tr>
<tr>
<td>- fire</td>
</tr>
<tr>
<td>- electrical hazard…</td>
</tr>
<tr>
<td>- people related</td>
</tr>
<tr>
<td>- accident (traffic, sport…)</td>
</tr>
<tr>
<td>- ill and/or infectious people</td>
</tr>
<tr>
<td>- undue external control, intrusion</td>
</tr>
<tr>
<td>- criminal activity:</td>
</tr>
<tr>
<td>- theft</td>
</tr>
<tr>
<td>- fraud, forgery, counterfeiting</td>
</tr>
<tr>
<td>- illicit materials and commerce</td>
</tr>
<tr>
<td>- cybercrime</td>
</tr>
<tr>
<td>- violence…</td>
</tr>
<tr>
<td>- espionage</td>
</tr>
<tr>
<td>- terrorism or sabotage (NRBCE = nuclear, radio, biological, and chemical threats, arms and explosives…)</td>
</tr>
<tr>
<td>- nuclear proliferation</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Events due to internal dysfunction of the asset</th>
</tr>
</thead>
<tbody>
<tr>
<td>- faulty function</td>
</tr>
<tr>
<td>- reliability</td>
</tr>
<tr>
<td>- software integrity over the product’s lifetime…</td>
</tr>
</tbody>
</table>

*Table 14 – Examples of harmful events (threats) which could be considered in the Safety and Security application domain.*
### Examples of assets potentially affected by harmful events and necessitating security measures

<table>
<thead>
<tr>
<th>People</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical assets</td>
</tr>
<tr>
<td>- goods (private or professional) including real estate (home, professional building), furniture, belongings…</td>
</tr>
<tr>
<td>- public infrastructures (information networks and nodes (servers…), airports, ports, public transportation (trains, buses…), roads, hospitals, schools, defense, buildings, utilities, waste treatment…)</td>
</tr>
<tr>
<td>- private infrastructures (in agriculture, industry or services, <em>e.g.</em>, shops, factories…)</td>
</tr>
<tr>
<td>- borders</td>
</tr>
<tr>
<td>- international interconnection of infrastructures</td>
</tr>
<tr>
<td>Traceable and guaranteed supply (food, water, energy, electricity, fuel…)</td>
</tr>
<tr>
<td>Continuous flows</td>
</tr>
<tr>
<td>- supply chain (flow of goods)</td>
</tr>
<tr>
<td>- flow of people</td>
</tr>
<tr>
<td>Immaterial assets</td>
</tr>
<tr>
<td>- information (personal identity, data (<em>e.g.</em>, on persons or assets), communication protocols, software programs, interoperability, cloud computing and distributed processing, Future Internet…)</td>
</tr>
<tr>
<td>- “wellness” (liberty, privacy…)</td>
</tr>
<tr>
<td>- finance</td>
</tr>
<tr>
<td>- services (e-banking, e-commerce, e-health, e-ID and e-passport, e-government…)</td>
</tr>
<tr>
<td>- safety of a community (homeland / national security, international security…)</td>
</tr>
</tbody>
</table>

**Table 15 – Examples of assets which could be considered in the Safety and Security application domain.**

---

45 This item covers supplies as goods irrespective of the supply chain.

46 Obstruction in the flow of people and goods induce slow-down and crowding which is favorable for attacks (*e.g.* terrorism).
Measures to prevent, avoid or mitigate the impact of harmful events or threats to assets

- regulation, procedures and training
- detection
  - identification of persons: (multimodal) biometric systems either in a static mode (fingerprint, signature…) or in a dynamic “on-the-fly” mode (iris, retina, face recognition…)
  - positioning and localization (e.g., from triangulation across multiple sensors)
  - tracking systems, auto target-following systems
  - imaging (in the whole electromagnetic range or using ultrasound)
  - image / scene analysis and detection of activity and of abnormal behaviors
  - chemical analysis (multi-spectral analysis of chemical compound)
  - sensor networks
  - detection of dangerous goods (such as CBRNE, drugs, explosives)
- authentification and authorization, access control, integrity check
- traceability
- security by design (e.g., physical unclonable function)
- human intervention (e.g., first aid rescue team)

Table 16 – Examples of security measures which could be considered in the Safety and Security application domain.

Some technologies and technology trends needed in Safety and Security domains are not specific to that area: Table 17 outlines those items which will benefit from the general progress of the microelectronic industry.

---

Security research has determined that for a positive identification, elements from at least two, and preferably all three, factors be verified:
- the ownership factors: something the target identity has (e.g., wrist band, ID card, security token, software token, phone, or cell phone)
- the knowledge factors: something the target identity knows (e.g., a password, pass phrase, or personal identification number (PIN), challenge response (the user must answer a question))
- the inherence factors: something the target identity is or does (e.g., fingerprint, retinal pattern, DNA sequence […], signature, face, voice, unique bio-electric signals, or other biometric identifier).

Technology trends needed for security systems which are not specific to the Safety and Security domain

- miniaturization
- computing power
- low-power / low-energy operation
- broadband communications

Table 17 – Examples of technology trends needed in the Safety and Security application domain.

Other technologies (see Table 18) are however more specific technologies to the Safety and Security domain, either in requiring customization of technologies developed for other fields (e.g., wireless sensor networks) or because this field is expected to drive the technology.

Technologies specific to the Safety and Security domain

- dedicated architecture (e.g., adaptive local intelligence vs. remote sensing and control)
- dedicated software, incl. algorithms, data fusion and filtering\(^{48}\), accommodation for variability in the conditions for detection (scenes, weather condition, light intensity, image quality…)\(^{49}\)
- trusted personal devices, including smart cards and electronic tagging (rf-id)
- “security by design” techniques (attack- and probing-resistant component design\(^{50}\), design for reliability, (high bandwidth) encryption for computing and data storage, physically unclonable functions)
- (autonomous smart) sensors for detection (either physical, chemical, biological)
- electromagnetic image sensors (on the whole spectral range from rf, to THz, visible, X-ray and γ-ray and often multispectral)
- ultrasound image sensors
- smart and secure packaging (resistant to harsh environment, tamper-resistant\(^{51}\)) including embedded micro-batteries
- smart clothes (for first responders)

Table 18 – Examples of technologies specific to the Safety and Security application domain.

\(^{48}\) e.g. Bayesian modeling, neural networks, tracking toolkit, etc.
\(^{49}\) The use infrared sensors / imagers allow a global scene analysis without light-dependent artifacts.
\(^{50}\) e.g. flat electromagnetic signal emission and power supply, resistance to fault injection
\(^{51}\) One can counteract an intrusion, once detected, by either inhibiting the normal operation of the system (e.g. by destroying the encryption key or by physically destroying critical parts of the system) or by applying appropriate countermeasures (potentially inducing a degraded mode of operation)
3.3.2. Existing roadmaps

CATRENE (and MEDEA/MEDEA+ before), ENIAC and EPoSS are European organizations which issued strategic documents in the Safety and Security area.

In the CATRENE / ENIAC VMS document, security and safety technical trends are classified under three major items:

- security for the consumer and citizen (= people)
- security of new applications
- security of infrastructures

The EPoSS Strategic Research Agenda focuses on IT security (trusted personal devices, IT infrastructure and associated technologies, see Fig. 21) and Homeland security (detection, authentication and surveillance; critical infrastructure protection; supply chain security; see Fig. 22).

---

Fig. 21 – Example of the roadmap of Smart Systems for IT security proposed by the EPoSS Strategic Research Agenda.

---


54 essentially packaging, sensors, Electronic Design Automation and obstruction techniques
### Fig. 22 – Example of the roadmap of Smart Systems for Homeland Security proposed by the EPoSS Strategic Research Agenda

Defense agencies issue also strategic documents which could be useful in addressing the specific defense market segment.

#### 3.3.3. Why it is eligible for technology roadmapping?

No public market study addressing the whole field of Safety and Security was identified: it is thus difficult to assess the size of such a market. Many security and safety measures are taken within other application domains (e.g., automotive or energy) and are not accounted for as a specific application field. Finally standardization, norms and regulation may play an important role in the way the market will develop in the future.

A well defined community of industrial players exists, including in their product portfolio this specific field.

On the technical side in many cases security devices will rely on the existence of driving markets (e.g., consumer and mobile communication) and customize them for more secure use. On the other hand the requirements of products for security especially in the defense area can be very challenging and could drive the technology development even though the market size is small. Finally some technologies are mostly applied for security purposes like infrared / THz imagers, on-body electronics and secure hardware (e.g., packaging).

---

55 e.g. for Europe the European Defense Agency (http://www.eda.europa.eu/)

56 The 2009 EPoSS Strategic Research Agenda mentions that “the safety and security equipment market can be estimated at approximately €25Bn, of which €5Bn relates to electronics devices, with an expected growth rate of 7%.”
### 3.3.4. Technical challenges and potential solutions

<table>
<thead>
<tr>
<th>Technology</th>
<th>Challenges</th>
<th>Potential solutions</th>
</tr>
</thead>
<tbody>
<tr>
<td>biometric devices</td>
<td>low reject ratio and false acceptations</td>
<td>high speed fingerprint sensor</td>
</tr>
<tr>
<td></td>
<td></td>
<td>multi-modal biometry (fingerprint, face, iris, retina recognition, signature …)</td>
</tr>
<tr>
<td>low-power, embedded systems and</td>
<td></td>
<td>energy harvesting</td>
</tr>
<tr>
<td>wireless networks of multimodal</td>
<td></td>
<td>wake-up</td>
</tr>
<tr>
<td>and real-time sensors</td>
<td></td>
<td>low-power communication in sensor networks</td>
</tr>
<tr>
<td>multispectral image sensors in less common</td>
<td></td>
<td>powerful, versatile (multispectral), compact and low cost THz sources</td>
</tr>
<tr>
<td>spectral ranges (infrared, THz, X-ray and γ-ray)</td>
<td></td>
<td>1D or 2D, highly sensitive, uncooled, fast and small size THz detectors</td>
</tr>
<tr>
<td></td>
<td></td>
<td>low cost, uncooled infrared detectors</td>
</tr>
<tr>
<td>chemical and biochemical sensors</td>
<td></td>
<td>optical spectroscopy</td>
</tr>
<tr>
<td>with high selectivity and sensitivity and low</td>
<td></td>
<td>THz spectroscopy</td>
</tr>
<tr>
<td>drift</td>
<td></td>
<td>integrated GCMS 57</td>
</tr>
<tr>
<td></td>
<td></td>
<td>photo-acoustic detection</td>
</tr>
<tr>
<td></td>
<td></td>
<td>quantum cascade lasers</td>
</tr>
<tr>
<td>low cost, monolithically-integrated</td>
<td></td>
<td>integrated pre-concentration for gases and liquids</td>
</tr>
<tr>
<td>“lab-on-chip”</td>
<td></td>
<td>manipulation of extremely small sample volumes</td>
</tr>
<tr>
<td></td>
<td></td>
<td>miniaturized microfluidic systems</td>
</tr>
<tr>
<td>packaging and heterogeneous integration</td>
<td>attack-proof packaging (invasive and non-invasive attacks)</td>
<td>buried components in substrates</td>
</tr>
<tr>
<td></td>
<td></td>
<td>attack-reactive embedded devices</td>
</tr>
<tr>
<td></td>
<td></td>
<td>smart coatings (inks, nanomaterials)</td>
</tr>
<tr>
<td>tamper-proof packaging</td>
<td></td>
<td></td>
</tr>
<tr>
<td>anti-counterfeiting techniques</td>
<td>smart coatings (inks, nanomaterials)</td>
<td></td>
</tr>
<tr>
<td>embedded energy sources</td>
<td>micro-batteries</td>
<td></td>
</tr>
<tr>
<td>smart clothes</td>
<td>security by design</td>
<td>physically unclonable functions</td>
</tr>
<tr>
<td>design</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 19 – Some technical challenges of MtM devices specific to the Safety and Security domain.**

---

57 Gas Chromatography and Mass Spectroscopy
3.3.5. Conclusions

<table>
<thead>
<tr>
<th></th>
<th>FOM</th>
<th>ECO</th>
<th>SHR</th>
<th>WAT</th>
<th>LEP</th>
<th>Public roadmaps?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Safety &amp; Security</td>
<td>?</td>
<td>+</td>
<td>=</td>
<td>+</td>
<td>?</td>
<td>partial</td>
</tr>
</tbody>
</table>

FOM = Figure Of Merit  
ECO = Existing Community  
SHR = Willingness to Share Information  
WAT = Wide Applicability of Technology  
LEP = “Law” of Expected Progress

*Table 20 – Potential of the domain of Safety and Security for MtM roadmapping.*
4. Devices

4.1. Taxonomy of “More-than-Moore” devices

As sketched in the chapter on methodology (see Fig. 4) “More-than-Moore” devices can be split in two major categories:

– transducers which allow the interaction of the packaged system with the outside world, either in communicating, sensing or actuating

– devices allowing the powering of the packaged system

4.1.1. Transducers

As mentioned in the Chapter 2 the transducer field can be arranged in a three dimensional representation:

– if it is a sensing element (i.e., converting a physical / (bio)chemical parameter into an electrical signal) or an actuator (i.e., applying a physical / (bio)chemical action in relation to an electrical input)

– according to the nature of the physical or (bio) chemical parameter. A non-exhaustive list includes:
  
  • static electromagnetic field (i.e., electric field or magnetic field)
  
  • electromagnetic wave from rf to mm-wave, THz, visible, UV, X-ray and γ-ray radiations
  
  • mechanical parameters like:
    
    ▪ displacement and its temporal derivatives (speed, acceleration…)
    
    ▪ strain / stress
    
    ▪ etc.
  
  • thermal parameters (e.g., temperature, heat, etc.)
  
  • etc.

– the amount and type of information which is gathered / actuated by the transducer:

  • multidimensional 58 when many different parameters are acquired / actuated at the same time (a typical motion sensor has from 6 to 11 degrees of freedom)
  
  • 2D array for a two-dimensional image
  
  • 3D for the coming imaging systems in three dimensions
  
  • 4D when the temporal evolution of a 3D image is considered

Rather than trying to cover the whole variety of potential combinations of transducers the following sections selected few emblematic examples of transducers:

– MEMS as a sensing element of a physical (mechanical) parameter

– biochip as a sensor of biochemical entities

58 The term “multiple degrees of freedom” would be more accurate.
lighting (and more specifically solid-state lighting) as a optical actuator
all of them being “one-dimensional”

– image sensor as a way to sense two-dimensional images

By no mean this exercise looks for exhaustivity, but it will help to better assess to what extent the methodology proposed in the Chapter 2 is applicable to some typical transducers.

### 4.1.2. Power devices

The proposed taxonomy in the field of devices powering packaged systems is still embryonic. One can however outline few generic high-level functions:

– energy sources (*e.g.*, integrated fuel cells) generating energy by themselves

– energy scavenging devices (*e.g.*, MEMS using the ambient vibrations and converting them into electrical energy) which transform energy / power present in the environment into electrical energy / power

– energy delivery systems transforming external energy sources (*e.g.*, power from a power plug) into an useable energy for the packaged system

– energy / power conditioning devices which transform the electrical energy / power inside the package (*e.g.*, a dc-dc converter)

– energy / power removal devices which take care of removing dissipated power out of the package (*e.g.*, a Peltier device or a heater spreader)

The boundary between the different devices is still fuzzy and would need further refinements. Rather than going into further discussion on this taxonomy the next section will consider integrated power electronics as a whole.
4.2. Integrated Power

Joachim Pelka, Fraunhofer Gesellschaft – Group Microelectronics

4.2.1. Scope & taxonomy

What is “power” with respect to “More-than-Moore”?

“Power” applications of microelectronics comprise a broad range of parameters. Voltage may range from millivolts to hundreds of kilovolts, the electrical power ranges from microwatts to megawatts and the structure size of the (semiconductor) components differs from micrometers to nanometers. Moreover, also energy efficiency, energy generation and energy distribution are directly linked to the term “power” and have to be considered as well.

Dealing with roadmapping in such a wide field requires a careful classification and a close look at the different technologies and applications. As a first approach it is suggested to focus on the low and medium power range, which can be called more or less “integrated power”. Power plants and the related high current / high voltage technologies are not regarded as core part of the “More-than-Moore” technologies. Megawatt power electronics for smart power grids are therefore excluded.

Fig. 23 – 8 orders of magnitude: From a 3W sugar-cube sized power supply for mobile phones (top) to a power plant with more than 100 MW (bottom). Automotive applications (<100kW) belong to the medium power segment (middle).

The low power domain includes energy harvesting, low power energy conversion (e.g., step-up converters) and management and some aspects of storage, but not low power semiconductor technologies. Low power semiconductor technologies are covered by the ITRS for the digital domain.

Medium power includes energy management and power converters up to the kW range, power devices, and modules etc. Medium Power may also include the automotive sector with energy and battery management, plugs and switches and the so-called power train.

From an application point of view also aspects related to energy efficiency should be included. This comprises for example solid state lighting systems and drive control for electrical drives (e.g., air conditioning).

and private communication from Dr. Vincent Lorentz, Fraunhofer IISB
Towards a “More-than-Moore” roadmapping

ICT for Energy Efficiency may be included at least partially, because traffic telematics, car-to-car communications, sensor systems and any kind electronics for measuring, adjusting, controlling and billing of energy require specific hardware from the “More-than-Moore” area.

Having a closer look on these topics, “More-than-Moore”-related areas can be defined as:

- **Power electronics** including converters, smart power supplies, sensors, controllers, drivers, switches, power factor correction
- **Power generators** with a focus on MEMS harvesting, photovoltaics, fuel cells, …
- **Storage** based on (integrated) batteries, capacitors, and/or inductors
- **Components** like power devices, smart driver ICs, … as basic technologies
- **Packaging** as an important technology for future system design (e.g., SiP technologies)

### 4.2.2. Why it is eligible for technology roadmapping?

#### 4.2.2.a. Power Electronics – from technology to the system level

*Motor drives* today use 50-60% of all electrical energy consumed worldwide. *Lighting power electronics* is expected to improve the efficiency of fluorescent and high-intensity discharge ballasts by minimum 20%. Advanced power electronics for dimming together with light and occupancy sensing can save on average another 30%. New concepts for *power supplies* may improve overall efficiency of 2-4% by reducing low power and stand-by consumption or a reduction in losses of 14 to 30%. Digital control techniques can further reduce energy consumption. In *home appliances* electronic thermostats for refrigerators and freezers can yield 23% energy saving and an additional 20% can be saved by using power electronics to control compressor motors.

The connection of *renewable energy sources* to power grids is not possible without power electronics: Photovoltaic (PV) power electronic converters optimize the efficiency of PV solar panels, inverters are necessary for wind generators etc. In *automotive* applications electric and hybrid drive trains are only possible with efficient and intelligent power electronics. X-by-wire concepts operated by power electronics will generate saving potential of more than 20%. (Source: ECPE Strategic Research Agenda 2008, European Center for Power Electronics, January 2008 60)

![Fig. 24 – Power electronics integrated into the clutch housing of a gear box of a hybrid car (Source: Fraunhofer IIISB)](image)

Power electronics is used for any kind of energy conditioning like power converters, switching, drive control etc., but a lot of functionality is depending from software and logic. Moreover, there are a plenty of possible combinations of voltage, current, power, AC/DC; but

---

60 European Center for Power Electronics, Nuremberg, Germany, *Strategic Research Agenda on Intelligent Power Electronics for Energy Efficiency*, 2008
no simple measures like speed or geometry. Power devices will comprise (new) device concepts and materials and may be combined with smart driver circuits (Smart Power). Sensors for voltage, current, temperature and so on have to be considered. The challenge to be solved is how to convert this into technological roadmaps for power devices, passives, sensors, etc.

This technological point of view has to be extended on the module and system level, which includes the mounting and interconnect technologies, which are used for better life time, higher reliability, and reduced size and costs, as well as packaging. At the end “Smart Power” will describe from the today’s smart components to a smart “(Power) System in Package”

Due to this broad variety of applications and technologies involved, even technological roadmaps have to be differentiated according to the different classes of application.

4.2.2.b. Energy Harvesting – the low power domain

For the Low-Power Domain the focus will lay on energy harvesting 61, which is closely related to autonomous sensors. However, up to now this is still a niche market with very specialized developments and only few contributors compared to, e.g., CMOS. It comprises:

- Conversion in electrical power (harvesting principles)
- Electrical voltage level conversion (to make the electrical energy usable)
- Energy Storage
- Energy Management systems

to build up fully integrated energy systems.

Harvesting principles can be distinguished between vibrational (motion), thermal, photovoltaic, and RF conversion and will cover a range from 0.1 µW/cm² (RF) up to 10 mW/cm² (photovoltaic outdoor). “More-than-Moore”-based converters can be built as solar cells, thermo-generators, piezoelectric generators or inductive converters. This will most probably result in different roadmaps for different technologies and applications.

---

61 see e.g. Costis Kompis and Simon Aliwell (Edts), Energy Harvesting Technologies to Enable Remote and Wireless Sensing, Sensors and Instrumentation KTN, June 2008
Available at http://server.quid5.net/~koumpis/pubs/pdf/energyharvesting08.pdf

Available at http://www2.imec.be/content/user/File/EAS_report_v28.pdf
In addition to these “physical” power converters, lowest voltage/lowest power converters for electrical energy (step-up converters) have to be considered, because energy from the environment is available in small quantities only. Most of the above mentioned converters will deliver very low voltages (50-500 mV) which have to be transformed to a level usable for electronic systems. In combination with a suitable energy storage (capacitors and/or batteries with low leakage currents and low self-discharge) and energy management it will result in an integrated energy system for energy autonomous systems.

4.2.2.c. Energy Generation and Storage – not really “More-than-Moore” but nevertheless a must

Efficient energy generation itself is a challenge for sources like fuel cells, wind generators and solar panels, and “More-than-Moore”-technologies may become more and more involved. However, this is not yet a major MtM domain and it is presently covered under the headings of physical sensors and actuators.

Electrical energy storage is usually based on super capacitors when high power density is needed and on lithium-based battery technologies when high energy densities are required. However, pure battery technology is completely outside the scope of “More-than-Moore”. On the other hand, integrated micro-batteries – although still at research level – may become an integral part of future microsystems and will therefore be part of “More-than-Moore”.

As for the other topics, energy generation and storage deal with a variety of basic parameters including the cost factor. Therefore, suitable figures of merit will depend on the technology as well as on the application.

“Energy Management” is an important part of this section.

![Fig. 26 – Integrated micro batteries (Fraunhofer IZM)](http://www.inemi.org/)

4.2.3. Existing roadmaps

There are some roadmaps and strategic research agendas (SRAs) available which can give hints on the expected development of integrated power. A lot of general information on the development of Energy Efficiency given above was extracted from the 2008 ECPE Strategic Research Agenda. Trends for the development of autarchic or energy autonomous systems are for example given in the 2009 CATRENE report on Energy Autonomous Systems (EAS). Additionally, the iNEMI Roadmap 2009 includes only a short chapter on photovoltaics.
4.2.4. Technical challenges & requirements

At the present status it is difficult to give a well designed classification of integrated power systems and to define related figures of merit, because the variety of technologies, applications and optimization criteria is too big. However, a first rough estimation of future developments can be given derived from the EPoSS SRA and the CATRENE report on EAS.

4.2.4.a. Energy conversion systems

**Fig. 27 – The EPoSS Roadmap for energy conversion (EPoSS SRA, 2009)**

Power conversion systems will focus on new industry-compliant wide bandgap semiconductor materials (SiC, GaN,…) and will face a change from SiC to GaN device technologies which will allow for new system architectures. Further challenges are thermal management and packaging. All topics together will lead to specific integration challenges at both technological and system levels.

It can be assumed that the development will be driven by the cost per watt of the technology, which is a function of the efficiency of the converters and the cost to manufacture. Since this is not yet a mature technology, there is plenty of room for further improvements and opportunities.

4.2.4.b. Smart Power for Autarchic Systems

Autarchic Systems require the ability to scavenge energy, store it and convert it in a way that it can be used efficiently. For miniaturized systems the technological efforts will lie on the use of nanomaterials, nanostructures, and nanolayers with a certain focus on thermoelectric converters and multispectral photovoltaic cells which seem to be most advanced. Fuel cells may be a future option for the replacement of batteries in implantable devices if a reliable direct glucose fuel cell can be achieved.

Energy management will be of importance for ultra low power sensors as well as medium and high power applications.
Fig. 28 – Smart Power Management Roadmap (EPoSS SRA 2009\textsuperscript{29})

<table>
<thead>
<tr>
<th>Source</th>
<th>Characteristics</th>
<th>Physical Efficiency</th>
<th>Harvested Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHOTOVOLTAIC</td>
<td>Office: 0.1mW cm(^2)</td>
<td>10-24%</td>
<td>10 (\mu)W/cm(^2)</td>
</tr>
<tr>
<td></td>
<td>Outdoor: 100mW cm(^2)</td>
<td></td>
<td>100 (\mu)W/cm(^2)</td>
</tr>
<tr>
<td>VIBRATION/MOTION</td>
<td>Human: 0.5m@1Hz</td>
<td>max power is source</td>
<td>4 (\mu)W/cm(^2)</td>
</tr>
<tr>
<td></td>
<td>1m/s@50Hz</td>
<td>dependent</td>
<td>100 (\mu)W/cm(^2)</td>
</tr>
<tr>
<td></td>
<td>1m@5Hz</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>10m/s@1kHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>THERMAL ENERGY</td>
<td>Human: 20mW/cm(^2)</td>
<td>0.10%</td>
<td>25 (\mu)W/cm(^2)</td>
</tr>
<tr>
<td></td>
<td>Industry: 100 mW/cm(^2)</td>
<td></td>
<td>1-100 (\mu)W/cm(^2)</td>
</tr>
<tr>
<td>RF</td>
<td>GSM: 900MHz/1800MHz</td>
<td>0.3-0.03 (\mu)W/cm(^2)</td>
<td>50%</td>
</tr>
<tr>
<td></td>
<td>0.1-0.01 (\mu)W/cm(^2)</td>
<td></td>
<td>0.1 (\mu)W/cm(^2)</td>
</tr>
</tbody>
</table>

Fig. 29 – Characteristics of energy harvesting principles
(Report on EAS, CATRENE 2009\textsuperscript{62})

Fig. 30 – Color code used in the Technology Readiness Level (TRL) tables below
4.2.4.c. Energy Storage

Storage techniques include ink batteries, micro-batteries, and super capacitors where the use of 3D nanostructures and nanomaterials are beneficial for energy density optimization. The relevance for “More-than-Moore” is given as soon as micro-batteries are integrated. Today the development is still more or less at the laboratory level and markets are not more than some niche markets.
4.2.4.d. Applications

Many aspects of energy generation, storage and use in the “More-than-Moore” domain are application driven. EPoSS has identified 6 different application categories for the European industry which may be a basis for application oriented roadmapping activities on “integrated power”.

<table>
<thead>
<tr>
<th>Energy Conversion</th>
<th>Wireless &amp; sensor networks</th>
<th>Power management</th>
<th>Chemical &amp; biological sensing</th>
<th>Printed systems</th>
<th>Smart textiles and foils</th>
<th>Vision systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medical &amp; Healthcare</td>
<td>Wireless &amp; sensor networks</td>
<td>All electric plane</td>
<td>NIRS detection</td>
<td>Flexible</td>
<td>Smart clothes &amp; home monitoring</td>
<td>Photoactivated for fluorescence</td>
</tr>
<tr>
<td>Internet of things</td>
<td>TeIo</td>
<td>Hybrid &amp; electric Vehicle</td>
<td>Cabin air quality</td>
<td>Low cost RFID</td>
<td>First responders safety</td>
<td>CMOS image for mobile phones</td>
</tr>
<tr>
<td>TeIo</td>
<td>Security</td>
<td>Wireless sensor networks</td>
<td>Power management</td>
<td>Low cost antenna systems</td>
<td>Smart clothes</td>
<td>All in one camera</td>
</tr>
<tr>
<td>Aeronautics</td>
<td>Automotive</td>
<td>Power management</td>
<td>Power train control</td>
<td>Maintenance floors</td>
<td>Pedestrian detection</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 34 – Application categories for the European “More-than-Moore” industry (EPoSS SRA, 2009)

Power aspects will play a major role especially during the development of the hybrid and full electrical vehicles. Here energy management, power electronics but also switches and plugs will need a lot of R&D before reaching the required technology readiness levels.

Fig. 35 – The EPoSS roadmap for electrical vehicles (EPoSS SRA, 2009)
The primary focus of EPoSS’ SRA on the smart power train is to provide a framework for Smart Integrated Systems enabling efficient Full Electrical Vehicles (EVs). Leveraging mass use of EVs however is currently facing several weaknesses. Solutions may be found at the level of the subsystems for energy storage, electric power train, and energy management.

4.2.5. Potential solutions

The main technological challenge for integrated power will most probably be the improvement of energy efficiency by power electronics. The major impact lies on the integration of power electronics, ICT and sensors into smart integrated power electronic modules and systems. Big issues currently are caused by the passives: capacitors (reliability, temperature limits), inductors (efficiency, interferences, integration), and transformers (size, efficiency, integration). Important research topics will be:

Fig. 36 – A state-of-the-art IGBT chip photo (Fraunhofer ISIT)

4.2.5.a. Module & System Level

- High power modules: power switch modules, converter modules
- Single power components: discrete device packaging (diodes)
- High power optoelectronics: packaging of High Power Laser Bars and high brightness LEDs
- High power RF Packaging: high power amplifier, bonding over filled air bridge (dielectric bridge)

in more detail

- heat Spreading/Transfer (thermal conduction, heat spreading, active cooling)
- thermal isolation of temperature sensitive components from heat sources / of high temperature components (e.g., gas sensors)
- thermal Management
- high temperature packaging
- interconnects with high electrical current capability (heavy wire bonding, ribbon bonding, die bonding, high conductive flip chip bumps)
- front side soldering for ultra thin power devices
- vias for front side drain
- less inductivity by modules without wire bonding
- die attach
- packaging solutions with high voltage isolation resistance
- packages providing high current capability and low thermal resistance
- reliability issues
4.2.5.b. Components

- New materials: change from SiC to GaN, nanomaterials, nanostructures
- Reduction power MOS $R_{on}$
- Integration of power MOS with (lateral) transistors and sensors (current, voltage, temperature)
- Reduction of IGBT losses
- Integration of IGBTs with diodes and sensors (current, voltage, temperature)
- Fuel cells powered by glucose
- New device architecture (bidirectional, reverse blocking)
- New passives / integration of passives / reliability of passives (capacitors, inductors, transformers)

4.2.6. Conclusions

- There will be not one or very few, but several roadmaps for “integrated power”.
- Before starting a roadmapping activity a suitable classification has to be found. This process may be as difficult and labor intensive as the setup of detailed roadmaps itself.
- It should be decided for which classes roadmaps should be started depending on parameters like market volume for products, research intensity, heterogeneity of the class, etc.

<table>
<thead>
<tr>
<th></th>
<th>FOM</th>
<th>ECO</th>
<th>SHR</th>
<th>WAT</th>
<th>LEP</th>
<th>Public roadmaps?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integrated Power</td>
<td>+</td>
<td>+</td>
<td>=</td>
<td>+</td>
<td>?</td>
<td>few</td>
</tr>
</tbody>
</table>

FOM = Figure Of Merit
ECO = Existing Community
SHR = Willingness to SHaRe information
WAT = Wide Applicability of Technology
LEP = “Law” of Expected Progress

Table 21 – Potential of the domain of Integrated Power for MtM roadmapping.
4.3. Lighting

Joachim Pelka, Jens-Uwe Pfeiffer, Joachim Wagner
Fraunhofer Gesellschaft – Group Microelectronics

4.3.1. Scope & taxonomy

The main drivers for the development of solid state lighting or solid state illumination are still the increasing efficiency (or more precisely, efficacy, *i.e.*, lumen per watt) of LEDs and OLEDs, along with the simultaneous drop of the cost per lumen and the increased inherent robustness and long lifetime of these semiconductor light sources. To make LEDs really beneficial for actual lighting applications, the further development of LED technology has to be complemented by the development of matching long-lived driving electronics, compatible with the conventional 230 V AC power grid, as well as by the development of LED specific luminaires, *i.e.*, by generating true LED lighting solutions.

As solid state lighting is an emerging technology, the cost per unit is high and the capital equipment utilization is slow, just driven by the savings in operating costs (power costs, replacement costs). Shown in Fig. 37 is “Haitz’ Law”, a curve that demonstrates how the cost of LED lighting (cost per lumen) decreases while the efficacy (lumens per watt) increases over time. Note that “Haitz’ law” shows that the cost per lumen declines exponentially with time, a situation analogous to “Moore’s Law” for ICs.

The effort to produce high efficient white light from solid state materials, the development of improved phosphors as well as new solutions for packages and luminaires have proven to be the enablers of the new lighting technologies.

Moreover, LED-based lighting does not present any environmental risk, during or after disposal. This is a major consumer benefit over mercury-containing fluorescence tubes and Compact Fluorescent Lamps.

Semiconductor-based solid state light sources can be classified from a technological point of view as

- light emitting diodes: incoherent light sources for lighting, signage and displays
- semiconductor-based LASERs: coherent light sources for optical communications, data storage, materials processing, medical engineering and optical sensors
Major issues for the future development of semiconductor light sources are:

- Reduction of energy consumption (>90% quantum efficiency intended)
- Environmental aspects during production (green production, no risk to the environment)
- Increased intensity
- Extended spectral range from IR to UV
- Improved lifetime in particular of organic light sources
- Enlarged panel size for organic light sources (target >20m²)
- Quality of white light/ direct white light generation
- Reduced manufacturing cost

Main applications of LEDs as incoherent semiconductor-based light sources are:

- energy efficient lighting (solid state lighting)
- large area displays
- sensors

Key applications of semiconductor lasers are:

- optical fiber based communication
- materials processing (either via pumping of solid state lasers or, increasingly, also direct application of diode lasers)
- medical diagnostics an therapy
- optical sensors
- displays (flying spot projection)
It has also been considered to use ultraviolet (UV) or blue emitting diode lasers in conjunction with luminescence conversion phosphors for white light generation as possible solid state light sources for lighting. This idea has been triggered by the fact that semiconductor diode lasers can be very efficient light sources with demonstrated power efficiencies in the 60-70% range for 980nm emitting devices. But for the UV-blue spectral range the efficiency of diode lasers is still much lower, lacking far behind that of LEDs emitting in the same spectral range. Therefore, semiconductor lasers are only expected to play a significant role in lighting applications once their power efficiency in the short-wavelength range exceeds that of corresponding LEDs.

Today, solid state lighting based on LEDs made from inorganic and organic materials is in the main focus of future light source development because 16% of the energy generated worldwide is used for lighting purposes and this portion is expected to grow further. Energy efficient light sources will therefore significantly reduce energy consumption. However, the mere replacement of the conventional light bulbs by solid-state light emitters (the RETROFIT market) is only a first step. In the end smart lighting systems will deliver light only where and when it is needed. This will save another 50% of energy and may add additional services like optical data communication without the need for extra hardware and energy. Thus, development of the related module and system technologies has to be included, too. Of course, there is a strong overlap with the integrated power chapter (power electronics) due to the need of smart driver electronics.

---

64 http://www.newscenter.philips.com/pwc_ne/main/shared/assets/newscenter/2009_pressreleases/Lightfair/Philips_MASTER_LED.jpg
Fig. 39 – The success of SSL is determined by the total SSL system, not by the LED chip only (from G.Q.Zhang – Philips Lighting, CATRENE workshop on “More-than-Moore” Roadmapping, Oct.4, 2010 Neubiberg)

Development of lighting is now leaving the device level (replacement of conventional light bulbs) and is entering the system level.

The change from LED chip towards integrated LED lighting systems requires:

- vertical integration along the value chain (O)LED – mounting – packaging – luminaire
- integration of solid state lighting into the 230V electrical power infrastructure
- (O)LEDs-based luminaires with full control of light intensity and color coordinates, brought about by appropriate driving electronics
- high quality warm white LED light sources especially for domestic applications
4.3.2. Eligible technologies for roadmapping

At present, commercially available LEDs are almost exclusively made from either (AlGaIn)N or (AlGaIn)P compound semiconductor materials. Blue and green LEDs are based on (AlGaIn)N heterostructures, while red to yellow emitting LEDs are made from (AlGaIn)P.

Since the light from a LED is fairly monochromatic in color such as red, green, or blue, generation of white light is typically accomplished by either mixing the output from three or more LEDs (typical red, blue and green) or by combining a blue or UV LED with one or more phosphors that absorb the high energy light and re-emit light at a longer wavelength in the visible range.

Either of these two configurations has its own unique set of advantages and challenges, but both are being used to produce white light for commercial applications. Inherent with the use of a phosphor to produce longer wavelength light is the energy loss in converting short wavelength light into longer wavelengths. Therefore a possible advantage of the color mixing technique is the potential for higher efficiency lamps. While the energy conversion loss is eliminated in the color mixing scheme, it requires that high efficiency light be produced across the visible spectrum at least in three or four wavelengths and sophisticated optics to appropriately mix the colors to produce white light. An approach to avoid the color mixing challenge is to stack LEDs emitting at different primary colors monolithically. Currently green GaInN LEDs are lower in efficiency than blue or violet emitting LEDs based on that material. In either scheme the effort to produce higher efficiency and brighter white light centers on materials and device research to produce better LEDs and phosphors as well as packaging and luminaire development:

Inorganic LEDs: dominantly group III-Nitride based (AlGaIn)N) LEDs for blue, green and white emitting devices, the latter via luminescence conversions (AlGaIn)P based LEDs for red-orange emitting devices

Organic LEDs: Polymer based OLEDs
Small molecule based OLEDs

New materials / devices: Chemo-luminescent materials
Efficient Silicon based LEDs and LASERs
Meta materials (negative refraction index)
Flexible substrate based emitters (OLEDs)
Direct (phosphor-less) white light generation in a single chip
UV-LEDs (UV-A, UV-B)
Integration of LEDs with driver electronics

4.3.2.a. Targeting on a roadmapping process, possible figures of merit (FOM) are:

- Efficiency (target >90% quantum efficiency, >90% light extraction, 55% overall efficacy)
- Intensity (target 5000 lm)
- Spectral range from IR to UV
- Lifetime of organic light sources (>20,000h)
4.3.3. Available roadmaps

There are only a few current and freely available roadmaps and strategic research agendas, because major companies usually set up their own roadmapping processes which will not be published. Current European public roadmapping processes on photonics are performed as part of the Strategic Research Agenda of the Photonics 21 platform (Europe) and in the Photonik 2020 Research Agenda (German Ministry for Education and Research - BMBF). Former European roadmaps on photonics were issued through the European project MONA in 2008 and through the group of European projects MEL-ARI Opto in 1999.

Another roadmapping initiative is the iNEMI roadmap which was last updated 2009. This roadmap includes also a chapter on solid state lighting (SSL), or as it is called there “solid state illumination”. It seems to be the first of its kind in the SSL field that seeks to bring a supply chain focus and industry needs assessment broader than that identified by the conventional materials and device roadmaps identified by government and university research communities.

Recently the US DoE has published the Solid-State Lighting Research and Development Multi-Year Program Plan (March 2010) and the Solid-State Lighting Research and Development: Manufacturing Roadmap (July 2010) which give a detailed insight in the present status of solid-state lighting and the expected development.

These documents can be considered as a suitable basis for further activities. Most of the technical details in this report are taken out of the current Photonics 21 SRA and the iNEMI roadmap 2009 as well as out of the DoE documents.

---

65 “Lighting the way ahead – Second Strategic Research Agenda in Photonics” Available at http://www.photonics21.org/AboutPhotonics21/SRA.php
### 4.3.3.a. General Trends

The following pictures show some general trends in Solid State Lighting.

![General trends in lighting](image)

*Fig. 40 – General trends in lighting*

![Philips technology roadmap for OLEDs](image)

*Fig. 41 – Philips technology roadmap for OLEDs*  

---

71 from e.g. http://www.olednet.com/focus/focus_board/focus_view.asp?idx=268&mem_stat=0
The LED efficacy forecast (Fig. 43) was published by the US Department of Energy in 2010. It shows the expected improvement of inorganic single-chip white LEDs, segmented into cool white and warm white products as well as laboratory demonstrations. As can be seen from this graph, the annual increase in white LED efficacy is expected to slow down significantly as we approach the projected maximum efficacy barriers, while the related R&D efforts and expenses will have to stay at least at their present level.
A respective roadmap for OLED panels is shown in Fig. 44.

![Fig. 44 – White OLED Panel Efficacy Targets of DoE (2010)](image)

### 4.3.4. Technical challenges

Taking into account the change of focus from light emitters to illumination systems, the complete value chain has to be taken into account in the future. According to Fig. 45 not only manufacturing equipment, solid-state light emitters and driver electronics have to be considered but also new materials, thermal management, and optics. All these topics together form the basis for innovative light design and planning, but do not yet include sensors, communications and smart control systems which will enhance functionality and will allow for further energy savings.

![Fig. 45 – The SSL value chain (from K. Streubel – OSRAM CATRENE Workshop on “More-than-Moore” Roadmapping, Oct.4, 2010, Neubiberg)](image)
In the Photonics 21 SRA the following challenges and research areas are defined, still focusing on light emitters, module level and next generation lighting systems:

1. **Inorganic LED**
   - High-quality white light for general illumination
   - Low-cost manufacturing
   - LED light engines and luminaires with high functionality

   - Inorganic LEDs aiming for $>$180 lm/W efficacy
   - LED light sources with high quality and high lumen package
   - Low-cost LED chip and package manufacturing
   - LED luminaries and intelligent light management

2. **Organic LED**
   - High-quality white light for general illumination
   - Low-cost manufacturing
   - Conformable, flexible and transparent OLEDs

   - Efficient OLED devices, materials and efficient light out-coupling
   - Low-cost manufacturing solutions
   - OLED reliability and lifetime
   - Substrates, barriers and encapsulation for flexible and transparent devices

<table>
<thead>
<tr>
<th>Efficacy</th>
<th>2009</th>
<th>2012</th>
<th>2015</th>
<th>2020</th>
</tr>
</thead>
<tbody>
<tr>
<td>- cold white</td>
<td>100 lm/W</td>
<td>150 lm/W</td>
<td>200 lm/W</td>
<td>$&gt;$ 200 lm/W</td>
</tr>
<tr>
<td>- warm white, conversion type</td>
<td>75 lm/W</td>
<td></td>
<td></td>
<td>150 lm/W</td>
</tr>
<tr>
<td>- overall efficacy</td>
<td></td>
<td></td>
<td>35%</td>
<td>55%</td>
</tr>
<tr>
<td><strong>Intensity per Package</strong></td>
<td>200 lm</td>
<td>1000 lm</td>
<td>...</td>
<td>5000 lm</td>
</tr>
<tr>
<td><strong>Spectral range / color rendering</strong></td>
<td>80</td>
<td>$&gt;$80</td>
<td>...</td>
<td>$&gt;$80</td>
</tr>
<tr>
<td><strong>Cost:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Substrate size</strong></td>
<td>4 inch</td>
<td></td>
<td></td>
<td>8/12 inch silicon or glass substrates</td>
</tr>
<tr>
<td><strong>$/klm</strong></td>
<td>25</td>
<td>$&lt;$5</td>
<td></td>
<td>$&lt;$2</td>
</tr>
<tr>
<td><strong>Lifetime of electronics</strong></td>
<td>20,000h</td>
<td>50,000 –</td>
<td>$&gt;$100 h</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>100,000 h</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 22 – Technology requirements “Inorganic LEDs”
Table 23 – Technology requirements “Organic LEDs”

The most pressing technological challenges today are

- For **inorganic LEDs:**
  - Increasing GaInN LED efficiency at high current density (fighting the “droop”)
  - Closing the Green Gap, *i.e.*, increasing the GaInN green-yellow-red efficiency
  - Improvement of light conversion for white LEDs
  - Development of phosphor-less single-chip white LEDs (need for efficient green-yellow-red emission within the same materials system)

- For **organic LEDs:**
  - OLED lifetime >5000h, LED level has to be reached
  - Improvement of blue OLED emitters with respect to lifetime and color coordinates

- At **system level:**
  - Cooling / Thermal management (instead of hot “light bulbs”)
  - Development of reliable driver electronics: increase in lifetime from 20,000 to 50,000-100,000 h
  - Driver circuits for dimming
  - Further reduction of cost (cent per lumen)
  - New concepts: *Light where you need it and when you need it* – “lighting on demand”
  - Integration of additional functionalities, such as display and transmission of information, into LED-based lighting systems – “intelligent lighting”.

### 4.3.5. Potential solutions

**Solid State Lighting—how will it look like in future?**

The future of solid-state lighting will lead to lighting environments that are sensitive and responsive to the need and presence of people: light sources will be distributed and embedded into the environment. They will know about their situational state; they can be tailored towards the individual lighting needs; they will recognize and distinguish persons; and they
can change in response to the individuals and their environment. Moreover, they will anticipate the desires of individuals without conscious mediation.

For this purpose solid-state light sources will be equipped with integrated sensors, control and driving electronics, specially designed and optimized for use with (O)LED light engines. Besides from energy efficiency of the light emitter itself they will save even more energy by smart generation and intelligent use of light. They will generate light just when and where it is needed (“lighting on demand”, “intelligent lighting”). Additional functionalities will be integrated for transmitting information via lighting (“talking lights”) and combining lighting and displays (“infotainment”).

This will require extended competences like:
- Material science and engineering
- Optics
- Thermal and Mechanics
- Semiconductors and “More than Moore”
- Distributed Systems Control
- Media Processing
- End-User Programming
- Computational Intelligence
- Interaction Design
- Experience Prototyping
- Human Factors

This overall vision can be called “Lighting goes digital”, which will be a global opportunity as well as a grand global challenge. It will require a joint European effort to keep the still leading position.

4.3.6. Conclusions

Is “Solid-State Lighting” a suitable topic for a roadmapping process?

Several roadmapping activities are already running. Photonics 21, OE-A, DoE and iNEMI cover most of today’s relevant topics. A combination of these roadmaps will give a nearly complete picture of the present situation and a view into the near future. More detailed roadmaps are with the companies but not published.

The light emitters themselves are still in the main focus of all available roadmaps and SRAs. System aspects are not yet considered so much. This may be a starting point for a CATRENE initiative on lighting, which should be dedicated to combine the existing roadmaps as well as to extend them towards system aspects.

Relevant figures of merit are available. For the light source a “law” of expected progress is available, from a system point of view this has to be defined according to the different applications.

---

72 Organic Electronic Association addressing the OLED field
A critical factor seems to be the willingness to share information among the lighting community. Some companies have already started an open innovation process and want to freely exchange information with their research partners for their own benefit; others are only willing to discuss about strategic research agendas. By the later, a new and comprehensive roadmapping process is regarded as too big a challenge.

Today the lighting market is aiming at the emerging retrofit business, which is expected to be small compared to the market for future lighting systems. It is expected to have a market of about 180 billions € till 2020 for (O)LED-based luminaires and systems and of 50 billions € for lamps and components (see Fig. 46). For innovative lighting a research budget, about 10% of the market revenues are assumed to be reinvested in R&D which means at least an amount of 5 billions €.

This future market will ensure a widespread application of the new lighting technologies. Consequently, Solid-State Lighting is an emerging market for smart systems and a European roadmapping initiative seems to be important in order to ensure a closer cooperation among the European partners and to maintain Europe’s leading position. In a first step, a CATRENE roadmapping process can combine the existing initiatives like OE-A and Photonics 21. In a second step these activities can be brought to the system level.

![Fig. 46 – The lighting market 2020 – build on R&D strength](from G.Q. Zhang – Philips Lighting, CATRENE Workshop on “More-than-Moore” Roadmapping, Oct.4, 2010, Neubiberg)

<table>
<thead>
<tr>
<th>Solutions &amp; Services</th>
<th>€700B?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminaire &amp; Systems</td>
<td>€180B</td>
</tr>
<tr>
<td>Lamps &amp; components</td>
<td>€50B</td>
</tr>
<tr>
<td>Materials &amp; equipment</td>
<td>€30B</td>
</tr>
</tbody>
</table>

Table 24 – Potential of the domain of Lighting for MtM roadmapping.

<table>
<thead>
<tr>
<th>FOM</th>
<th>ECO</th>
<th>SHR</th>
<th>WAT</th>
<th>LEP</th>
<th>Public roadmaps?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lighting</td>
<td>+</td>
<td>+</td>
<td>=</td>
<td>+</td>
<td>yes</td>
</tr>
</tbody>
</table>

FOM = Figure Of Merit
ECO = Existing CoMMunity
SHR = Willingness to SHaRe information
WAT = Wide Applicability of Technology
LEP = “Law” of Expected Progress
4.3.7. Additional references

4.3.1 Joachim Wagner, “LEDs for Green Lighting – current status and challenges,” Green Lighting event 2009

4.3.2 http://www.theledlight.com.cn/306-knowledge-SSL-LED-roadmap-recommendations.html


4.3.4 G.Q. Zhang, Philips Lighting, private communication
4.4. **Image sensors**

*Chris Van Hoof, IMEC*

4.4.1. **Scope & taxonomy**

Currently there are various imaging systems, each deserving its own merit. Despite this diversity, the most common detection scheme for visible light depends on the photosensitivity of a silicon photodiode. CCD’s (Charge-Coupled Devices) have dominated since their invention in the late 60’s but over the last decade, CMOS image sensors have received much attention. The arguments used in favor or against this transition are numerous. The general conclusion is that CMOS sensors have already replaced CCDs in many applications and will continue to improve in competitiveness in areas where CCDs are currently predominant. Although the present roadmap focuses on the domain of CMOS imagers, its treatment also embraces other imaging sensors since the general approach and the technical challenges are inherently of the same nature.

![Image of CMOS image sensor](image)

**Fig. 47 – Schematic top view and cross section of a CMOS image sensor with 2D array of pixels, peripheral electronics and bond-pads**

An image sensor – as depicted in Fig. 47 – consists of a 2-dimensional array of pixels (sampling points) that converts the light into an electrical signal. Color filters and focusing optics may also be present above the detector array. At the periphery of the array, appropriate electronic circuits are placed to read-out the analog pixel data. These may include simple analog pre-processors, digital circuitry, analog-to-digital converters, etc. The imager chip is connected to the outside world through the peripheral bond pads, and mounted on a suitable package.

In terms of operation, front-side illumination (FSI) seems to be the straight forward approach. Here, the front-side of the chip receives the incoming light rays. However, the increasing demand for high sensitivity has driven the development of backside illuminated imagers (BSI). Contrary to FSI, the back-surface of the chip, which is specially treated to receive the light, is in the path of the light-ray. This results in 100% fill-factor, and thus an increased sensitivity.

---


In terms of fabrication, the imagers can be processed using either monolithic or a hybrid technology. In the monolithic approach both the 2-D photosensitive array and the peripheral electronics are located on the same die, while in the hybrid approach they are fabricated on different dies that are subsequently connected vertically (e.g., pixel-wise). Although the cost/complexity of the latter is high, it offers certain advantages including the possibility for optimizing the different layers individually. Taking the hybrid approach a step forward, vertically integrated image sensor arrays consisting of multiple dies (tiers) stacked and connected using through-silicon vias (TSVs) can be developed, leading to a 3-D imager topology. The past few years has witnessed numerous development efforts on TSV enabled 3-D stacking of active silicon dies. This is a unique opportunity in the field of imaging: 3D integration technology for smart imagers.

The imager road-map can be split in the following sub categories:

- Monolithic FSI and BSI image sensors
- Hybrid image sensors
- 3D integrated image sensors
- “Peripheral components” roadmap: Flex, lens, filter

The integration complexity of the respective technology is given in the Fig. 48 below.

*Fig. 48 – Integration complexity vs. system performance in different imager technologies.*
4.4.2. Eligible technologies for road mapping

![Monolithic (front-side and backside illuminated) CMOS image sensor roadmap](image)

**Fig. 49** – Monolithic (front-side and backside illuminated) CMOS image sensor roadmap

### 4.4.2.a. Monolithic front-side illuminated CMOS image sensors

Typically, the most straightforward manner to realize a CMOS image sensor is to fabricate diode arrays with (or without) in-pixel electronics and peripheral readout circuitry (including row and column decoders, column amplifiers, and ADCs). These monolithic imagers are termed as monolithic front-side illuminated (FSI) CMOS image sensors (Fig. 50).

![A schematic of a front-side illuminated (FSI) CMOS image sensor with pixels and contact at the bond-pad level](image)

**Fig. 50** – A schematic of a front-side illuminated (FSI) CMOS image sensor with pixels and contact at the bond-pad level

The advantages of FSI imagers are:

1. Very close to standard VLSI process, no major change in process technology required.
2. Pixel scaling follows the “Moore’s law”. Very small pixel pitch possible as transistor scales.
3. Mass production possible due to extremely high pixel/sensor yield.
4. Cost effective (due to high volume production, high yield)

The disadvantages associated with monolithic FSI CMOS imagers include:

1. Lower quantum efficiency (QE) or light sensitivity due to fill-factor loss.
2. Lower full-well (charge holding) capacity of the photodiode due to smaller available area.
3. Usually standard (thin) epitaxial layer is used, leading to a drop in red response.
5. Optimized ARC is difficult to obtain due to plethora of (exotic) stack materials in the BEOL.

Thus the main application regime of FSI monolithic CMOS image sensors happens to be for high-resolution (coupled with very low pixel defect) system-on-chip imagers with average sensitivity for consumer applications.

![Image of FSI monolithic CMOS image sensor](image)

**Fig. 51** – Scaling towards higher resolution in an advanced node keeping the sensor size the same (Top). Concept of micro-lenses to effectively increase fill-factor (Bottom)

While the lower end of the consumer market may employ standard diodes for pixels, higher end consumer grade imagers may utilize special pixel topologies (e.g., pinned photodiodes), and even novel processing technology components such as micro-lenses, light pipes, special epitaxial layers, etc (Fig. 51)

4.4.2.b. Monolithic back-side illuminated CMOS image sensors

To mitigate the drawbacks associated with FSI, while preserving its benefits as much as possible, imagers that are illuminated from the back-side (BSI, see Fig. 52) are being tried out. In an ideal case, the only difference between FSI and BSI can be that an FSI is turned upside down.

![Image of FSI and BSI CMOS image sensors](image)

**Fig. 52** – A schematic of a backside illuminated (BSI) CMOS image sensor with pixels and contact at the bond-pad level made through a cavity

But in reality, some additional processing needs to be done which includes: backside thinning (~ 10-50 μm) by mechanical grinding and polishing, backside surface treatment with shallow ion-implantation and laser annealing, etc.

Furthermore some type of bonding scheme is to be realized for connecting to the bond-pads at the front side: either a cavity or through silicon vias (TSVs). The advantages of BSI include:

1. 100% fill-factor since all the silicon volume is receptive to incoming photons. Therefore high QE.

2. More in-pixel electronics can be added for smart processing.
3. Engineered epitaxial layer such as a graded doping profile can be employed for low cross-talk.

4. Backside free of metal or inter metallic dielectric layers. Thus optimized ARC can be applied.

The disadvantages associated with monolithic BSI CMOS imagers include:

1. Additional processing steps and facilities required, leading to additional cost and lower yield.

2. Increased photo-response non-uniformity unless wafer thickness tightly controlled.

3. Parasitic light leakage (lower shutter rejection ratio).

Thus, BSI CMOS imagers find applications in high-end consumer applications (digital single lens reflex cameras or SLRs), scientific applications requiring very high QE, etc.

### 4.4.2.c. Pixel topologies for CMOS image sensors

A very simple approach for light detection is a vanilla photodiode, where contrasting dopant types are used to form a junction. The junction can be operated either in the floating capacitor mode (e.g., 3-transistors pixel with a source-follower) or detection node with charge integration on a separate capacitor (e.g., a charge trans-impedance amplifier).

<table>
<thead>
<tr>
<th>Simple photo-diode</th>
<th>Buried photo-diode</th>
<th>Pinned photo-diode</th>
<th>High electric field/voltage based photodiodes</th>
<th>Special diodes</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Simple photo-diode" /></td>
<td><img src="image" alt="Buried photo-diode" /></td>
<td><img src="image" alt="Pinned photo-diode" /></td>
<td><img src="image" alt="High electric field/voltage based photodiodes" /></td>
<td><img src="image" alt="Special diodes" /></td>
</tr>
</tbody>
</table>

- For normal light sensing applications, e.g., 3-transistors pixel
- For low dark current, usually 3-transistors pixel
- For extremely low dark current, noise, e.g., 4-transistors pixel
- For extremely low light levels/single photons, e.g., avalanche detectors
e.g., deep trenches, fully-depleted operation, novel materials etc

- + ease of fabrication
- + simple timing
- + low dark current
- + cooling can be avoided
- + extremely low dark current
- + extremely low light levels
- + based on application requirement

- - large dark current
- - associated noise
- -fabrication difficulty
- -fabrication difficulty
- - fab complex operation scheme
- - fabrication complexity
- - high voltage operation
- - cooling required
- - Fabrication complexity
- - impact on other parameters
- -cost

**Table 25** – Some pixel topologies, merits and demerits.

*As a general rule, progress has been from left to the right.*
4.4.2.d. Hybrid back-side illuminated image sensors

**Fig. 53** – Hybrid (back-side illuminated) CMOS image sensor roadmap

Suppose one requires a tailored detector layer, probably consisting of novel process technologies like very deep trenches, or altogether new (or exotic) material base such as GaN (while preserving the merits of high performance CMOS readout), his option would be to utilize a “hybrid” image sensor (see **Fig. 54**).

**Fig. 54** – Schematic of a hybrid detector with pixel-to-pixel interconnects (bumps) and some contacts for global signal/readout at the periphery

Here, pixels are connected face-down (one-to-one) on readout (standard CMOS) and illuminated from the back-side akin to a BSI. The hybrid imager has all the advantages of the BSI on top of the following:

1. Detector array can be tailored and exotic materials can be used.
2. Additional area available in the second tier for memory nodes and smart electronics.
3. High shutter rejection ratio (low parasitic light leakage).

The disadvantages are similar to BSI including increased post-processing challenges. Another major disadvantage is that typically the pixel pitch is restricted to the bump pitch, unless in-pixel electronics are employed.

Various exotic materials can be used in the detector layer: high resistivity Si substrates, InGaAs, CdTe, (Al)GaN, etc for various targeted applications, including X-ray, (Near) Ultra-Violet, (Far) InfraRed, etc.
4.4.2.e. 3D stacked image sensors

Recent advances in 3D integration technology could also be used to make 3D stacked image sensors. TSV (through silicon via) technology offers a way out of the classical 2D chip world. The increased interconnectivity can be applied to achieve smaller chip sizes, increased on-chip functionality and/or previously unattainable functionality. If the gain in performance sufficiently justifies the increase in process complexity and cost, then 3D integration is the way to go. In the long term this is indeed the expectation.

A first way to use 3D stacking technology is to apply it directly to FSI imagers (Fig. 55) to connect via TSV’s from the backside to the peripheral bonding pads. The main advantage of this procedure is that no additional area is lost anymore besides the chip for wire bonding.

Possible applications where this principle would be interesting are in consumer imagers (cell phones), endoscopic imagers (fitting in a narrow tube) and tiled imagers (with minimal dead zone between arrays) for large FPA’s (focal plane arrays). Of course, for each case it should be evaluated whether or not a suitable BSI approach could not give a better performance versus the effort needed.

A second area, where the benefits of 3D stacking technology will be exploited to maximum extent, is true 3D stacked image sensors (Fig. 56). These are image sensors where 3 or more layers are placed on top of each other, interconnected by area-distributed TSV’s and bumps. In fact it is a logical extension of hybrid image sensors where the readout is split up over different layers or additional functional layers are added.

Clearly, 3D stacked image sensors have the same advantages than hybrid image sensors and more:

1. Each layer can be tailored to its optimal technology and performance, e.g., digital and analog circuitry can be split over different layers, reducing noise levels.
2. Additional area is available in the 3rd (n th) layer allows for added on-chip functionality.
3. Low power, high bandwidth interconnectivity is provided between different layers.
4. Different layers could be built up modularly so as to make reuse possible in subsequent imager designs.
It is as good as impossible to identify one single performance metric which proves the better performance of a 3D stacked architecture for imagers. Rather, the benefit of a 3D stacked architecture is rather in that it relaxes the trade-offs between different performance metrics. It then depends on the specific needs of an application whether or not a 3D architecture is required. For example very high frame rates (10,000 frames/s and more) by themselves are possible to achieve with 2D imagers today with some special design tricks. However, doing this with high resolution for extended periods of time is not as trivial due to the limited off-chip bandwidth. Here, a 3D architecture could provide some additional trade-off margin as bandwidth to a second or third layer is very wide and data compression on chip can be performed. Similar conceptual examples (e.g., high dynamic range in combination with small pixel size, on-chip data compression and fast readout) can be given which indicate the potential advantages of 3D without necessarily being able to quantify the “trade-off gain”.

A major concern with 3D stacked architectures is the place required for one TSV and the minimum TSV pitch. Indeed, a TSV from the 2nd to the 3rd functional level takes place which otherwise could be used for additional circuitry. Nevertheless, by appropriately balancing the TSV diameter with respect to the TSV pitch, this loss in area can be made minimal percentage wise.

In addition, any TSV technology will impose constraints in terms of TSV diameter, minimal/maximal TSV pitch and TSV capacitance and resistance. When one wants, e.g., one TSV per pixel, an explicit link is made between TSV pitch, pixel pitch and pixel performance parameters. However, in general such link is arbitrary and in fact it is better to see TSV’s on a different hierarchical level merely as signals paths within the readout layers. As such a few TSV’s per group of pixels can be used, allowing for better system optimization. TSV and pixel pitch can therefore both have their own independent scaling roadmap.

### 4.4.2.f. Optics

Parallel to the improvements in the detector and integration technologies, there has also been a development trend regarding the (integrated) optics. The innovations with increasing (design/fabrication) complexity are summarized in the figure below.

![Fig. 57 – Innovations in optical layer with increasing (design/fabrication) complexity (adapted from YOLE)](https://example.com/fig57.png)
4.4.3. Available roadmaps

There have been several roadmaps in the past on image sensors-- mostly prepared by commercial establishments/industry vying for an increased stake in the market. Thus, it is not surprising that these reports focus almost entirely on the FSI monolithic approach which is very viable in terms of yield and cost-effectiveness. Some examples include the Panasonic roadmap \(^{74}\) and by other leading image sensor manufacturers such as Sony and STMicroelectronics. An exhaustive report has been prepared by Yole \(^{75}\). But they all fall short of the much global view of emerging and next-generation image sensors.

4.4.4. Technical challenges

4.4.4.a. Frontside illuminated imagers

The technology used for a typical (FSI) imager does not deviate considerably from a standard CMOS technology. However, since the drive for aggressive integration nodes is centered on digital electronics, there is some impact for use of the technology for sensing photons.

Smaller (transistors) for an image sensors can indeed render smaller pixels (higher resolution), but also more noise and leakage. Nevertheless, for commercial imager applications like digital still cameras (DSC) and cell phones, there is a continuing trend towards smaller pixel sizes while keeping imager size the same. The roadmap for CMOS imager pixel scaling (and the CMOS technology employed), lags a few generations behind that of advanced CMOS technology scaling. For instance, to retain signal quality, dual gate oxides (thicker for some in-pixel transistors) are required, while retaining thinner oxides in the peripheral digital circuitry.

Good light sensitivity, with the best possible signal to noise ratio, is essential for an image sensor. Therefore, each incoming photon needs to be guided with minimum loss to the photosensitive area where it can be converted into charge with maximum efficiency. This charge should then be amplified into a readable voltage with minimal noise.

With a front-side illuminated imager, the light needs to be guided through the entire backend towards the photosensitive silicon. Any light hindering metallization needs to be avoided as much as possible, rendering a very complex routing scheme. Moreover, any overly reflective interfaces or absorbing layers in the path of the light should be avoided or cleared in the region of interest (e.g., silicides, exotic oxide materials etc). Performance enhancing features like micro-lenses (for increasing the fill factor), light pipes and color filters need to be applied, which as well increases manufacturing complexity. Finally, light incidence on other locations than the region of interest should be shielded as this could result in unwanted transistor effects, which implies first order or multiple metal layers.

Once the photons are converted into the charge domain, efficient collection of the charges is paramount. Charge-sharing needs to be curtailed as well. These require some modifications to the epitaxial layer, dopant concentrations etc. For the lowest possible dark-current and noise, surface/side-wall interactions need to be minimized requiring additional doping layers as well.

4.4.4.b. Monolithic backside illuminated imagers

By employing a BSI approach, some of the concerns pertaining to FSI are avoided. The backend dielectrics and metallization are not a concern in BSI. Moreover, an optimal anti-

\(^{74}\) http://www.semicon.panasonic.co.jp/en/catalog/cat/pdf/A00006PE.pdf

reflecting coating stack can be applied in combination with color filters. Micro-lenses could still be useful (with a potential loss of field of view or FOV) to keep crosstalk low.

However, the technological challenges increase as well. For instance, thinning of the substrate from the backside is required. As absorption in silicon for the typical wavelength of interest (visible) occurs in the first few microns (1-5 µm), the substrate needs to be thinned a few microns from the front-side to avoid cross-talk. Special techniques need to be foreseen to handle thin substrates including carrier and transfer technologies. (Permanent) carrier bonding mandates oxide bonding or using appropriate polymers.

In addition, the harsh thinning procedure renders the back-surface full of defects / recombination centers due to crystal damage and dangling bonds. Thus, suitable backside passivation techniques need to be applied including shallow ion-implantation and laser annealing.

In addition, the bond pads (present on the front-side) need to be brought to the outside world. Typically, this is done by TSVs, but presents huge technological challenges in itself.

Finally, all of these process steps need to be combined in a feasible, cost-efficient and reliable process flow. The benefits however outweigh the disadvantages of BSI, and hence BSI image sensors are starting to appear in the market.

4.4.4.c. Hybrid backside illuminated imagers

The technology required for hybrid image sensors includes all the BSI steps. However, depending on the implementation, temporary (instead of permanent) carrier bonding might be necessary for thin wafer flips to a secondary carrier substrate. Moreover, a high yield, high density bumping technology is needed to enable inter-chip pixel-wise interconnections.

Important to note is the difficulties that arise in making assemblies out of two or more chips with high interconnectivity. First of all, there is the problem of testability: without appropriate test structures, it is almost impossible to ascertain whether the individual layers function satisfactorily (before the final assembly). In an unfortunate instance of device failure, there is always the uncertainty as to where the problem lies. This results in ambiguity regarding supplier liability. Further, there is the question of whether to perform die-to-die (D2D), die-to-wafer (D2W) or wafer-to-wafer (W2W) stacking. W2W stacking allows for parallel assembly; however the compound yield will drop fast if individual die yield is not high enough. D2W assembly is a good compromise as it allows for KGD (known good die) selection, while thermo-compression bonding can be done in parallel.

Alignment accuracy requirement (between the two stacks) compounds the problem. Alignment becomes more difficult with large chip sizes or with W2W bonding. Moreover, if the two layers are processed using different substrate materials, thermal mismatch between the two substrates need to be taken into account.

4.4.4.d. 3D stacked image sensors

For the realization of full 3D stacked imagers, additionally TSV technology is required for the intermediate layers. TSV technology comes with a whole range of complexities. TSV aspect ratio limitations imply the need for wafer thinning and thin wafer handling by carriers. Filling of a TSV with conductive material is not a trivial procedure. Choices are to be made whether to use pre-processed or post-processed TSVs, from front-side or back-side, etc.

Moreover, the exact order of the assembly sequence needs to be thought over in detail. Bumping technologies used to interconnect different layers need to be stable during subsequent processing (stacking) steps.
4.4.5. Conclusions

<table>
<thead>
<tr>
<th></th>
<th>FOM</th>
<th>ECO</th>
<th>SHR</th>
<th>WAT</th>
<th>LEP</th>
<th>Public roadmaps?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Image sensors</td>
<td>+</td>
<td>=</td>
<td>−</td>
<td>=</td>
<td>+</td>
<td>no</td>
</tr>
</tbody>
</table>

FOM = Figure Of Merit  
ECO = Existing Community  
SHR = Willingness to SHaRe information  
WAT = Wide Applicability of Technology  
LEP = “Law” of Expected Progress

Table 26 – Potential of the domain of Image Sensors for MtM roadmapping.
4.5. **Biochips & lab on chips**

*Marco Tartagni, University of Bologna*

### 4.5.1. Scope & taxonomy

In the last decades, there has been a great effort in biology, chemistry, and engineering to pursue the advantages of miniaturization for cheaper, better, faster devices to be used in the life sciences such as bio-microsystems, which encompass a variety of devices, depending on the technology used or the targeted application.

Advantages are very similar to those obtained from the silicon integrated circuit: to get massive parallelism in measurements, as well as the possibility to carry out many experiments under exactly similar conditions, a situation which improves reliability in a field intrinsically prone to experimental uncertainties.

The main points where biosensor technology is strictly related to the evolution of the microelectronic industry are:

- **Parallelism.** As learned from the microelectronic industry, miniaturization can lead to massive parallelism. The need to carry out reactions in a parallel fashion, *e.g.*, for screening compounds of potential pharmaceutical activities, has progressively led to the development of standard plates with an increasing number of smaller and smaller reaction wells, as a substitute for the classical test tubes (microwell plates or microplates).

- **Reduced reagent consumption.** These compounds are often very expensive and reducing the volume of the reaction vessel of orders of magnitude was immediately perceived as an important benefit. Another major benefit of miniaturization is the cost reduction for screening the compound libraries, which pharmaceutical companies systematically test to establish their potential activity in a given cell-biology problem.

- **Speed/throughput.** The shrinking of technology features can not only improve the above performance parameters, but it has also additional advantages which are bound to the physics of the experiment itself, when heat or mass transfer are involved.

- **Functional Integration.** One of the most exciting opportunity from miniaturization will be in functional integration, which will allow one to quickly and cheaply perform complex multi-step analytical protocols, which traditionally require a host of different machines.

In **Table 27**, a subdivision of biochips into categories is drawn according to the application segment. In the last three columns, each category is evaluated according to the use (actual and potential) of main fabrication techniques: 1) Polymer/glass microfluidic. It is related to low-cost, low-resolution lithography based on polymeric materials and glass. 2) Silicon based microfluidic. This is related to the use of silicon-based, high-resolution patterning techniques. It also considers use of microelectronics as interface or sensing and actuation. 3) Nanotechnology with the use of nanodevices such as nanowires and nanopores.

The relationship of each technology with fabrication techniques is fundamental to foresee incidence of microelectronic industry in the field and to understand possible roadmaps. It is
interesting to see how the most advanced lithographic techniques are involved where molecular/cellular sensing is required.

<table>
<thead>
<tr>
<th>Diagnostic Segment</th>
<th>Purpose</th>
<th>Technology</th>
<th>Role of:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clinical chemistry</td>
<td>Measurement of compounds or enzymatic reaction products in body</td>
<td>Silicon gas sensors (silicon, etc.)</td>
<td>★★★</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Glucose sensors</td>
<td>★★★</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Enzymatic sensors</td>
<td>★★</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Enzymatic immunosensors</td>
<td>★★</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Urine and blood samples</td>
<td>★★★</td>
</tr>
<tr>
<td></td>
<td></td>
<td>pH sensors</td>
<td>★</td>
</tr>
<tr>
<td>Hematology</td>
<td>Characterization of blood components</td>
<td>Differential blood cell counters</td>
<td>★★★</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Whole blood analysis</td>
<td>★</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hemoglobin and blood lactate analysis</td>
<td>★</td>
</tr>
<tr>
<td>Microbiology</td>
<td>Investigation of the presence of disease-causing agents</td>
<td>Microbial sensors</td>
<td>★★★</td>
</tr>
<tr>
<td>Immunocchemistry</td>
<td>Detection of specific types of proteins using ligand chemistry</td>
<td>Microbe-oriented immunosensors</td>
<td>★★★</td>
</tr>
<tr>
<td>Molecular/cellular diagnostics</td>
<td>Uniprobe devices for cellular: DNA, RNA and protein detection</td>
<td>DNA sensors</td>
<td>★</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Immunosensors</td>
<td>★</td>
</tr>
<tr>
<td>In-vivo devices</td>
<td>New devices to be directly coupled with the patient's body</td>
<td>Non-invasive monitoring (pressure, heart rate, etc.)</td>
<td>★</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bioimplants (microcapsules, etc.)</td>
<td>★</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Drug delivery (intraocular, intranasal devices)</td>
<td>★</td>
</tr>
</tbody>
</table>

*Table 27 –Biosensor taxonomy. Role and potential use of fabrication techniques: ★ = poor, ★★★ = fair, ★★★★ = large.*
The Table 28 shows the biosensor taxonomy related to the segment of molecular/cellular diagnostics and high throughput screening (HTS) together with relationship with micro and nanotechnology.

<table>
<thead>
<tr>
<th>Process stages</th>
<th>Functions</th>
<th>Technology</th>
<th>Role of Micro- and Nanotechnology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell sorting</td>
<td>Isolation of cells from heterogeneous mixture of cell population</td>
<td>Flow cytometry</td>
<td>★★</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dielectrophoresis Electrophoresis</td>
<td>★★★</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Electro-magnetic sorting</td>
<td>★★★</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Optical tweezers and Micro filters</td>
<td>★</td>
</tr>
<tr>
<td>Cell lysis</td>
<td>Disruption of cell membrane for releasing intra cellular material</td>
<td>Thermal</td>
<td>★</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Acoustic, mechanical</td>
<td>★★</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Chemical and electrical lysing</td>
<td>★</td>
</tr>
<tr>
<td>Analytical purification</td>
<td>Purification/ amplification of analytical molecules</td>
<td>PCR amplification (for nucleic acids)</td>
<td>★★</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Purification using adhesion based technique</td>
<td>★</td>
</tr>
<tr>
<td>Molecular sensing</td>
<td>Detecting the presence of analyte molecules such as proteins and nucleic acids</td>
<td>Electrical</td>
<td>★★★</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mechanical</td>
<td>★</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Optical and Acoustic</td>
<td>★</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Magnetic sensing</td>
<td>★★★</td>
</tr>
</tbody>
</table>

Table 28 – Biosensor taxonomy for the class of molecular/cellular diagnostics and high throughput screening. The role of micro- and nanotechnology: ★ = poor, ★★ = fair, ★★★ = large.

In this segment one of the most relevant applications includes the acceleration of DNA amplification and detection and other molecular analyses from pre-processed samples. Applications in the “proteomics” area are being explored while in the “cellomics” field products are ready for the market. To attain the pervasiveness enjoyed today by electronic devices, a much higher degree of functional integration will be required, to address the new goal of sample-to-answer systems. Analytical methods are critical in a wide range of industry sectors, from pharmaceutical research to the food industry, from environmental control to diagnostics, to name a few.

4.5.2. Eligible technologies for roadmapping

Molecular biology and genomics has altered in-vitro diagnosis and opened up great possibilities for early and personalized diagnosis. Design of diagnostics devices is a system problem. The development of fully integrated point-of-care medical diagnosis requires the
miniaturization of several functional steps that are used today to perform a biological analysis in a laboratory:

- sample collection and preparation
- amplification and sample analysis
- detection

The development of these key functions needs a multidisciplinary approach where technologists, engineers, biologists and medics are closely working together, especially at the interface level.

The future enabling technologies to achieve the above-mentioned goals are:

- greater feature definition to address smaller targets or denser arrays
- merge of top-down with bottom-up techniques
- merge of microelectronic substrates with nanotechnology patterns

Such platforms are at the interface between the micro- and nano-worlds, exploiting system integration of the key enabling technologies. These systems should offer greater user flexibility through the incorporation of novel transducer configurations, organic surface chemistry and optimized biochemical probes, all integrated in a durable, simple and cheap package.

*Fig. 59* shows the typical features of the biochip technology components

But does microfluidic sample size always matter? This is important since this requirement could dictate the minimum features of the technology. As shown in *Fig. 60*, minimum volume depends on the application and could be larger for molecular detection than clinical assays.
4.5.3. Available roadmaps

Very few roadmaps or reports are freely available on the subject and among them:


- “Roadmaps at 2015 on nanotechnology application in the sectors of: materials, health & medical systems, energy” from the FP6 NanoRoadmap project (2005)

- “Roadmapping Personal Health Systems: Scenarios and Research Themes for Framework Programme 7th and beyond” from the FP7 PHS2020 project (2008)

- “Roadmaps in nanomedicine, towards 2020”, from the ETP Nanomedicine (2009)

Some roadmaps regarding nanodevices in the next 10 years are here below listed (ETP Nanomedicine).

---

76 Available at http://www2.imec.be/content/user/File/Biochips_FinalReport_1_.pdf
77 Available at http://www.nanowerk.com/nanotechnology/reports/reportpdf/report8.pdf
Table 29 – In-vitro diagnostics, product and applications.

Table 30 – Nanodevices, technology
Towards a “More-than-Moore” roadmapping

Table 31 – Nanodevices, products and application

![Graph showing nanodevices, products and application]

Table 32 – Market size forecast of MEMS for medical applications with respect to other segments (Source: iSuppli).

4.5.4. Technology requirements

One of the most researched fields relates to the electrical readout, based on implementation of electrical signal generation and electronic detection integrated using CMOS technology. Various other types of biosensor transducers are currently being developed and have reached different stages of maturity. A common theme in the evaluation of these transducer systems should be the focus on the direct detection of targeted bio-species without the incorporation of
biomolecular labeling. As an example, the coupling of magnetic labels to biomolecules can provide interesting perspectives for realizing novel diagnostic chips. Under the influence of magnetic gradients on chip, the labels can be manipulated to direct the attached biomolecules to the chip surface or specific locations on chip. The presence of the magnetic labels can be detected, enabling to monitor for instance hybridization results. The technique appears to be very sensitive and to reach very low detection limits. Typical examples in this area are the detection of cardiac markers, stroke markers and of prostate specific antigen (a marker for prostate cancer). The major challenge associated with label-free detection is the requirement of a low background even in the presence of large number of other molecules (this is also a problem with labeled detection, but it is reduced by the use of specific label attachment chemistry).

A remarkable trend in the increase of signal-to-noise ratio (SNR) has been achieved in the recent years (see Fig. 61 and Fig. 62). An example of this trend is the reduction of noise in current and voltage sensing as illustrated in the following table. Reduction of noise is due to either new circuit technique and to reduction of stray capacitance due to miniaturization.

![Fig. 61 – Reduction of noise in current-sensing interfaces](image)
Towards a “More-than-Moore” roadmapping

Fig. 62 – Reduction of noise and power in voltage-sensing interfaces

4.5.5. Conclusions

<table>
<thead>
<tr>
<th></th>
<th>FOM</th>
<th>ECO</th>
<th>SHR</th>
<th>WAT</th>
<th>LEP</th>
<th>Public roadmaps?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biochips</td>
<td></td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>no</td>
</tr>
</tbody>
</table>

FOM = Figure Of Merit  
ECO = Existing Community  
SHR = Willingness to Share information  
WAT = Wide Applicability of Technology  
LEP = “Law” of Expected Progress

Table 33 – Potential of the domain of Biochips for MtM roadmapping.
4.6. MEMS

André Rouzaud, CEA-Leti

4.6.1. Scope & taxonomy

4.6.1.a. Physical sensors with respect to “More-than-Moore”?

Today, we observe the development of a wide range of microsystem-based sensors for mechanical, optical, magnetic, and chemical measurements. Derived from microelectronics technologies mixed with some specific micro-technologies, this collective manufacturing allows significant cost reductions compared to traditional sensors. This approach, very general (many different products) and pervasive (many different markets), is illustrated in the figures below.
Fig. 63 – 2006-2013 sectorial MEMS evolution. Source: iSuppli 2009

Fig. 64 – 2006-2013 MEMS evolution by product. Source: iSuppli 2009

1. Products:

However, this large landscape hides large differences in the products maturity which strongly varies depending on the considered component. Basically, mechanical MEMS (pressure sensors, accelerometers and gyroscopes) are today by far the most mature components, which are widely used in many different mass markets such as automotive, gaming, computing, and cell phones to improve or increase the devices performances. Data from Fig. 64 show that today half of the MEMS production is focused on this MEMS family (pressure sensors, accelerometers and gyroscopes). These mature components are therefore the most interesting ones to be considered for effective roadmapping.
2. Technologies:

Collective technologies used to manufacture such components are mainly derived from standard microelectronics technologies (lithography, etching, coating, doping…) of older generations since:

- the typical dimensions to deal with are compatible with 0.5-0.35µm technological nodes.
- the volume of production is compatible with 150 – 200mm tools.

However they need to be combined with some very specific microtechnologies (wafer bonding, deep RIE etching, sacrificial layer release), for which there are no specific standard or agreed equipment roadmaps.

3. Generic technical blocks:

Although there are many attempts to standardize some approaches, technical modules or process flows, there is no today general agreement on basic “sub-systems” or technical blocks (analog to MOS transistor in ITRS) which could federate the technologies and be universally used to build standard MEMS: the empirical law “one product, one process” is still alive. The added value of the present group should be to identify in advance some few “federating” technical blocks.

4.6.2. Available roadmaps

Due to their soaring presence, and their attractive growth forecast (Yole Developpement sees a $6.5B MEMS device market in 2009 swelling to >$16B by 2015, and an even bigger surge in units. iSuppli sees MEMS growing 11% this year to $6.B and expanding to $9.8B by 2014, a 10.7% CAGR; units rising from 3.44B in 2009 to 4.14B in 2010, and 8.5B units by 2014), many approaches have been started to roadmap MEMS components. The most significant initiative is probably coming from Micromachine Center in Japan which is very active in promoting international standardization activities in MEMS fields. Due to the high diversity in this field, Micromachine Center has established roadmaps which remain very general and are divided into two main categories: fundamental technologies and MEMS devices (by application). The general roadmap for automotive applications is presented below, as well as the one for fundamental technologies.

---

79 see e.g. http://www.mmc.or.jp/e/outline-e/activities.html#standard
Fig. 65 – MEMS roadmap in the Automotive industry. 
Source: Micromachine Center

Fig. 66 – Fundamental technologies needed for MEMS
Source: Micromachine Center roadmap
Other initiatives have been launched by SEMI through a MEMS technical committee, but remain right now under construction and quite fuzzy, as seen in the two figures below.

![Fig. 67 – SEMI taxonomy table for MEMS.](image)

![Fig. 68 – SEMI roadmapping effort in MEMS](image)

More recently roadmapping efforts have been started within the iNEMI and ITRS frames: results are expected from 2011 onwards.

### 4.6.3. A possible approach

A possible three fold approach can be proposed, based on the triptych “generic blocks”, technologies and mature products, according to the scheme below.
The idea should be to develop roadmapping on mature mechanical MEMS where accurate figure of merit can be easily defined. Targeted improvements would have in turn a direct impact on the dedicated technologies (such as hermetic packaging and bonding…) as well as on the MEMS subsystems (such as resonators, seismic masses, membranes…) which appear as a background.

Some preliminary work has been initiated in the frame of 3D accelerometers to identify pertinent figure of merit. The ratio of the Dynamic Range to die size appears very pertinent since it implicitly includes influences of non-linearities, coupling, noise, and technology accuracy. Moreover this parameter seems to be generic enough for all mechanical sensors.

### 4.6.4. Conclusions

<table>
<thead>
<tr>
<th></th>
<th>FOM</th>
<th>ECO</th>
<th>SHR</th>
<th>WAT</th>
<th>LEP</th>
<th>Public roadmaps?</th>
</tr>
</thead>
<tbody>
<tr>
<td>MEMS</td>
<td>+</td>
<td>+</td>
<td>−/+</td>
<td>−</td>
<td>=</td>
<td>on-going</td>
</tr>
</tbody>
</table>

FOM = Figure Of Merit  
ECO = Existing Community  
SHR = Willingness to SHaRe information  
WAT = Wide Applicability of Technology  
LEP = “Law” of Expected Progress

**Table 34 – Potential of the MEMS domain for MtM roadmapping.**
4.7. Emerging Research Devices
Michel Brillouët, CEA-Leti

4.7.1. Scope, taxonomy and proposed focus
The ITRS in its “Emerging Research Devices” (ERD) chapter\(^{80}\) intends “to survey, assess, and catalog viable new information processing devices for their long-range potential, technological maturity, and to identify the scientific/technological challenges gating their being accepted by the semiconductor industry as having acceptable risk.” Over time the list of potential candidates will evolve either in suggesting that the device is mature enough to be considered for more industrial development or in acknowledging the lack of significant activity or progress towards a potential replacement of more standard technologies. In the last years the ITRS ERD chapter was “restricted to information manipulation, transmission, and storage” (i.e., the “More Moore” domain). It is thus tempting to extend this approach to the “More-than-Moore” domain.

Most of the published nano-enabled devices pertain to the fields of photonics (Table 35), energy (Table 36), (bio)chemical sensors (Table 37) and to the wireless domain (Table 38).

| Quantum confinement (λ tuning) |
| Digital photonics (photonic crystals…) |
| Transparent electrodes |
| (CNT, graphene, Ag NW, Cu nanofiber,…) |
| NW LEDs |
| Single photon laser |
| Plasmonic devices |
| … |

Table 35 – Some examples of nano-enabled MtM devices specific to the photonics domain.

| Nanostructured electrodes |
| Nanostructured thermoelectric materials |
| Nanowires for photovoltaic applications |
| Nanogenerators (energy scavenging) |
| … |

Table 36 – Some examples of nano-enabled MtM devices specific to the energy domain.

| NEMS (mass measurement) |
| Nanopores (DNA sensing) |
| Chemical functionalization of nanostructures (higher area/volume ratio) |
| … |

Table 37 – Some examples of nano-enabled MtM devices useful to (bio)chemical sensors.

Spin torque nano-oscillator
NEMS resonator
C-electronic mixer
Resonant tunneling diodes for ADC
Metamaterials (antenna...)

... 

Table 38 – Some examples of nano-enabled MtM devices applicable to the wireless domain.

All these domains are worthwhile for further roadmapping. However if one like to assess and benchmark emerging devices with respect to the “ultimate” performances of existing technologies one need to consider MtM domains where quantitative technology roadmaps already exist.

From the previous sections one can draw the conclusion that photonics could fit the requirement. A long term vision of this field was actually already addressed by the European project MONA 67 looking more specifically on the impact of nanotechnologies in the photonics field. It may not be wise to duplicate this effort in the present report.

On the other hand, from 2011 on, the ITRS ERD chapter will add a section on “More-than-Moore” initially on wireless devices. The rationale behind this initial focus is that one of the major chapters in ITRS dealing with the MtM field is the Wireless chapter: it will then be easier to benchmark emerging devices with respect to more established solutions and to assess their maturity for further development towards an industrial implementation. It is thus a timely exercise to envisage potential European inputs to this international initiative.

4.7.2. Technical challenges and requirements

The proposed approach (Fig. 70) will be a combination of:

– the methodology proposed in the present report starting in focusing on a specific application (e.g., wireless sensors network), partitioning in generic functional blocks (energy supply, rf front-end module, etc.), and finally deducing basic functions which could be fulfilled by emerging devices

– and the present ITRS ERD approach in the digital domain where any emerging device is analyzed as a potential switch and benchmarked with respect to the “ultimate” expected performance of the classical technology – the CMOS switch –

In this section we will outline some examples of emerging devices able to fulfill some basic functions.

It should be stressed – and that is especially true in the “More-than-Moore” domain – that a single device can fulfill higher level functions. That is why it is important to start from the functional analysis and not trying to replace existing devices which are most often related to a very specific underlying architecture.
To explicit this remark let us consider a rf front-end receiver. The “black-box” function of such a module is to transform a modulated electromagnetic wave into a digital representation of the signal under some control conditions. One of the elements of this functional block is a converter able to extract an analog form of the signal from the received electromagnetic wave. In 2007 K. Jensen and co-workers\(^\text{81}\) proposed an elegant approach to this problem. The general concept is as following:

- a carbon nanotube (CNT) is attached to an electrode and brought in close proximity of a counter-electrode
- a dc bias will charge the CNT – like in a capacitor – and tune the resonant frequency
- the charged nanotube will oscillate under an electromagnetic wave tuned to the nanotube’s resonance frequency
- field emission of electrons from the tip of the nanotube is used to detect the vibrations and at the same time amplify and demodulate the signal
- the demodulated signal will be read as a current

In short one single device was able to tune the reception, amplify and demodulate the signal, \textit{i.e.}, accomplishing a complex higher-level function by itself. Unfortunately not so many articles did follow this initial, well advertized result: this may imply that a robust implementation of an “all-in-one” sensitive receiver faces significant issues.

More realistically many elementary building blocks can be achieved using disruptive materials and devices. We will consider two examples – though many more can be considered and are partially mentioned in the Fig. 70 –, namely the use of carbon-based electronics in achieving a mixer and NEMS-based resonators.

Carbon-based electronics is a promising research field as carbon nanotubes and more recently graphene sheets show among other unique properties an extremely high mobility. It induces that this material could be useful for devices operated at very high frequency and low power. The role of parasitics has still to be assessed and it is not granted that the final integrated device will perform much better than the more classical SiGe and III-V transistors.

There is however more opportunities using graphene in rf applications. A carbon-based transistor has the property that in normal operation it shows ambipolar transport. This specific property can be used to build frequency doubler or mixer using a single transistor (Fig. 71).

![Fig. 71](image1.png)

**Fig. 71** – Using the ambipolar transport of graphene transistors one can build a one-transistor frequency doubler (a) or mixer (b) (from T. Palacios, Allen Hsu, and Han Wang, “Applications of Graphene Devices in RF Communications,” IEEE Comm. Mag., vol. 48, no.6, June 2010, pp. 122 – 128 (2010)).

The other example of using nano-structured devices for rf applications is in using NEMS as resonators or local oscillators. As for MOS transistors MEMS have some scaling laws which show the benefit of going down to submicron dimensions (Fig. 72).

![Fig. 72](image2.png)

**Fig. 72** – Scaling laws of MEMS devices.

---

Towards a "More-than-Moore" roadmapping  

Reducing the dimension of the moving beam will increase its resonant frequency to a point where it could be considered for rf communication, i.e., in the GHz range.

The full exploration of this promising and disruptive field is still at its beginning. Many more examples of a clever use of emerging devices for a disruptive introduction into "More-than-Moore" functions could be outlined: it is not the aim of this limited document to draft a full list of these emerging ideas even in the narrow field of rf applications. It is expected that this work will be pursued and extended within the Emerging Research Devices Technology Working Group of the ITRS and that a first text regarding this approach will be publicly available by the end of 2011.

As already mentioned for the digital domain, the ITRS ERD chapter proposes "first to introduce a set of overall technology requirements and evaluation or relevance criteria and second, based on these criteria, to offer an assessment of the potential of each emerging research technology entry [in order] to consider the long-term potential and advantages offered by a new device technology compared to the projected performance of [more standard] technologies." This benchmarking activity is important in assessing the potential of new ideas. For the "More-than-Moore" domain some additional remarks should be made:

- The function which is under scrutiny should be explicitly described along with the underlying architecture of the packaged system: some clarification in that direction is most often needed in many of the existing "More-than-Moore" technology roadmaps

- This benchmarking effort assumes that each function which could be addressed by the new device is well characterized in terms of Figures of Merit and their evolution up to their "ultimate" capabilities. While it is applicable in few examples, this roadmap has still to be explored in many cases

- Once more and as exemplified above the disruptive aspect of new devices may be more in a new way of achieving the same functionality (e.g., rf mixer with graphene transistor) rather than achieving better performances in mimicking existing devices and architectures (e.g., the high mobility of graphene for rf transistors)

One great achievement of the ITRS ERD chapter was to propose research vectors (or "guiding principles") which translate into challenging scientific questions relevant issues for long-term progress in the digital field. This work was initiated in the US through several workshops and led to the NRI program whose intent is to address these challenges and coordinate the academic research effort in that field. Clearly we are not at this stage in the "More-than-Moore" area of emerging research devices, but Europe could take the lead in proposing an equivalent federating approach of the academic research in some dedicated "More-than-Moore" fields.

---

83 see e.g. M. Brillouët, "NanoElectroMechanicalSystems: the challenge of combining microsystems and nanotechnology for new market opportunities," Symposium on Design, Test, Integration and Packaging of MEMS/MOEMS – DTIP 2009

84 “these “Guiding Principles” provide a useful structure for directing research on any “Beyond CMOS” information processing technology to dramatically enhance scaling of functional density and performance while simultaneously reducing the energy dissipated per functional operation.” (from the ITRS ERD Chapter – 2009)

85 http://www.src.org/program/nri/
4.7.3. Conclusions

The long-term opportunities of emerging research devices in the “More-than-Moore” domain were considered in the fields of photonics, energy, (bio)chemical sensors and wireless. In the case of optical functionalities, as the long-term view is addressed by the European photonics community, it is suggested to pursue this effort within the same context. On the other hand the ITRS in its “Emerging Research Devices” chapter intend, from 2011 on, to add a section on “More-than-Moore” initially focused on wireless applications. The authors suggest joining this international effort.
5. Conclusions

From this report, some general conclusions can be drawn:

1. There will not be a single roadmap of the “More-than-Moore” domain, but many dedicated roadmaps for those applications or technologies which fits the prerequisites for an efficient roadmapping.

2. The identification of generic / basic “More-than-Moore” functionalities is a central part of the effort. It can be obtained:
   a. either in partitioning the application domain under consideration, making explicit the underlying common architectures of the packaged systems and then extracting the few generic functions worth the roadmapping effort. It should however be stressed that to the authors’ knowledge there is no formal proof that the set of elementary functions which would be selected will form a complete set allowing the realization of any architecture of the explored domain.
   b. or from some elementary devices or building blocks build generic functions which could be applied in many different domains.

The present report is an attempt in that direction. However a huge effort is needed to reach significant conclusions: this was not fully achieved within the limited scope of the present exercise.

3. Figure(s) of Merit and “Law(s)” of Expected Progress has to be defined at the function level rather than at the device level: they could thus be partly dependent of the application.

4. An ideal process – which would require many iterations – would be as following:
   a. identify generic functional blocks per application (see above)
   b. for these functions which are used in many domains choose the most demanding application as a technology driver.

There are many existing roadmaps and strategic research agenda in specific “More-than-Moore” domains. However most of them fail to produce a technology roadmap equivalent to the ITRS in the digital domain. Part of this is related to the fact that such documents mix up different functional levels (applications, functions and sometimes devices) in describing the expected temporal evolution of their domain and most often no underlying functional architecture is even described. There is a definite need for clarification in such documents.

---

86 In contrast, for digital processing, DeMorgan’s theorems state that all logical operations can be reduced to combinations of NOT and AND functions or combinations of NOT and OR functions.
Towards a “More-than-Moore” roadmapping

In this report the different selected application domains and “More-than-Moore” devices were assessed with respect to the prerequisites of further roadmapping efforts: this is summarized in the following table.

<table>
<thead>
<tr>
<th>Domain</th>
<th>FOM</th>
<th>ECO</th>
<th>SHR</th>
<th>WAT</th>
<th>LEP</th>
<th>Public technology roadmaps?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Automotive</td>
<td>?</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>?</td>
<td>few</td>
</tr>
<tr>
<td>Wearable healthcare</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>?</td>
<td>few</td>
</tr>
<tr>
<td>Security &amp; Safety</td>
<td>?</td>
<td>+</td>
<td>=</td>
<td>+</td>
<td>?</td>
<td>few</td>
</tr>
<tr>
<td>Integrated power</td>
<td>+</td>
<td>+</td>
<td>=</td>
<td>+</td>
<td>?</td>
<td>few</td>
</tr>
<tr>
<td>Lighting</td>
<td>+</td>
<td>+</td>
<td>=</td>
<td>+</td>
<td>+</td>
<td>yes</td>
</tr>
<tr>
<td>Image sensors</td>
<td>=</td>
<td>+</td>
<td>=</td>
<td>=</td>
<td>+</td>
<td>no</td>
</tr>
<tr>
<td>Biochips</td>
<td>=</td>
<td>+</td>
<td>=</td>
<td>=</td>
<td>+</td>
<td>no</td>
</tr>
<tr>
<td>MEMS</td>
<td>+</td>
<td>+</td>
<td>=</td>
<td>=</td>
<td>=</td>
<td>on-going</td>
</tr>
</tbody>
</table>

FOM = Figure Of Merit  
ECO = Existing Community  
SHR = Willingness to Share information  
WAT = Wide Applicability of Technology  
LEP = “Law” of Expected Progress

Table 39 – Potential of different application domains and devices for MtM roadmapping.

From this table one can draw the following interim conclusions:

- automotive and security are two application domains where dedicated “More-than-Moore” roadmaps could develop
- energy as such is a too broad field but few associated device roadmaps (e.g., integrated power and lighting) are meaningful
- healthcare need a more in-depth analysis of which sectors would be worth further roadmapping
- integrated power and lighting are ripe for further roadmapping effort
- for different reasons image sensors and MEMS are more difficult to roadmap while the domain of biochips is probably the most challenging one

Finally for each selected domain we would like to detail some conclusions and potential follow-ups.

For energy and considering only “More-than-Moore” packaged devices the authors suggest focusing on the compact medium-energy integrated power electronics (see the related comments on “integrated power” below) which is the domain having the biggest interaction with the semiconductor community. Furthermore it should be outlined that there are many scattered references to energy challenges in the ITRS roadmap and it would be worthwhile to analyze and consolidate these contributions. No further effort in this application field is suggested for the next future.

The electronics in the automotive sector is driven by safety, energy efficiency or impact on the environment, which translate into the need of better transducers and integrated power. It is suggested to focus on the requirements of the electrical car which will be addressed by the
Towards a “More-than-Moore” roadmapping

newly launched European project ICT4FEV. Further activity in this domain could also be pursued within the EPoSS frame, esp. through its Strategic Research Agenda.

The healthcare domain is very broad and diverse. From the point of view of the electronic industry a focus on diagnostics rather than therapeutics seems preferable. In some specific functions Figures of Merit evolving over time exist. However the field is very fragmented and it would be extremely challenging to find the right application-specific domains where a “More-than-Moore” roadmapping effort would make sense. The authors suggest postponing such an effort of covering the healthcare domain in its entirety to a later stage. On the other hand focused roadmapping effort can be envisaged in fields like wearable healthcare or biosensors (see below)

Some devices and technologies are driven by the security and safety application domain – possibly along with healthcare and automotive for some of them. This is especially true for infrared image sensors, THz spectroscopy and imaging, and secure hardware. The next steps would be to substantiate this statement through a roadmap program whose frame has still to be identified.

On the device / technology side, the field of integrated power is clearly worth further investigation. While the high power domain is suggested to be out of the scope of a roadmap on “More-than-Moore” devices, both the medium power and low power segments are in strong interaction with the microelectronics industry. The low power field (esp. looking at energy scavenging and low-power electronics) was addressed in a former report of the CATRENE Scientific Committee. Medium power should thus be a priority for roadmapping and further activity in this field may take place within the CATRENE Scientific Committee. A significant effort is also on-going through the ECPE organization and the authors suggest joining this roadmapping activity. Parts of this domain could also be addressed within the EPoSS frame.

In lighting some international roadmaps exist for LEDs as well as many roadmaps were issued in the last few years in Europe on photonics. However the system level is often not enough covered and the experience of the microelectronic community in this field could be beneficial. As a practical measure it is suggested to update the part of the ENIAC Strategic Research Agenda dedicated to lighting. Some stakeholders of the lighting domain may also be interested in joining the International Solid State Lighting Alliance (ISA) newly announced in China.

For image sensors – at least in the visible range – the short-term trends are clear. However this field is very competitive with few industry players and still fewer in Europe: it is thus unlikely that a roadmap in that domain will emerge. No further effort on this topic is

87 http://www.smart-systems-integration.org/
88 CATRENE, ENIAC or EPoSS – which all address this domain in their strategic documents – could be the right frame, provided the financial support of such an activity is provided.
89 http://www.ecpe.org/
90 http://www1.eere.energy.gov/buildings/ssl/techroadmaps.html
91 In the last decade at least three roadmaps were published in Europe addressing the photonics field. MELARI published a roadmap in the late 90’s (available at http://cordis.europa.eu/esprit/src/melop-ram.htm), the European Technology Platform PHOTONICS21 published a Strategic Research Agenda in 2006 (http://www.photonics21.org/downloads.php), while the European project MONA published a roadmap looking more specifically on the impact of nanotechnologies in the photonics field in 2009 (http://www.ist-mona.org/pdf/MONA_v15_190308.pdf).
92 see e.g. http://en.china-led.net/daily-information/international-solid-state-lighting-alliance-isa-founded-in-china.html
suggested for the next future. If any roadmapping activity emerges at the international level it would be most likely through the ITRS community.

**Biosensors** are a field which shares many common features with microelectronics such as the need of a significant parallelism, throughput and miniaturization. From the microelectronics perspective it is probably worthwhile to focus on few applications like molecular / cellular diagnostics and *in-vivo* devices. In this field the importance of the analog front-end was outlined: this remark applies for most transducer systems and will be further addressed below. As a next step it is proposed to focus the roadmapping effort on molecular sensing, provided the right frame for action is found.

**MEMS** is a very limited market and a fragmented field which addresses many critical applications. Identifying long-term trends and drivers is challenging and was not really successfully achieved with the limited resources of the present Working Group. Few clear needs for roadmaps were identified in the domain of testing, Electronic Design Automation and process equipments which could be addressed within the present ITRS structure. As an international effort was started within iNEMI ⁹³ and will be also pursued from 2011 in the ITRS, the authors suggest that Europe play a significant role in these initiatives.

It has been stressed during this work that the **analog front end** is one of the main building blocks that any transducer system shares and which would be worth addressing as a stand-alone section. Part of this domain was discussed in the “Biochips” section of the present report. This concern is partially addressed in the “System Drivers” chapter of the ITRS – though strongly focused on the wireless application – and further work would take place most likely within this context.

The long-term opportunities of **emerging research devices** in the “More-than-Moore” domain were also considered in this report. Most of the published nano-enabled devices pertain to the fields of photonics, energy and (bio)chemical sensors. Few roadmaps address this long term vision ⁹⁴. On the other hand the ITRS in its “Emerging Research Devices” chapter intend “to survey, assess, and catalog viable new information processing devices for their long-range potential, technological maturity, and to identify the scientific/technological challenges gating their being accepted by the semiconductor industry as having acceptable risk.” Up to now this ITRS chapter focused on the digital information processing, but from 2011 on, it will add a section on “More-than-Moore” initially focused on wireless applications. The authors suggest joining this international effort.

In summary, following the ITRS White Paper on “More-than-Moore”, this report goes one step further in suggesting some area of focusing further MtM technology roadmaps and in proposing some suitable frames for action. The follow-up of this report will strongly depend on the willingness of the European “More-than-Moore” stakeholders to dedicate resources in these “More-than-Moore” roadmaps and to take some leadership in accompanying the stronger international interest in this MtM domain.

---


⁹⁴ The MONA roadmap (see the footnote of the preceding page) is one of the few exceptions.
Appendix A : Glossary

“Moore’s Law”

ITRS 2009 Glossary:
An historical observation by Gordon Moore, that the market demand (and semiconductor industry response) for functionality per chip (bits, transistors) doubles every 1.5 to 2 years. He also observed that MPU performance [clock frequency (MHz) × instructions per clock = millions of instructions per second (MIPS)] also doubles every 1.5 to 2 years. Although viewed by some as a “self-fulfilling” prophecy, “Moore’s Law” has been a consistent macro trend and key indicator of successful leading-edge semiconductor products and companies for the past 30 years.

“More Moore”: Scaling

Short definition
Continued shrinking of physical feature sizes of the digital functionalities (logic and memory storage) in order to improve density (cost per function reduction) and performance (speed, power).

ITRS 2010 Glossary

Geometrical (constant field) Scaling refers to the continued shrinking of horizontal and vertical physical feature sizes of the on-chip logic and memory storage functions in order to improve density (cost per function reduction) and performance (speed, power) and reliability values to the applications and end customers.

Equivalent Scaling (occurs in conjunction with, and also enables, continued geometrical scaling) refers to 3-dimensional device structure (“Design Factor”) improvements plus other non-geometrical process techniques and new materials that affect the electrical performance of the chip.

Design Equivalent Scaling (occurs in conjunction with equivalent scaling and continued geometric scaling) refers to design technologies that enable high performance, low power, high reliability, low cost, and high design productivity.

“More-than-Moore”: Functional diversification

Short definition
Incorporation into devices of functionalities that do not necessarily scale according to “Moore’s Law”, but provide additional value in different ways.

The “More-than-Moore” approach allows for the non-digital functionalities to migrate from the system board-level into the package (SiP) or onto the chip (SoC).

---

Towards a “More-than-Moore” roadmapping

ITRS 2010 Glossary

Functional Diversification (“More than Moore”) [refers to] the incorporation into devices of functionalities that do not necessarily scale according to “Moore’s Law,” but provides additional value to the end customer in different ways. The “More-than-Moore” approach typically allows for the non-digital functionalities (e.g., RF communication, power control, passive components, sensors, actuators) to migrate from the system board-level into a particular package-level (SiP) or chip-level (SoC) potential solution.

System-on-Chip (SoC)

WikiPedia definition

System-on-a-chip or system on chip (SoC or SOC) refers to integrating all components of a computer or other electronic system into a single integrated circuit (chip). It may contain digital, analog, mixed-signal, and often radio-frequency functions – all on one. A typical application is in the area of embedded systems.

Comment

We would like to emphasize that “a single integrated circuit” is in fact monolithic (single die) and that, consequently, all components (functions) have to be manufactured in a single (CMOS-compatible) process technology.

System-in-package (SiP)

System in Package (SiP) is a combination of multiple active electronic components of different functionality, assembled in a single unit that provides multiple functions associated with a system or sub-system. A SiP may optionally contain passives, MEMS, optical components and other packages and devices.

[Definition from The next Step in Assembly and Packaging: System Level Integration in the package (SiP), White Paper ITRS 2008]

Heterogeneous integration

Functional combination of dissimilar (electrical, optical, thermal, magnetic, mechanical) components onto a silicon substrate and/or within a single package. The domain covered by the term “heterogeneous integration” is schematically depicted by the light blue triangle in the diagram below.

---

96 http://en.wikipedia.org/wiki/System-on-a-chip
Fig A1. The “heterogeneous integration” domain (light blue triangle).
Appendix B: Combining Focus and Variety: The Photolithography example

We will identify knowledge creation, “idea” generation and, generally speaking, follow the cognitive process of innovation and knowledge production, using a representation of the reasoning activities proposed in one of the most recent theories of design reasoning, the C-K theory (Hatchuel and Weil, 2003). 98

The C-K theory describes a design reasoning as the interaction between two spaces, the concept space C and the knowledge space K. Design begins with an initial concept, a proposition that is neither true nor false, i.e., is undecidable in the K space. Such a design brief cannot be said feasible or unfeasible, marketable or not... “Reducing the physical gate length”, without specifying how to do it, is such a concept. The design process consists in refining and expanding the concept by adding attributes coming from the knowledge space (the gate can be printed using photon imprint, or e-beam, or...). The process can also lead to the production of new knowledge (e.g., how to control over-etching, reticle enhancement techniques ...) to be used in the design process. The initial concept set is actually step by step partitioned in several, more refined, subsets. The process unfolds until one refined concept is enough specified to be considered as true by the designer: the concept becomes a piece of knowledge. The generic structure of a design reasoning is presented in the figure below (source: Hatchuel 2009 99)

Fig. B1. The generic pattern of a design reasoning in the C-K design theory

The C-K framework helps to follow cognitive processes (expansion of knowledge space, expansion of the conceptual brief into several, varied alternatives…). In particular, it allows to assess the intensity of knowledge acquisition (apparent when the “K” space is populated with knowledge not known at the beginning of the design process), and the variety of the concept produced (apparent when the concept “tree” has many branches). Applying this representation to the photolithography recent past developments, and future solutions, one gets the following “high level” picture:

**Fig.B2. Example: C-K framework for lithography**

Clearly the lithography innovation process displays both knowledge intensity and variety. One would probably find similar representation in many other domains of the roadmap (see, for example, device architectures). In fact the ITRS process allows for the exploration of a variety of technical solutions to achieve a constant high rate of technological progress in the long term, while focusing on the most realistic ones for the shorter term. This, coupled with a continuous updating process, allows the incorporation of unforeseen technological breakthroughs.