WWW.EFMN.INFO The European Foresight Monitoring Network

# MONA: A European Roadmap for Photonics and Nanotechnologies

**Foresight Brief No. 158**

**Authors:** Dirk Holtmannspötter (holtmannspoetter@vdi.de) - Future Technologies Division at VDI TZ GmbH
Laurent Fulbert (laurent.fulbert@cea.fr) - CEA-LETI
Marie-Joelle Antoine (MJ.Antoine@opticsvalley.org) - OPTICS VALLEY
Bjorn Maes (Bjorn.Maes@UGent.be) - IMEC - Ghent University
Rainer Beccard (R.Beccard@aixtron.com) - AIXTRON AG
Eric Mounier (Mounier@yole.fr) - Yole Développement
Thomas Pearsall (pearsall@epic-assoc.com) - EPIC
**Sponsor:** European Commission
**Type:** European Roadmap for Photonics and Nanotechnologies
**Organizer:** MONA Project Consortium (www.ist-mona.org)
**Duration:** 06/2005–11/2007 **Budget:** 950,000 € **Time Horizon:** until 2015 **Date of Brief:** Dec. 2008

## Purpose

Photonics and nanotechnologies are highly multi-disciplinary fields and two of the principal enabling technologies for the 21st century. They are key technology drivers for industry sectors such as information technologies, communication, biotechnologies, transport, and manufacturing. Photonics/nanophotonics and nanomaterials/nanotechnologies can benefit from each other in terms of new functions, materials, fabrication processes and applications. The MONA Roadmap identifies potential synergies between photonics/nanophotonics and nanomaterials/nanotechnologies. The challenge of mastering nanoelectronics and nanophotonics science and technologies at an industrial scale is of utmost strategic importance for the competitiveness of the European industry in a global context.

## Context and Objectives of the MONA Roadmap

The MONA project (Merging Optics and Nanotechnologies), funded by the European Commission, is the first concerted effort to coordinate work in two of modern science and technology's most important areas: photonics and nanotechnologies. Six European countries and regions have been involved in the execution of MONA, under the leadership of the CEA-LETI (Electronics and Information Technology Laboratory of the French Atomic Energy Commission), with input from important industry and research players like Acreo, AIXTRON, Alcatel-Thales, ASMI, the European Photonics Industry Consortium (EPIC), IMEC, OpticsValley, Schott, VDI Technologiezentrum (VDI TZ), and Yole Développement.

This project has established a roadmap for photonics and nanotechnologies that includes technologies, fabrication processes, and applications as well as research needs for the future. Correspondingly, this project has dealt with the following questions: How will the field of optics be affected by the emergence of various nanotechnologies? Which opportunities for optics arise from nanotechnology? How will the processes and the equipment, the materials and the technologies change with nanotechnologies entering the production process in photonics? What are the key issues related to the fabrication of nanophotonic devices?

There were three principal objectives for the MONA Roadmap:

1. Create a consensus viewpoint on the development of research, technologies and innovation in the areas of photonics and nanotechnologies.

The EFMN is financed by the European Commission DG Research. It is part of a series of initiatives intended to provide a 'Knowledge Sharing Platform' for policy makers in the European Union. More information on the EFMN and on the Knowledge Sharing Platform is provided at WWW.EFMN.INFO

2. Promote the timely worldwide exchange on scientific results, market development perspectives, and technology trends related to photonics and nanotechnologies.

3. Contribute to the intelligent deployment of resources at the regional, national, and European levels for the development of photonics and nanotechnologies.

# MONA Roadmapping Methodology

A roadmap describes a future environment, objectives to be achieved within this environment, and plans for how these objectives will be achieved over time. It lays out a framework, or architecture, as a way of understanding how the pieces of a complex technological system fit together, interact and evolve. It links applications, technical challenges and the technological solutions together, and it helps set priorities for achieving the objectives. Roadmaps generally must answer a set of "why-what-how-when" questions to develop action plans for reaching the objective (see Figure 1). The first part (the "know-why") can describe the domain of the roadmap in terms of markets and applications for nanophotonics. The second level ("know-what") defines the nanophotonic products needed for level 1. The third part ("know-how") can be split in two: technology and infrastructure. This part describes the evolution of the technologies and resources that will be needed to achieve the products. The fourth plan ("to-do") defines the action plan and risks. It identifies key development actions, resources required, the technology investment strategy and recommendations. All parts of the roadmap are laid out over time (the "when" of a roadmap).

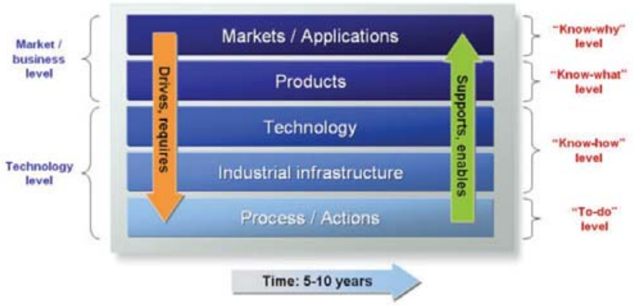


Figure 1: the different levels of a roadmap

The MONA ("Merging Optics and Nanotechnologies") consortium has developed its roadmap for photonics and nanotechnologies in Europe in two years of work using workshops, symposia and expert interviews. Almost 300 people from industry and academia have contributed to the construction of the roadmap that gives insight into the future of materials, equipment, processes and applications. It also highlights the European position and outlook on nanophotonics and offers recommendations.

# MONA Roadmap Findings

## Nanomaterials

The MONA roadmap identifies key nanomaterials having the strongest impact for nanophotonics. They are:

- Quantum dots and wires in Si, III-V and II-VI
- Plasmonic nanostructures
- High-index-contrast Si and III-V nanostructures
- Carbon nanotubes
- Integration of electronics with photonics
- Nanoparticles in glasses or polymers

## Equipment

Equipment and processes are crucial for the improvement of the performance of nanophotonic devices.

- The processes that will have the highest potential impact on nanophotonics and at the same time have potential for mass production are MOCVD, CNT CVD, colloidal synthesis, nanophosphor fabrication, sol-gel synthesis, OVPD, UV lithography, nanoimprint and etching.
- The types of equipment and processes with the broadest field of applications are MOCVD, MBE and colloidal chemistry as bottom up technologies and UV lithography, e-beam lithography and nanoimprint lithography as top-down technologies.

## Devices

The analysis highlights the most important devices that European industry should focus on for the different applications of nanophotonics. In the table below, key devices for major applications are identified. For displays, the nanophotonic devices that are expected to have a large technical impact are LCD backlighting with CNT or LED. OLEDs are a particular case. Although the technical impact will not be so strong, there are strong competencies in Europe that justify OLEDs as a key device for Europe (both for FPDs and lighting). For the lighting application, it is LED with II-VI quantum wires (ZnO) and III-V photonic crystals. For datacom and telecom, the effort should be put on high-index-contrast-Si photonic devices (laser, waveguide, switches and detectors), active fibre (amplifier) with nanoparticles and nanophotonic devices using CMOS semiconductor process. Optical interconnects should take benefit from development on laser sources and gates with Si nanocrystals, nanophotonic devices using CMOS semiconductor process and lasers with III-V quantum dots. For photovoltaics, it is III-V quantum-dot solar cells that will have a large impact. Infrared photodetectors with III-V quantum dot (QDIP) and plasmonics are important for imaging. Fluorescent markers with quantum dots and biological or refractive-index sensors using plasmonics will be important for next generation of biosensors.

| APPLICATIONS (2009 market value) | KEY DEVICES | EU POSITION | | RISKS | TECHNICAL RECOMMENDATIONS | BENEFITS |
|---|---|---|---|---|---|---|
| | | R&D | Indus-trial | | | |
| Displays ($90 B) | *CNT* | +++ | + | H | Improve manufacturability | Improved performance (lower power consumption, better image quality) |
| | *Organic LED* | ++ | + | L | Improve packaging | Flexible and thinner displays are possible |
| Photovoltaics ($50 B) | *Quantum dots III-V based solar cell* | +++ | + | M | Better QD formation control | Improve efficiency |
| Imaging ($10 B) | *CMOS image sensors with plasmonics* | +++ | ++ | H | Improve photon-plasmon coupling sensitivity | Increased sensitivity in VIS |
| | *III-V QD infrared imager* | +++ | +++ | L | Improve responsivity | Improved performance<br>Potentially simpler fabrication process |
| Lighting ($6.8B) | *ZnO nanowires-based LED* | ++ | ++ | M | Improve p-doping, carrier injection and manufacturability | Excellent materials quality |
| | *LED with III-V photonic crystal* | +++ | +++ | M | Achieve low-cost process | Optimized light extraction |
| Data/Telecoms ($4.5B) | *High index contrast Si photonic devices* | +++ | + | M | Improve packaging and coupling for PICs<br>Integration with silicon.<br>Need for generic technology for a broad range of functionalities | Lower cost<br>More compact devices |
| | *Active fibre with nanoparticles* | ++ | ++ | M | Improve manufacturability and performance. | Low losses |
| | *Electronic/ photonic integration* | +++ | ++ | M | Low-cost, wafer-scale approaches to incorporate III-V devices on Si | Low-cost, high-performance optical links<br>Low-cost optical transceiver possible |
| | *All Si link* | +++ | ++ | H | Manufacturing issues (CMOS compatibility) | Compactness and high performance |
| Sensors ($4.2 B) | *Fluorescent markers with QD II-VI* | ++ | + | L | Accurate control of size distribution, production up-scaling | Enhanced sensitivity for biosensors<br>Longer lifetime |
| | *Plasmonic biosensors* | ++ | + | M | Integration with existing technologies (e.g. Si-platform), integration on chip | Enhanced sensitivity<br>Ultra-small sensors (dense sensor arrays) |
| Optical Inter-connects ($0.8 B) | *QD III-V laser source* | ++ | ++ | M | Improve manufacturability and CMOS compatibility, temperature stability | Compact devices<br>High performance (data rate)<br>Microelectronics manufacturing equipment can be used |
| | *Si QD-based laser source* | +++ | + | H | Control of the size and density of Si nanocrystals | Compactness and high performance<br>Light emission from silicon can be obtained |
| | *Chip to chip link with flip chip source* | +++ | ++ | L | Low-cost solution needed | Mature process |
| | *Link with hybrid integrated source* | +++ | ++ | M | Improve manufacturability (CMOS compatibility) | Compactness and high performance |
| | *All Si link* | +++ | ++ | H | Improve manufacturability (CMOS compatibility) | Compactness and high performance |

## MONA Roadmap Policy Recommendations

MONA's key recommendations are:

- Provide support services for displays such as R&D and process equipment (CVD for carbon nanotubes for example) since strong European competencies exist in the field of carbon nanotubes, glass substrates and display systems. Moreover, Europe could benefit from OLED rigid display development by providing R&D services, materials and equipment. There is also room for innovation on flexible displays that have not yet reached the stage of industrial production.
- Develop quantum-dot technology for solar cells. The photovoltaics market is growing.
- Maintain R&D on visible and infrared sensing in various application areas. There are industrial players in Europe (STM, e2v). Moreover, in infrared sensing, Europe has key players like Sofradir. These companies could be interested in III-V quantum dots as an alternative to MCT and conventional QWIPs.
- Intensified R&D for lighting. There is a large market for nanophotonics; so securing a successful industrial development appears as an important objective. Moreover, the presence of two major European players (Osram, Philips) is a major asset.
- Maintain R&D for datacom/telecom (Bookham, 3S Photonics and many start-ups), specifically for further integration of optical and electronic chips.
- Europe should maintain its R&D on microstructured fibres, II-VI quantum dots and plasmonics for nanophotonic-based sensors (for example, surface plasmon resonance instrumentation has been successfully commercialized by Biacore in Sweden).

- Maintain R&D competence in optical interconnects. This effort should be continued in order to compete with the USA where DARPA, big microelectronics companies (Intel, IBM) and start-ups (Luxtera, Kotura) are already very active.

## MONA Roadmap Conclusions

One of the nanophotonics' challenges would be to share and combine the efforts in order to create synergies between different applications. This could be done by common work on nanophotonic devices that are similar for different final application fields. We have identified two potential synergies resulting from commonalities between devices.

For display and lighting applications, the objective is to generate and distribute light with high brightness and efficiency. In both fields, there is an increasing requirement to reduce power consumption and meet Kyoto protocol goals. The main devices under development, which will be impacted by nanophotonics, are: LED, CNT-FED and OLED.

That means that future development efforts on those three devices will benefit both fields of application. Europe has a strong industrial position in lighting with two major players (Osram and Philips). Although the display market is currently mainly dominated by Asian players, the growing light source business and the development of flexible displays could provide European players an inroad into that market. For OLED displays, it is unlikely that Europe could become a large OLED manufacturer, but it could have a strong position as a supplier for materials and technologies.

The second synergy identified is for optical interconnects and data telecom. In both applications, indeed, photonics have either been substituted or the aim is to eventually substitute them for the traditional metallic connection in order to manage an ever-increasing amount of data. Datacom/ telecom deals with long distances above the chip-to-chip or board-to-board scale whereas optical interconnect is below the board-to-board scale in medium to short distance and even inside chips. Datacom/ telecom has been using photonics for twenty years whereas optical interconnect is in its infancy. The shorter the distance, the more entrenched is the metallic connection. However, in both cases, the light is generated, filtered, transported, received and treated as an information unit. Hence, nanophotonics will impact common devices to both application fields: laser source, wave guide, switches or gates, links or fibres, transceivers, and detectors. Nanophotonics will allow improvement of datacom/ telecom devices to reach data rates higher than 40 Gb/s, whereas it will be the "must have" in the optical interconnect small dimension world. However, in the latter case, very harsh competition with copper electrical links exists and low cost, high volume fabrication processes (e.g. CMOS compatible process) are mandatory in order for photonic devices to replace electrical counterparts. Moreover, high index contrast structures and quantum dots nanophotonic material play a strong role in both applications fields.

There are also synergies between organic solar cells and OLEDs because challenges related to encapsulation and lifetime are similar. As for displays, these two application fields are facing similar manufacturing challenges related to the fabrication and positioning of nanostructures on very large area substrates. The situation is thus different from nanoelectronics where the wafer and the device sizes are kept about one order of magnitude smaller (e.g. $cm^2$ range for device, $dm^2$ for the wafer).

Although Europe's position in manufacturing nanophotonic devices is not so strong compared to Asia and the US (except for LEDs with Philips and Osram) and the majority of the manufacturing of semiconductor or photonic devices is done outside Europe, there is a strong equipment industry in Europe. This is the case for MBE, MOCVD, lithography, ALD, etching, OVPD, CNT CVD equipment and also for equipment required for more exotic processes. European players are among the top ones for MOCVD with Aixtron (DE), MBE with Riber (FR), CVD/PVD with Oerlikon (CH), Photolithography with ASML (NL), NIL with Obducat (SWE), (deep) etching with STS (GB), Adixen (FR), ALD with ASM (FI).

To strengthen the European position in nanophotonics, actions could be taken through Photonics 21 and by the European Commission. However, since the funding from the European Commission represents less than 5% of all European RDI spending, a serious effort is needed to convince industry and national/regional commissions to read and implement the MONA roadmap.

## Sources and References

MONA Consortium (2008): MONA – Merging Optics & Nanotechnologies. A European roadmap for photonics and nanotechnologies http://www.ist-mona.org/pdf/MONA_v15_190308.pdf