The MONA Project : The Nanophotonics Roadmap

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ABSTRACT

The goal of the MONA project (Merging Optics and Nanotechnologies) is to leverage synergies in photonics and nanotechnologies, seeking to increase the impact and efficiency of investment in European research.
There are three principal objectives for the MONA project:

- Create a common site for the exchange of information concerning research, networks of excellence, and integrated projects in photonics and nanotechnologies.
- Promote the timely exchange of scientific results, market development, and technology needs through MONA-developed workshops.
- Develop a European roadmap for photonics and nanotechnologies.

Keywords: photonics, nanotechnologies, nanophotonics, roadmap

1. INTRODUCTION

MONA (Merging Optics and Nanotechnologies) is a project funded by the European Commission. **MONA** is the first European action to coordinate two of the most important new directions in science and technology today: Photonics and nanotechnologies. Photonics is a field with many applications and results. Yet, this field is poorly recognised by the general public. Nanotechnology is a field with few concrete results and applications,. Yet the field is much more widely recognised by the public. Clearly much activity is needed to achieve equal recognition of these two technologies in the mind of the public.

1. Raising awareness among both the nanotechnology and photonics communities about European research and technology development (RTD) projects involving nanotechnologies or photonics.
2. Developing a widely accessible database concerning materials and manufacturing tools for photonics and nanotechnology RTD
3. Publication of a Roadmap for Nanophotonics: technologies, processes, applications.
4. Public presentations of European RTD activities in nanotechnologies and photonics in Europe, in North America and in Asia
5. Presentation in Europe of RTD activities in photonics and nanotechnologies in Asia and North America on the MONA public web site.

In this presentation we review our development of a roadmap for nanophotonics, with a discussion of the general framework of such a roadmap its structure and contents.

Nanophotonics is an ensemble of disruptive technologies, which is another way of saying that the market for applications and products that would be supported by these technologies has not yet been identified. Nanotechnologies and nanomaterials are emerging domains that can dramatically change the situation in photonics. New materials are emerging (e.g. glasses or ceramics with nanoparticles, functional polymers, carbon nanotubes) with completely different properties and fabrication technologies. The development of the roadmap will be based on a bottom-up approach, which we call “technology push”. The organisation of this project is based on the following steps:

1. Determining a frame of reference, for example, considering which nanotechnologies and which photonics functionalities are most important.
2. Survey of Materials, Processes and Applications.
3. Assembly of the nanophotonics roadmap.

These steps are summarised in Figure 1.

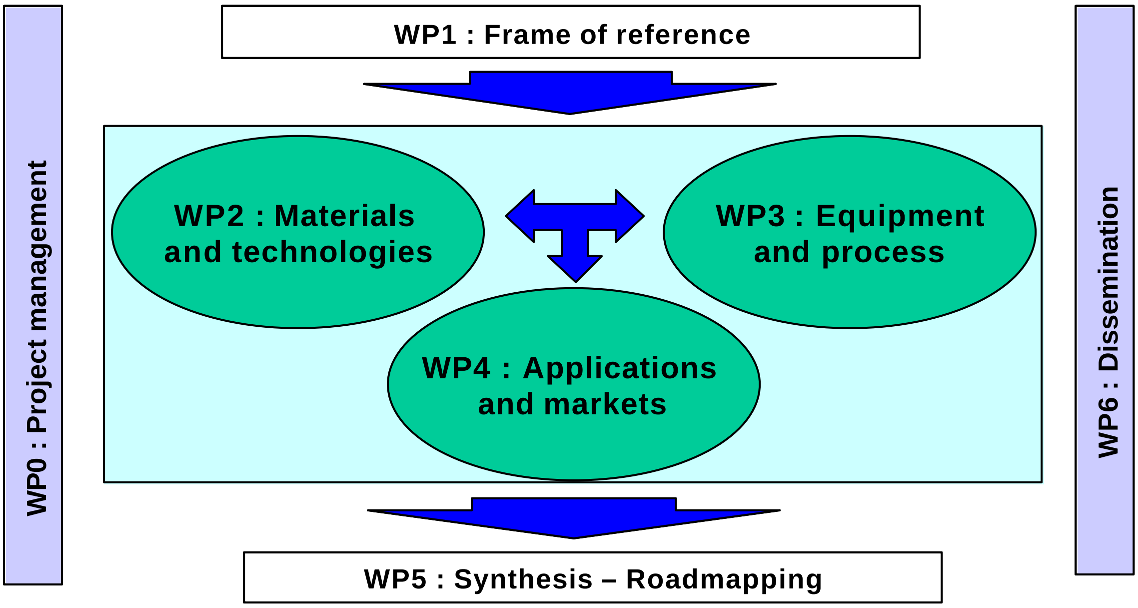


Figure 1 Information flow in the MONA project. Information about Materials, Processes and Applications is being gathered through interviews with a large number of players in each field.

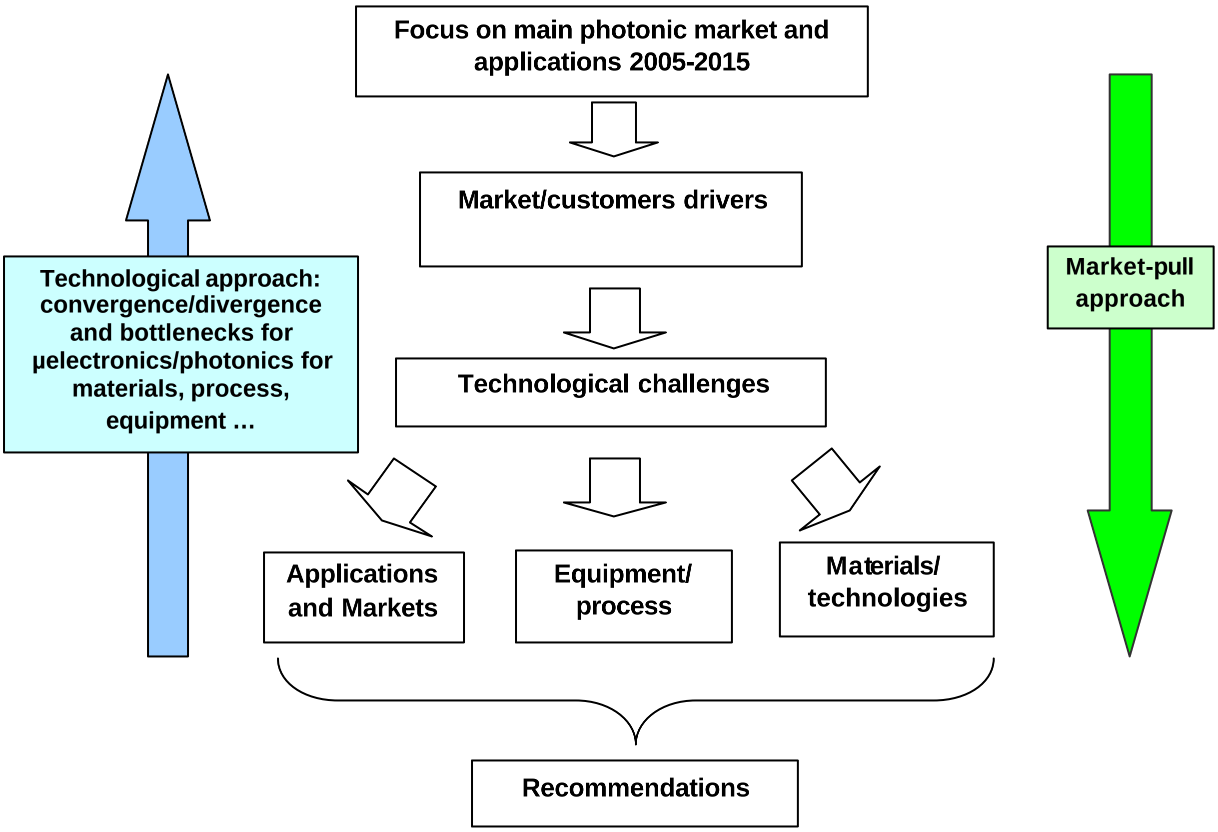


Figure 2. Building the roadmap based on the MONA project organisation

Roadmapping has been used very successfully in the integrated circuit industry. However, the International Technology Roadmap for Semiconductors (ITRS) appeared when the industry was approaching maturity, and there was consensus on future components and applications. In the IC industry there are two basic kinds of devices: logic and memory. In the case of photonics there are many quite different types of devices. In the IC industry there are only a few materials: silicon, SiO_2, some metals, and some insulators. In the photonics industry there are many different kinds of materials which do not share a common process technology. These differences are important, and the procedure for building the roadmap for nanophotonics will also be different.

The Roadmap process itself, shown in Figure 2, is based on a similar organisational concept as that shown in Figure 1.

2. THE FRAME OF REFERENCE

The Frame of Reference for the MONA project defines what is meant by merging optics and nanotechnologies, and following has worked to determine the subset of nanotechnologies and optics that could generate synergies leading to new materials, processes and applications. We have carried out the first survey in Europe of research and development projects that are addressing these fields at the state of the art. This 300-page study has been completed and is available to the reader (http://www.ist-mona.org/documents/default.asp).
The report is structured as follows:

- Introduction
- Current Production Technologies in Photonics
- Nanostructuring Technologies
- Photonics
- Summary and Conclusion - Key Issues
- Annexes
    - Equipment
    - Projects and Networks of Relevance
    - Glossary

This report sets the starting point of MONA regarding its content, by providing a joint frame of reference for the subsequent work packages. The approach is to summarize the state of the art in both nanostructuring technologies and nanophotonics. Then we have proceeded to analyse both fields with respect to materials and technologies and with respect to equipment and processes, particularly with reference to volume production.

Two results have emerged from this initial study:

- Optics and Nanotechnologies merge where lateral structures, layers, molecular units, inner boundary layers and surfaces with critical dimensions or production tolerances that extend from about 100 nanometres down to atomic size are produced, studied and utilized for the generation, transmission, manipulation, detection, and utilization of light.
- We will consider the capacity of nanotechnologies to impact future technologies and markets related to nanophotonics, but not the reverse.

3. MATERIALS AND TECHNOLOGIES

In order to build a roadmap on the materials and material technologies used in nanophotonics, the first step has been to identify the major classes of materials and to make an overall assessment of the critical issues relevant for those materials. In a next step the most prominent applications will be identified for each material system and a roadmap will be elaborated for these material/application combinations.

The major classes of materials studied in MONA are

- Semiconductor quantum dots&wires
    - in silicon
    - in III-V
    - in II-VI
- Plasmonics/metallic nanostructures
- Photonic Crystals/High index contrast nanostructures
    - in silicon

  - in III-V
  - in other materials
- Colloidal nanostructures
  - in semiconductor
  - in metal
- Organic nanostructures
- Nanoparticles in glass or polymer
- Left-handed metamaterials
- Integration of nanophotonic materials/structures with electronic ICs

For each of those classes the main critical issues have been identified with inputs from experts in each of those fields. Without going in detail for each of those, a number of generic challenges – relevant for several of these material systems – can be identified. We will discuss here three such generic challenges.

A first challenge is the fact that the optical properties of many nanophotonic materials are sensitive to nanometer-level geometry variations, and in some cases even to sub-nanometer geometry variations. Even if some research-oriented material structuring or synthesis tools may be capable to meet this requirement, it is a massive challenge for production-oriented manufacturing tools, in particular in terms of uniformity and reproducibility. This is true both for bottom-up techniques such as self-assembly methods, in which case the level of control over size and position of nanoparticles is often not good enough, as it is the case for top-down nanostructuring techniques, such as deep-UV projection lithography, in which case both resolution and accuracy are to be improved. For the latter the field of nanophotonics is heavily dependent on the developments in CMOS technology, where Moore's law (still) rules and provides an enormous gear towards further downscaling with techniques such as immersion lithography at 193 nm and extreme-UV lithography. In parallel there is rapid progress now in the field of nano-imprint lithography (NIL) and there is an emerging research community to use NIL for nanophotonic purposes.

A second generic challenge is the fact that the physical understanding of and the capability to numerically simulate and design nanophotonic materials is still limited. This is caused by two factors: even if the theoretical models for nanophotonic materials are mostly well understood, the numerical simulation of 3D structures with complex geometries and material compositions is very demanding. For this reason there are efforts underway, eg in the Network of Excellence ePIXnet, to develop a modelling platform based on large computer clusters and to provide access to this platform for the nanophotonics community. The second factor has, once more, to do with reproducibility of technology. It is very hard to exactly know the nanometric structure of a nanophotonic material and to reproduce it. This implies that it is a challenge to reliably analyse the functional behaviour of nanophotonic materials across their material parameter space.

A third generic challenge is that the wide diversity in materials and material technologies is – by itself – jeopardizing the rapid deployment of nanophotonics into products, because all research efforts are diluted very heavily across this wide diversity. While there is no obvious solution to this problem, there is an increasing consensus that at least part of the efforts should seek some kind of convergence. The most straightforward way of finding convergence is to make use, as much as possible, of mature technologies with a critical mass which exist in other disciplines. The most obvious example is of course CMOS technology. If one can make use of nanophotonics in a way which is – as much as possible – CMOS-compatible, then the route towards industrial deployment all of a sudden looks much brighter. CMOS-compatibility can mean many different things here. It can mean using Silicon as a mere carrier and use the machines, normally used for CMOS-production, to structure devices in whichever nanophotonic materials above Silicon. But it can also mean to integrate nanophotonic structures with CMOS-circuitry and do so in a CMOS-fab with the standard front-end or back-end tools of those fabs. The latter is of course vastly more difficult than the first but so is the potential leverage. These concepts are fully compatible with the rapidly emerging "More than Moore" trend in micro-electronics and therefore it is realistic to believe that a critical mass of research will happen, leading to convergence and deployment.

Europe is in a strong position for most nanophotonic materials. There are strong research projects and networks already in place. However, Europe is weak in manufacturing technologies. There is little focus on manufacturing sciences. This is coupled with a lack of multidisciplinary integration at the university level. At the same time industry is showing relatively little interest in longer term research directions, and instead is expecting the university community to undertake this effort.

4. EQUIPMENT AND PROCESSES

Equipment and processes can be divided conveniently into two groups: "Top-down" and "Bottom-up". "Top-down" refers to equipment that creates nanostructures in already existing material. Examples of "Top-down" equipment are various forms of lithography, including nano-imprint and soft-imprint methods, Etching, and definition of nanostructures by imposed electric fields, magnetic fields, or confinement by optical beams. On the other hand, examples of "Bottom-up" equipment are: thin-film deposition (e.g. MBE, MO-CVD, and PE-CVD) self-organised assembly, and printing (e.g. ink-jet, protein ink printing)

Processes involve metrology and analysis, as well as the synthesis methods referred to above. Important analytical processes are those which can reveal imbedded nanostructures such as electron microscopy (TEM, SEM, and STM), other kinds of scanning probe microscopies, like AFM and SNOM. Optical techniques such as ellipsometry, reflectometry, and photoluminescence are capable of determining material properties with nanometre resolution. Many "Bottom-up" deposition processes require high-precision in-situ metrology in order to function successfully.

For equipment and processes, the key question is, "What are the limitations of today's technologies and methods when it comes to nanophotonics?" We are seeking the answers through workshops and expert interviews. At the present time we are noting the following results:

There is neither equipment nor process dedicated to nanophotonic device fabrication at the present time. Currently, a variety of standard equipment is used; processes are adapted to nanophotonics requirements.

Concerning "Bottom-up" processes, MO-CVD is dominating semiconductor epitaxial deposition, but in-situ metrology will be required to reach the level of uniformity and repeatability needed to reach production at industrial volumes. Definition of nanostructures by applied external fields may provide a direction toward structures that can be fabrication using high-volume techniques while also providing for means to adjust the size or the electronic levels to desired values post-fabrication.

5. APPLICATIONS AND MARKETS

Generally speaking, the most important applications of nanophotonic technologies can be related to three different functions that a nanophotonic component could play: *Light emission*, *Transport*, including modulation and switching, and *Detection*. Examples of these categories are given below:

? Light emission
    Lasers, LEDs, Phosphors, Displays
? Transport / modulation / switching
    Transmission fiber, Lenses, Modulators, Switches, Isolators, Filters, Sensors
? Detection
    Detectors, Image sensors, Other sensors, Photovoltaic cells

In terms of global markets, it seems that a few sectors will drive the nanophotonics applications and markets in the near future. Among the most important are

Flat panel displays, LED Lighting, lasers, and diagnostic and analytic instruments for healthcare. According to one recent market study, the global market for nanophotonic devices is projected to grow from $420.7 million in 2004 to $9.3 billion in 2009, with an average annual growth rate of 85% between 2004 and 2009. Light-emitting diodes, used for back-lighting in flat panel displays, accounted for over 82% of the market in 2004. Light-emitting diodes are not only the largest, but also appear to be the fastest-growing nanophotonic market segment, with a projected growth rate of more than 90% between 2004 and 2009. This extremely high growth rate reflects their growing adoption in monitor and display applications. By 2009, this segment is expected to represent nearly 94% of the nanophotonics market.

In the MONA roadmapping project, we are emphasizing applications market rather than quantifying market sales volumes. The objective of MONA is to relate, when possible, the potential applications to well defined devices and their parameters in order to understand how a particular nanophotonics component will replace existing photonics device, based on macrotechnologies. We are focusing on the following applications:

? Optical Interconnects
? Communications

? Lighting
? Data storage
? Imaging
? Sensors
? Displays
? Photovoltaics
? Instrumentation for diagnostics and metrology

For each application we associate the nanomaterials and processes involved and we transmit these findings to the other two research groups in the MONA project. The applications, materials and processes constitute a matrix in which each material or process will be related to a given application. At the materials-applications cross point it will be possible to identify a device or several devices.

6. THE NANOPHOTONICS ROADMAP

A Roadmap is a documented, consensus-based plan that industry develops with input from the research community (and the govt. if appropriate).

What drives a Roadmap?
Market share dynamics of competing technologies
Market expectations not being met
Costs of R&D/Infrastructure too large for one company/country

To begin the roadmapping project, we had to develop and agree on a methodology shared by all project team members. This enables the integration of the data and analysis in the three areas of enquiry: materials, processes, and applications. Data for the roadmap is gathered both through workshops that MONA is running, plus interviews with selected companies and R&D laboratories that are working in the nanophotonics area.

The resulting Roadmaps must answer a set of "*why-what-how-when*" questions in order to develop actions plan for reaching the objective. The relevance of these questions is illustrated below in Figure 3.

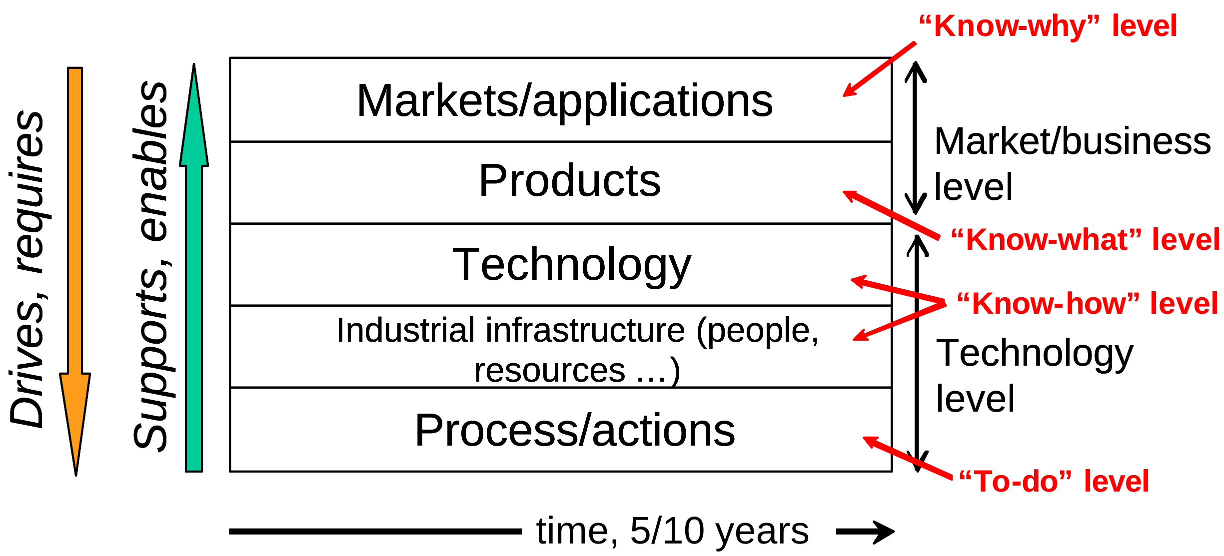
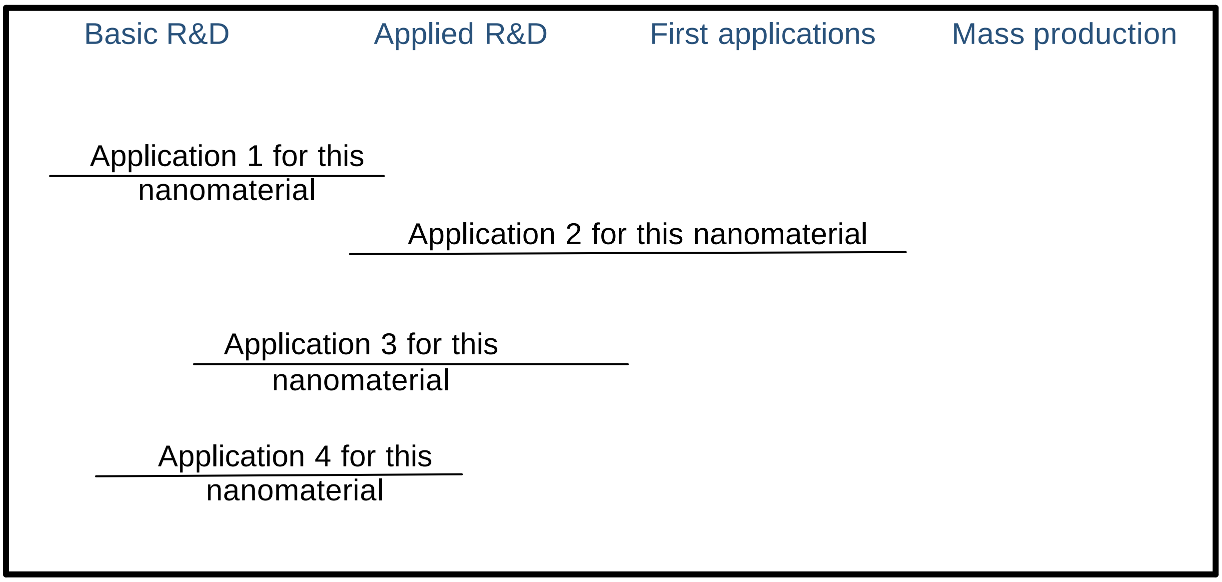
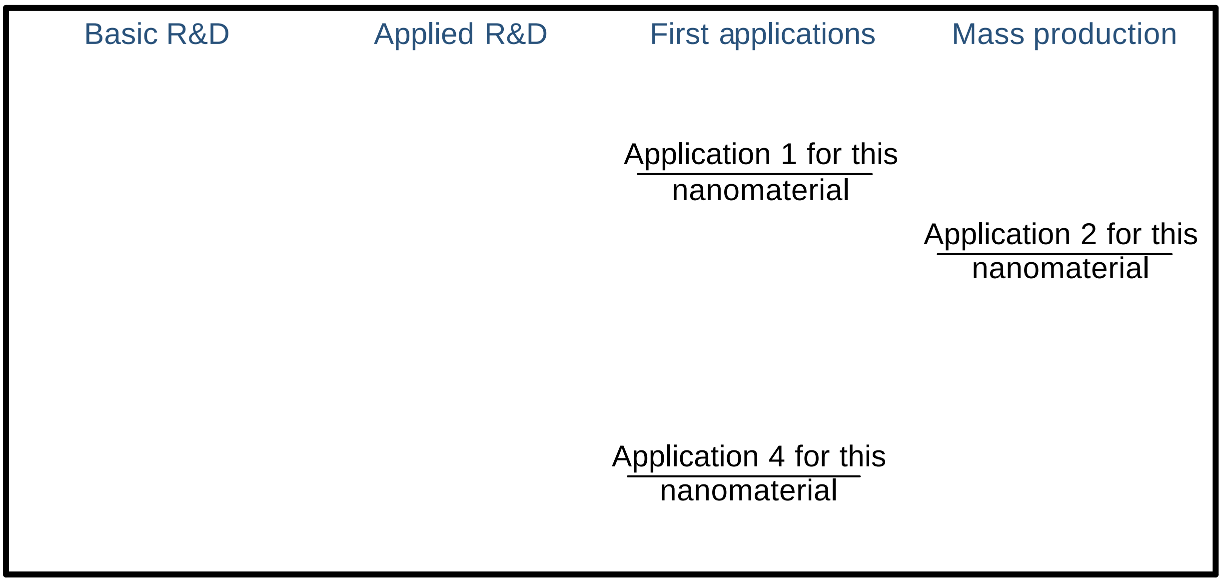


Figure 3. Key questions are posed at the interfaces between the important components of the development of a high-tech product based on nanophotonics.
The "know-why" describes the domain of the roadmap (market and applications) for nanophotonics.
The "know-what" defines the nanophotonics products .
The "know-how" describes the evolution of the technologies and resources.
The "to-do" defines the action plan and risks (key development actions, resources required, technology investment strategy, action programs, R&D programs, standards/legislation

An example of the Roadmap that emerges from this methodology is shown in Figure 4, a&b. For a given material, several applications are identified. In Figure 4a, the position of these applications between basic research and mass production is shown. The horizontal bar show that some products are more advanced than others. In Figure 4b, 10 years later, it can be seen how these application areas have evolved toward more mature products.



4 a. Overview of Applications in 2005



4b. Overview of the Same Applications in 2015

Figure 4

4a. This roadmap shows for a specific material (e.g, InAs/GaAs quantum dots) that there are 4 major application areas. The horizontal bar shows that there is a range of commercial development for each application.

4b. In 2015, the evolution of the application areas has moved clearly toward mass production. However, Application 3 has disappeared because it has been merged, or made obsolete by Application 2.

7. SUMMARY

The nanophotonics Roadmap is an effective way to:

1. Reduce uncertainties in investments
2. Use changes among competing technologies as opportunities
3. Increase the probability for more robust economic performance
4. Guide critical research

5. Assist in setting priorities for resource allocations and
6. Accelerate the rates of both technology development and deployment.

These benefits are particularly important for the development of new materials, processes and applications that may require significant capital investments. The ITRS roadmap has demonstrated that less money is wasted by development of competing technologies. Decision-makers from different organizations (comp, research, govt.) alter their attitudes towards one another, and thereby, enable more cooperation. There is sharing of pre-competitive information, expenses and risks which results in acceleration of the development of advanced manufacturing technologies. It becomes more simple and straightforward to create and implement open interfaces and standards. The result is that profit margins for exploiting nanotechnologies are improved, and the time to market is reduced. Successful roadmapping results in a competitive advantage for the participating companies.

A useful Roadmap needs to be reviewed/updated/rewritten regularly. MONA is organising a seminar and a second workshop in Grenoble the 28th and 29th of November 2006. You are invited to participate to discuss the first roadmap results. More details can be found on the MONA web site: http://www.ist-mona.org/

A 3rd Workshop is being organized during Photonics West in San Jose, 20-25 January 2007.