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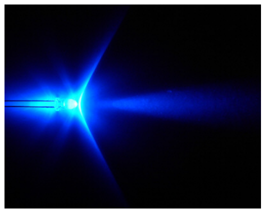
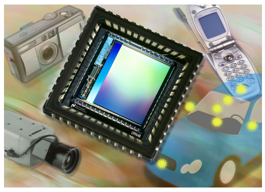
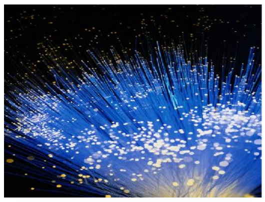
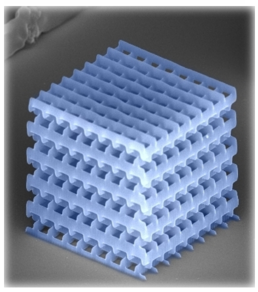


MONA
Merging Optics & Nanotechnologies





A European roadmap for photonics and nanotechnologies



Contents

Contents 2

1. Executive summary 6

2. Introduction and acknowledgements 9

3. Roadmapping methodology 10

4. Applications and devices 14

4.1. Applications 14

4.2. Devices 16

4.3. Nanophotonics benefits for each application 17

4.3.1. Flat Panel Displays 17
4.3.2. Photovoltaics 17
4.3.3. Imaging 17
4.3.4. Lighting 18
4.3.5. Data storage 18
4.3.6. Optical interconnects 18
4.3.7. Data & Telecom 18
4.3.8. Sensors 19
4.3.9. Instrumentation 19

5. Nanomaterials: challenges and impact 21

5.1. Key nanomaterials for nanophotonics 21

5.2. Impact of nanomaterials per nanophotonic applications 23

5.3. Nanomaterials challenges 25

6. Nanophotonics equipment: challenges and impact 26

7. Synthesis of each application 28

8. Recommendations for European Science and Industry 36

8.1. Most important nanophotonic devices 36

8.2. The technical recommendations 37

8.2.1. Displays 37
8.2.2. Photovoltaics 37
8.2.3. Imaging 37
8.2.4. Lighting 38
8.2.5. Data Storage 38
8.2.6. Datacom & Telecom 38
8.2.7. Sensors 39
8.2.8. Optical Interconnects 39

8.2.9. Instrumentation 39

9. Conclusions **48**

Annexes A: Report on the 5 to 10-year roadmap on materials **50**

A.1. Introduction **51**

A.2. Materials synthesis **52**

A.2.1. Quantum dots and wires in silicon **52**

A.2.2. Quantum dots and wires in III-V materials **53**

A.2.3. Quantum dots and wires in II-VI **54**

A.2.4. Plasmonics in metallic nanostructures **55**

A.2.5. High index-contrast nanostructures in silicon **56**

A.2.6. High-index-contrast nanostructures in III-V **57**

A.2.7. Microstructured fibres **58**

A.2.8. Organic nanostructures **59**

A.2.9. Carbon nanotubes **60**

A.2.10. Integration of electronics and photonics **61**

A.2.11. Nanoparticles in glass or polymer **62**

A.2.12. Left-handed meta-materials **64**

A.3. Analysis **65**

A.4. Timelines for each material **67**

Quantum dots and wires in silicon **67**

Quantum dots and wires in III-V **67**

Quantum dots and wires in II-VI **68**

Plasmonics in metallic nanostructures **69**

High index contrast nanostructures in silicon **70**

High index contrast nanostructures in III-V **71**

Microstructured fibres **71**

Organic nanostructures **72**

Carbon nanotubes **72**

Integration of electronics and photonics **73**

Nanoparticles in glass or polymer **74**

Left-handed meta-materials **75**

Annexes B: 5 to10-year roadmap for equipment and processes **76**

B.1. Introduction **76**

B.2. Equipment and process analysis ... 77

B.3. Bottom-up technologies ... 78

B.4. MOCVD ... 79

B.5. MBE ... 83

B.6. Other CVD processes ... 86

B.7. Miscellaneous deposition processes ... 88

B.8. Top-down technologies ... 92

B.9. Photolithography including deep UV and EUV ... 93

B.10. X-ray lithography ... 95

B.11. Electron beam lithography ... 96

B.13. Focused ion beam lithography ... 100

B.14. (Dry) Etching ... 101

B.15. Summary and analysis ... 103

B.16. First recommendations in the European context ... 108

B.17. Equipment and process roadmaps ... 109

Annexes C: Report on the 5-10 years roadmap on applications and related markets ... 114

C.1. Introduction ... 114

C.2. Applications and markets - roadmaps consolidation ... 114

C.2.1 General description ... 114

C.2.2 Applications overview ... 115

C.2.2.1. Optical Interconnects ... 115

C.2.2.2. Datacoms & Telecoms ... 116

C.2.2.3. Lighting ... 118

C.2.2.4. Data Storage ... 120

C.2.2.5. Imaging ... 121

C.2.2.6. Sensors ... 122

C.2.2.7. Displays ... 124

C.2.2.8. Photovoltaics ... 125

C.2.2.9. Instrumentation and equipment ... 127

C.3. Conclusion ... 129

C.4. Devices as mentioned in the roadmaps for each application ... 130

Optical Interconnects ... 130

Datacom & Telecom 132
Lighting 135
Data Storage 136
Imaging 137
Sensors 138
Displays 140
Photovoltaics 142
Instrumentation and equipment 145

C.5. Timelines for the application 146

Optical Interconnects 146
Datacoms & Telecoms 148
Lighting 150
Data Storage 151
Imaging 152
Sensors 153
Displays 154
Photovoltaics 156
Instrumentation and equipment 158

Annex D: List of MONA members, contacted experts and workshop participants 159

Annex E: List of acronyms 160

1. Executive summary

The MONA ("Merging Optics and Nanotechnologies") consortium has developed this roadmap for photonics and nanotechnologies in Europe following 2 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 with respect to nanophotonics, and offers recommendations.

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 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.

The MONA Roadmap identifies key devices for major applications in the table below.

APPLICATIONS (2009 market value)	KEY DEVICES	EU POSITION		RISKS	TECHNICAL RECOMMENDATIONS	BENEFITS
		R&D	Industrial			
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 Potential 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*	+++	+	H	Improve packaging and coupling for PICs Integration with silicon. Need for generic technology for a broad range of functionalities	Lower cost More compact devices
	Active fiber 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 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 Longer lifetime
	Plasmonic biosensors	++	+	M	Integration with existing technologies (e.g. Si-platform), integration on chip	Enhanced sensitivity Ultra-small sensors (dense sensor arrays)
Optical Interconnects ($0.8 B)	*QD III-V laser source*	++	++	M	Improve manufacturability and CMOS compatibility, temperature stability	Compact devices High-performance (data rate) 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 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

Europe has a very strong R&D background in photonics, and specific efforts for each application should be done to stay competitive.

The key recommendations of MONA 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 which are not industrialized yet.
- 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 are 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 fibers, 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.

The MONA roadmap has been developed in the context of world-wide contributions and competition. Strategic cooperation with roadmapping activities in Japan, Korea, Taiwan and the USA has ensured the overall relevance of the roadmap.

MONA should serve as an informed input for the future FP7 workprogrammes. In particular, the MONA results can be used to build upcoming strategic research agendas for both nanomaterials and photonics.

To be useful, a roadmap has to be alive and evolving. The MONA roadmap will be regularly updated through the MONA website (www.ist-mona.org). It allows the nanophotonics community to stay informed on the research and industrial evolution of nanophotonics.

2. Introduction and acknowledgements

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, 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.

The goal of this project is to establish a roadmap for photonics and nanotechnologies that includes technologies, fabrication processes, applications as well as research needs for the future. Correspondingly, this project is concerned 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?

This document synthesises the outputs of the MONA project and provides recommendations to support nanophotonics in Europe. We use information from the roadmaps, established in the MONA project, to identify the main challenges and the most promising applications from a materials and equipment point of view. Furthermore, we have compared the different materials with respect to their potential impact.

The first section introduces the MONA project and its objectives. We present a brief overview of the methodology used during the MONA project. Following, we show the different market size and growth rates for all applications targeted by nanophotonics. We have analyzed a broad variety of photonic devices, emphasising commonalities between application fields. In the next section we present the key impact and challenges for a broad range of nanomaterials as well as the key types of equipment and challenges, including a synthesis for each application showing the development timelines of most promising devices. Finally, we discuss the European position in nanophotonics and present an outlook and recommendations. In the annexes, the reader will find detailed reports presenting the roadmap from the points of view of materials, equipment and applications.

The authors would like to thank all the experts who contributed to this roadmap by participating to workshops and symposia or by completing specific roadmaps. The complete list is given in Annex 4.

Finally, the financial support by European Commission under project 017255-MONA is acknowledged

3. 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 actions plan for reaching the objective (see Figure 1). The first part (the "know-why") can describe the domain of the roadmap in terms of market and applications for nanophotonics. The second level ("know-what") defines the nanophotonic products which will be needed for the level 1. The third part ("know-how") can be spit 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, technology investment strategy and recommendations. All parts of the roadmap are laid out over time (the "when" of a roadmap).

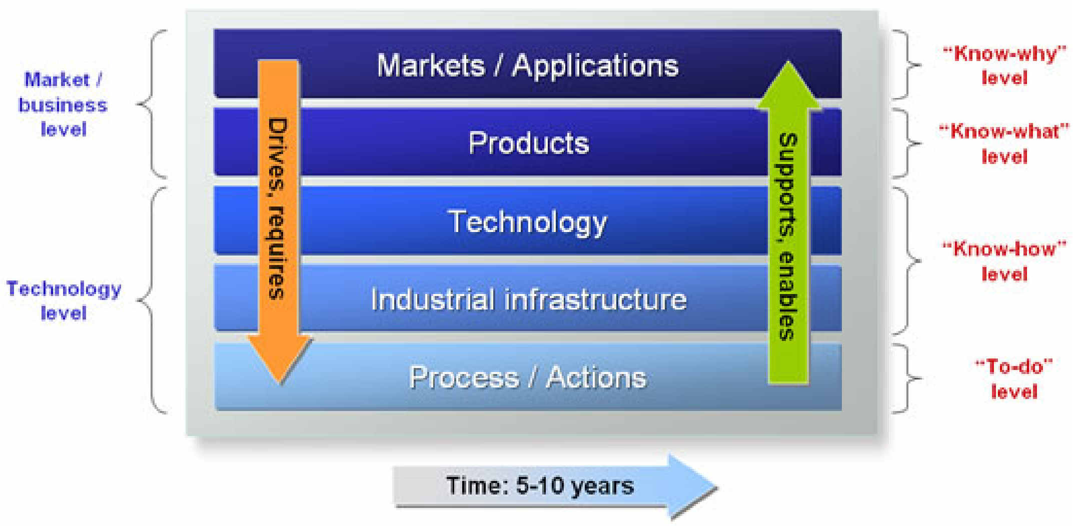


Figure 1: the different levels of a roadmap

A roadmap may be constructed beginning with the key needs of the marketplace and customers – a market-pull perspective. Conversely, a roadmap may start with a key technology and seek to define the market needs that could be served with the new technology – a technology-push. However, because of the disruptive nature of nanophotonics, it is easily recognised that a market-pull approach is not a useful approach to build a roadmap. It is difficult to imagine markets for functions and materials which have not yet been manufactured on a commercial scale. As a consequence, a technology-push approach has been adopted.

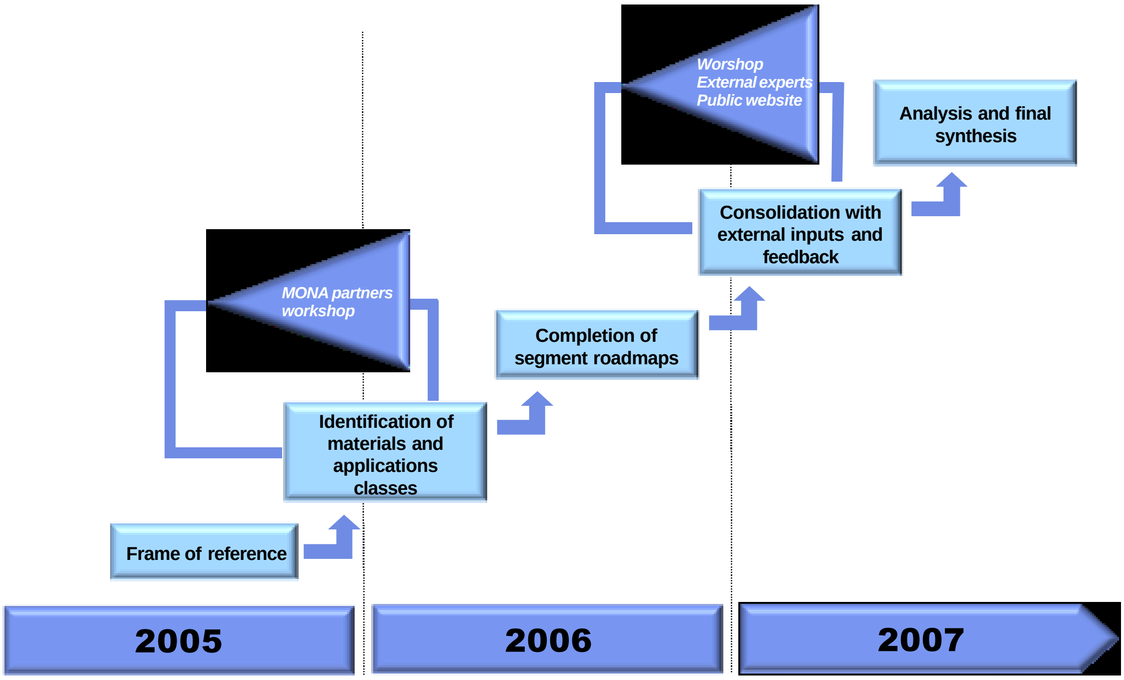


Figure 2: MONA roadmapping process

The MONA project has been funded by the European Commission under the IST & NMP thematic priorities. It has been operational from June 2005 to December 2007. The first step has been to set the *Frame of Reference* to describe the nanostructuring technologies, the new nanophotonics approaches and devices. The *Frame of Reference* (available at www.ist-mona.org/documents/default.asp) provides the guidelines for selecting the most important nanomaterials, equipment/processes and devices for nanophotonics. The relation between optics and nanotechnologies has been considered from the optics point of view. That means the key question has been: *How will nanotechnologies improve and enable the field of optics in the future?* We consider that, optics and nanotechnologies are merging in the regime where lateral structures, layers, molecular units, inner boundary layers and surfaces with critical dimensions or production tolerances that extend from about 100 nanometers down to atomic orders of magnitude are produced, studied and utilized for the generation, transmission, manipulation, detection, and utilization of light. In addition to this definition, the MONA consortium decided to study in the roadmap only 2D and 3D structures. 1D structures such as quantum wells for instance are already well-known and used and have not been investigated in depth in this roadmap. Based on this definition, the selected technologies and photonic devices have been covered:

- Top-down technologies: lithography, nanoimprint and soft lithography, etching
- Bottom-up technologies: thin films assembly, epitaxy, self-assembly, printing
- New nanophotonics approaches: near-field optics, quantum-confined materials, plasmonics, high index contrast structures
- Nanotechnology for photonic devices: laser diodes, LEDs, sensors, displays, photovoltaics, single-photon systems, silicon photonics, electronic/photonic convergence.

Figure 2 shows the different steps for the MONA roadmap establishment.

The MONA roadmapping process has been subdivided into 5 major steps:

1. First MONA has identified the most promising classes of materials and applications for nanophotonics to be investigated (year 1).
2. At each crossing point of the materials/applications matrix, the relevance of the nanophotonic devices (which will benefit from nanomaterials for nanophotonic application) has been assessed (no potential use of the considered materials in the application, maybe a potential use, identified use of the considered material/nanostructure class in the application …). This has been done at each matrix crossing point (nanomaterial/application) through desk research, market surveys, and interviews with experts.
3. After selecting the material/application couple, an individual roadmap has been done for each material/application couple. These individual roadmaps have been updated several times by collecting feedback from experts. Thus, benefiting from validations from different sources, MONA has been able to build up in a precise way the different roadmaps. The template is a specific tool for collecting data. There are 2 kinds: applications-materials templates and generic equipment templates. As an example, the applications-materials template content was:
   - Description of the application
     - Overview
     - Type of nanomaterials
     - Market trends & sales figures
   - Devices & functions
     - For each device: description of the devices, performance (actual & foreseen), requested specification
   - Nanomaterial solution
     - For each device: what is the added value of nanophotonics, the key challenges
   - Process & equipment
     - For each device, what are the process characteristics and challenges
   - Timeline for application development
     - Basic R&D, Applied R&D, First Applications, Mass Production
   - Conclusions
     - Impact of nanophotonic-based device for the application
     - Description of the European context and key recommendations (to strengthen the European position).
4. An analysis of segment roadmaps, from the materials, equipment and applications viewpoint has then been made. In each analysis, the impact, the maturity level, the challenges, the European position and/or the potential for mass production have been discussed. Deliverables D2.1, D3.1 and D4.2 explain this analysis
5. Finally a consolidation has been made to get the final synthesis: the final synthesis is to a large extent based on the material, equipment and application analysis. It highlights the major conclusions and recommendations of the MONA project.

At this point, it is important to define the notion of technical impact, as this concept will be used many times in the synthesis.

Definition of technical impact:
MONA has defined technical impact as the contribution of the nanophotonics solution in the replacement of existing technologies and/or the creation of a totally new technological approach. It includes the possibility to improve overall performance or to bring a cost reduction by improving devices manufacturability. The technical impact has been used both for quantifying the nanomaterials and equipment contribution to the different nanophotonics applications.

- Considering materials, the technical impact level is the contribution of nanomaterials to the application. It can be of different types and the impact will be strong if there is a good fit with application issues and needs (which also means there is a strong market driver). It could be a better device performance, lower cost, power savings… For example, LCD flat panel technology is today replacing CRT technology and LCD backlighting power consumption is two times larger than CRT power consumption. Hence there is strong concern for energy consumption rise. So, in this case, carbon nanotubes field emission (CNT FE) backlighting could bring power consumption into line with that of the CRT.

- For equipment and processes, the technical impact is an average of 3 criteria which have been used to rank the types of equipment and processes:
    - their maturity
    - their potential to enter into mass production of nanophotonic devices
    - the broadness of application fields.

Finally, we have made a synthesis highlighting the major conclusions and recommendations of the MONA project.

4. Applications and devices

4.1. Applications

We have investigated nine application fields in which nanophotonics will have a major impact:

1. Sensors
2. Data & telecom
3. Data storage
4. Flat panel displays
5. Imaging
6. Instrumentation
7. LEDs and lighting
8. Optical interconnect
9. Photovoltaics

We have used the forecast market size in 2009 and their average growth in order to estimate market characteristics. These markets have been quantified at the system level (see **Table 1**).
Figure 3 shows that each market has its own dynamic properties.

Applications	Devices	2009 sales (US$ millions)	Market growth (2006-2009 CAGR)	Sources
Optical interconnect	PICs	735	25%	*BCC*
Data telecom	Lasers diode Fibers Optical switches Optical amplifiers Optical add/drop filters	2 500	13%	*BCC/Strategies Unlimited*
Lighting	LEDs	6 800	21%	*BCC*
Data storage	Lasers diodes Holographic memory	6 500	28%	*BCC/Strategies Unlimited*
Imaging	IR	2 655	14%	*Maxtech*
	VIS	9 821	22%	*WSTS/Yole Développement*
Sensors	Bio marker	4 250	46%	*Frost & Sullivan*
FPDs[1]	LCD OLEDs Plasma FEDs	90 000	14%	*BCC/DisplaySearch*
Photovoltaic[2]	PV panel	50 000	19%	*Yole Développement*
Instrumentation	SNOM probes	3	10%	*Yole Développement*

Table 1: applications and devices for nanophotonics

[1] For FPDs, backlighting is 27% of the cost breakdown for a 32" LCD TV panel (source DisplaySearch 2006)
[2] For photovoltaics, the nanomaterials part will represent a few % of the total cost of a panel

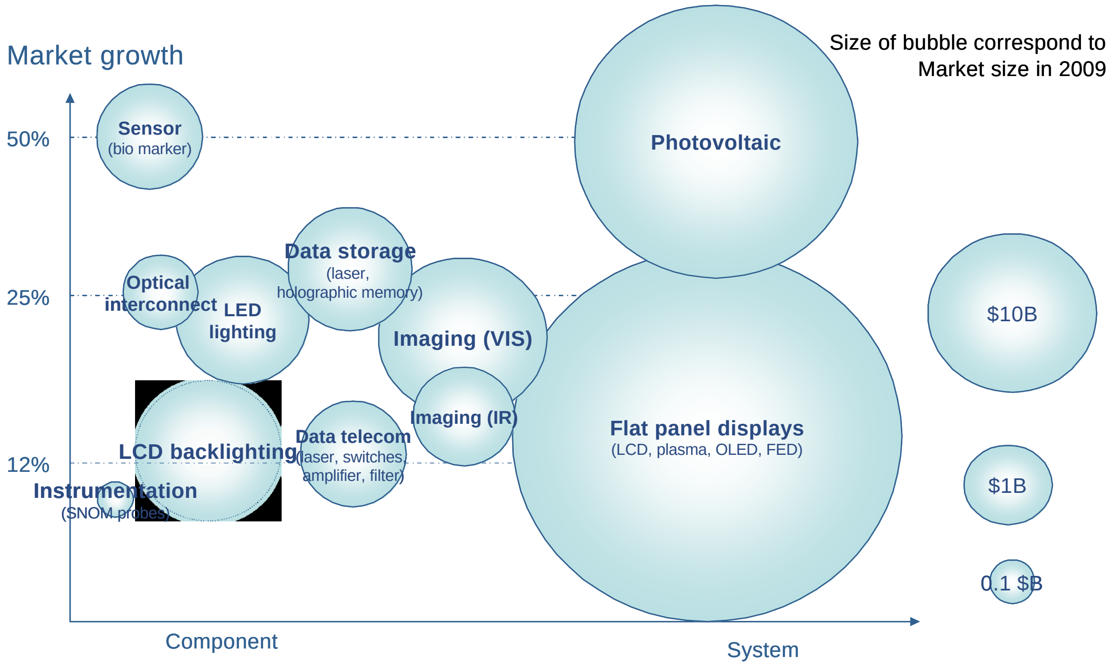


Figure 3: market growth and size for applications targeted by nanophotonics

The flat panel display market is definitively a large size market but with a rather low (about 12%) yearly growth rate. Although LCD, Plasma, OLED and FED do not have the same relative market size, here we show the total FPD market size in 2009. One should however be careful when comparing the market size for different applications. As shown on the X-axis, the market value for photovoltaics is at the system level while the market value for LEDs is at the component (die) level. For FPDs for example, one must consider that the device concerned by nanophotonics (backlighting) is only 27% of the total cost of a FPD. Photovoltaics represents a strong market opportunity, as it is second in value with a high growth rate (50%). Except for sensor market, it is the only one with such large market growth. Optical interconnects, LEDs and lighting, data storage and imaging are the sectors with good market growth (about 25%). The imaging market gathers IR and visible imagers market which have different relative sizes (the visible market is larger than the IR one). Datacom/ telecom is still today a small market with a low growth, and instrumentation is both small in value and market growth.

4.2. Devices

MONA has identified more than 50 different devices for which nanophotonics is expected to have a significant impact. . We list them below in Table 2.

Applications	Devices
Datacoms/Telecoms	Laser sources Fibre for transmission. Multiplexers, frequency converters, filters, delay lines, switches, modulators, transceiver Waveguides Amplifier Optical buffer Saturable absorber High index contrast devices Detectors
Optical Interconnects	Laser sources modulator, transistor High index contrast waveguide Metallic waveguides Optical gate Couplers (inverse taper or grating) Link (chip to chip, with hybrid, all silicon) Detectors (Ge or III-V based)
Displays	Green laser FED LCD backlighting (CNT or LED) SED AR organic coating OLED Nanophosphors Liquid crystal on Si projection display
Lighting	LED : visible (white, blue, green), UV OLED CNT FE
Data storage	Optical storage (SIL, SuperRens) Ultra high density data storage Quantum dot laser Quantum dot memory
Imaging	IR, visible, UV imaging device Passives devices (colour filters, microlens…)
Photovoltaics	DSSC Organic solar cells QD based Si solar cell II VI solar cells
Sensors	Fluorescent marker Bio sensors Strain or pressure, gas, liquid concentration sensors Optical sensor Spectrum analyzer
Instrumentation equipment	SNOM (probes, SiC superlens) SP lithography

Table 2: a wealth of potential in nanophotonic devices

4.3. Nanophotonics benefits for each application

4.3.1. Flat Panel Displays

For display applications, the LCD is becoming the FPD standard thanks to its good performance / cost ratio. Nanophotonic devices that might be integrated into this display technology (nanophosphors, backlighting, and IC integration) would be assured broad deployment with sales in millions of units. However, the display market is driven strongly today by cost reduction, and it is not expected that nanophotonics could contribute significantly to this trend. Hence we consider that the nanophotonic impact gained through a continuous improvement on the LCD technology will not generate significant additional sales. Nanophotonics could have a more important impact on FPD competing technologies: FED, OLED, QLED, and SED. Those technologies are all "nanophotonic" based. Their main advantages are generally the lower power consumption and for some, mechanical flexibility. FED and SED will compete with plasma on high-value large-size displays (40") while OLED and QLED are targeting smaller rigid displays (mobiles ...) and flexible new applications.

4.3.2. Photovoltaics

Two current trends in the development of photovoltaic cells have emerged: low-cost (low efficiency) approaches and high-efficiency (high-cost) techniques. While today most of the commercially available cells are made of bulk silicon, other thin film materials (amorphous-Si, Cu-In-Se and others) have been introduced to improve cell performance. Triple-junction solar cells represent state-of-the-art in photovoltaics today and are used mainly for space applications. Lattice-matched layers are grown on top of each other and are designed to absorb different parts of the solar spectrum. Quantum well structures can be grown to engineer the absorption bandgap of each layer. Quantum dots offer more flexibility to bandgap, current and strain management to achieve higher conversion efficiencies. III-V quantum dots can also be used to generate intermediate-band solar cell material.

4.3.3. Imaging

For imaging, the main challenge is to find the best compromise between Moore's law and the optical performance of the smallest possible detectors (pixel size < 1.5 μm). Denser chip integration leads to lower chip size, lower chip cost and thus larger use. Infrared sensors in the range of ~3- ~25 μm are of particular importance for a wide area of applications, ranging from night vision, surveillance, search and rescue, to medical diagnosis. At present infrared detectors are often based on mercury-cadmium-telluride (MCT) systems and quantum well infrared photodetectors (QWIP). However, due to sensitive dependence of bandgap on the material composition, reproducibility of manufacturing of MCT image sensors remains a challenge. In contrast, growth techniques for III-V systems include accurate control of composition and homogeneity, but the performance is lower. The main nanophotonic material used is InAs quantum dots embedded in quantum wells ("dot-in-a-well"). Due to the 3-dimensional confinement, quantum-dot-based detectors may offer substantial advantages, including higher operating temperatures and surface-normal direct absorption. Thus, quantum dot infrared photodetectors (QDIP) and quantum-dot-in-well detectors (DWELL) are studied extensively.

4.3.4. Lighting

There are continuous developments to develop new solid-sate lighting technologies such as LEDs or OLEDs. Nanophotonics could bring light sources which will be more energy-efficient, longer-lasting, and cost-competitive. The performance of OLEDs can be enhanced by using nanotechnology techniques, such as introducing inorganic quantum dots emitters or nanocomposite electrode coating materials for better carrier transport. Regarding LEDs, the progress in the development of LEDs is driven by various factors, such as internal quantum efficiency, outcoupling of the emitted light, chip shape, packaging. Future LEDs may even require new approaches to reduce dislocation densities in the epitaxial structures in order to minimize non-radiative recombination (especially for UV-LEDs). Nanophotonic concepts are considered in many parts of the LED structures, such as templates, buffer layers, active semiconductor structures, chip surfaces and luminescence converting phosphors.

4.3.5. Data storage

Nanophotonics will increase the storage capacity of memory disks. The techniques considered under "high-density optical data storage" are Near-field optical storage and SuperReNS (Super Resolution Near-field Structure) for the 4th generation data storage. Near-field optics allows a further increase of the numerical aperture of the focusing objective lens by using the evanescent waves coming out of a Solid Immersion Lens (SIL) on the basis of which the light is focused. The use of evanescent waves is possible if the distance between the solid immersion lens and the disc is a fraction of the wavelength (about 30-40 nm). SuperReNS is a clever way to introduce the near-field optics in the disc layer stack itself by using nonlinear properties of a specific thin film, and thus going beyond the diffraction limit. By doing so the disc remains removable and the distance between the disc and the objective lens is comparable to the resolution of lithography in Blu-Ray discs. The capacities of SIL and SuperReNS are several hundreds of GB per disk. The two technologies are now competing.

4.3.6. Optical interconnects

The cost of the devices is still too high for high-volume markets such as optical backplanes and data-links. Silicon photonics is the way to tackle the problem, by extending a massive, low-cost electronics manufacturing platform into the photonics domain. In this application area, integration with standard CMOS processes is one of the key issues. The photonic layer can be integrated following 3 different ways: front end process (the photonic devices are at the same level as the transistors), above IC (the photonic devices are fabricated in back end in-between the metallic interconnection layers) or bonding of photonic IC (the photonic devices are fabricated separately and bonded to the IC).

4.3.7. Data & Telecom

Voice and data traffic keep increasing at a quite significant rate, in particular owing to the widespread use of internet and mobile telephony, and to the huge amount of exchanged data. In order to face this steady trend, larger data rates are implemented in core, metropolitan and storage networks and optical fibre technologies are now introduced in the access network (e.g. Fibre to the Home). Optical transmission with wavelength multiplexing has been deployed in the core and metropolitan networks for quite a while for point to point connection, and wavelength agility /transparency is now identified as a main challenge for future network deployments. Optical devices and circuits used in optical transmission are basically light sources, modulators, transmission fibre, optical amplifiers, wavelength multiplexers and demultiplexers, photodetectors and combinations thereof. All these functions are expected to benefit from nanotechnologies, for instance:

- lasers with low threshold current and low temperature dependence, owing to Quantum Dots containing active regions,
- nanocavity (Photonic Crystal-based) laser arrays with low power consumption,
- add-drop filters and switches for wavelength routing,
- optical fibre amplifiers with nanoparticles or Photonic Crystal transmission fibre,
- quantum information devices.

4.3.8. Sensors

Using optics for sensors allows immunity to electromagnetic interference and can be used in harsh environments. They also provide good sensitivity, linearity and stability. Currently, most optical sensors are based on fibre optics or free space optics, but some new research deals with integrating the sensor functions on photonic ICs. SOI-based nanophotonic sensors will offer big advantages for bio-sensing applications. In addition to implementing low-cost mass-fabrication, the technology is suitable for sensing. Due to the extremely narrow resonance peaks of SOI micro-rings, they are suitable for the measurement of extremely small changes of the surface refractive index, caused by the binding of bio-molecules to the cavity's surface. Between other techniques, it should be noted that different types of sensing can be realized using plasmonics. In general an enhanced sensitivity of plasmonics sensors is based on an improved temperature control. Refractive index sensing is not yet done with nanostructures; e.g. there is no point localization possible so far. Thus, there is a need to step over from 2D detection to localized 3D point detection based on nanostructures. Refractive-index sensing sensitivity itself may be enhanced by one order of magnitude within one year. Further application fields of plasmonic sensing may be seen in health applications. Advantages are: single molecule sensitivity and a better biocompatibility of metallic nanoparticles compared to the more toxic behaviour of quantum dot markers and some organic dyes. One of the key challenges of plasmonic nanostructures seen for health applications is a specific (bio-) chemical functionalisation.

4.3.9. Instrumentation

For instrumentation, several techniques are used for characterizing nanophotonics components or materials. Scanning near-field optical microscopy (SNOM) is a versatile instrument for nanophotonics, since it can be used for example to characterize optical nanomaterials (quantum dots, quantum wires ...) and plasmonic components. Tapered optical fibres with a small optical aperture are commonly used in SNOM systems to collect near-field information, and are commercially available. However, fibre probes are still difficult to fabricate with high reproducibility, and have low throughputs. Silicon nanostructured probes for scanning near-field optical microscopy (SNOM) may offer significant advantages in terms of manufacturability. Moreover, the same probe structure can be used for both SNOM and atomic force microscopy (AFM) measurements. Meta-materials (negative index or refraction and negative magnetic susceptibility) may have an impact in this application area. Although left-handedness could be achieved for the RF-range and down to long IR, it has not yet been possible to reach negative refraction based on meta-materials for the optical and UV-range. Several devices used in this application area could be considered. The first device considered is the "superlens" based on silver thin-film (not a real metamaterial). It is considered that the first prototypes could achieve optical resolution of 1/3 to 1/5 of a wavelength. The second one is the SiC "superlens" for Near-Field Microscopy (not a real metamaterial). A first prototype achieved resolution of 1/20 of a wavelength. Plasmonic resonances are used at infrared or visible frequencies in metallic (Au, Ag, Al, Cu) nanostructures or colloid nanoparticles (1-50 nm). Research into potential plasmonics applications is still at an early stage. Surface plasmons are being explored for their application potential in subwavelength optics, data storage, light generation, microscopy and biophotonics.

5. Nanomaterials: challenges and impact

5.1. *Key nanomaterials for nanophotonics*

An objective of MONA is to highlight the key nanomaterials for nanophotonics. In the Table 3 we list the application areas with devices that are estimated to reach mass production maturity by 2011 and 2015, respectively. The particularly promising devices are also listed. The technical impact of the material for the application area is indicated: we write the application name in red (black) if the impact is estimated as strong (medium). This is also shown with (S) for strong and (M) for medium. In this way one can observe which nanomaterials have devices that are close to maturity and may provide a strong technical impact. These materials could then be strong drivers for growth. More details on nanomaterials are given in the appendices.

Material system	2011	2015
Quantum dots and wires in silicon	None	**Optical interconnects (S)** - Si QD gate **Photovoltaics (M)** - Si QD multi-junction cell **Sensors (M)** - Si QD UV sensor
Quantum dots and wires in III-V	**Imaging (S)** - QD IR detector **Photovoltaics (S)** - QD cell - QD intermediate band cell **Datacom/telecom (M)** - Improved semiconductor lasers	**Optical interconnects (S)** - III-V QD laser bonded on Si **Sensors (M)** - Quantum wire polarization sensor **Data storage (M-S)** - III-N QD laser for data storage - QD memory **Datacom/telecom (M)** - Narrow spectral width lasers - SOA **Lighting (M)** - III-N based LED with nanoconcepts
Quantum dots and wires in II-VI	**Lighting (M)** - GaN LED with QD nanophosphor **Sensors (S)** - Functionalized fluorescent II-VI nanoparticles **Displays (M)** - Nanophosphors based on II-VI QD	**Lighting (S)** - ZnO LED **Photovoltaics (M-S)** - Organic solar cell with QD materials
Plasmonic nanostructures	**Sensors (S)** - (Bio)molecule sensor - Refractive index sensor **Lighting (M)** - GaN based LEDs with surface plasmon enhancement	**Imaging (S)** - Nanostructured lenses **Lighting (M)** - OLEDs with surface plasmon enhancement **Data storage (M)** - Near-field storage with SIL - SuperReNS storage

Material system	2011	2015
High contrast Si nanostructures	**Datacom/telecom (S)** - Passive photonic integrated circuits - Slow switching/tuning functions - Electro-optic devices	**Datacom/telecom (S)** - Micro/nano-cavity laser sources - All-optical devices **Optical interconnects (chip-to-chip) (M)** - Coupling structures/low cost packaging - Laser sources (silicon or III-V based) **Optical interconnects (intra-chip) (M)** - Passive devices **Sensors (M)** - Biomolecule sensor - Strain/pressure sensor - Gas/liquid concentration sensor - Integrated spectrum analyzer
High contrast III-V nanostructures	**Lighting (S)** - White LED (GaN) with photonic crystal structure - GaN & AlGaInP LEDs with improved output beam **Datacom/telecom (M)** - Passive photonic integrated circuits - 1D photonic crystal reflector	**Lighting (S)** - Other LEDs (AlGaInP) with photonic crystal structure **Optical interconnects (chip-to-chip) (M)** - Laser sources **Datacom/telecom (M)** - 2D photonic crystal devices
Microstructured fibres	None	**Datacom/telecom (M)** - Microstructured fibres for FTTH or domestic applications - Microstructured fibres for long-haul transmission - Microstructured fibre for other applications (lasers, amplifiers…) **Sensors (M)** - Microstructured fibre sensors
Organic nanostructures	**Displays (M)** - OLED **Photovoltaics (M)** - Small molecule based bulk heterojunction solar cells - Small molecule based planar heterojunction solar cells - Small molecule/C60 based solar cell	**Photovoltaics (M)** - Fullerene (C60) bulk heterojunction solar cells - Multi-junction cells based on small molecules - QD based organic solar cells using small molecules
Carbon nanotubes	**Displays (S)** - Field Emission Display - small area, low complexity	**Displays (S)** - Field Emission Display – large area - Field emission backlighting for LCD - Surface-conduction Electron-Emitter Displays (SEDs) **Photovoltaics (M)** - Organic solar cell with single wall CNTs

Material system	2011	2015
Integration electronics/photonics	**Optical interconnects (S)** - Chip-to-chip link with flip-chipped source **Datacom/telecom (S)** - Transceiver (no WDM) with flip-chip source - Transceiver (with WDM) with flip-chip source **Imaging (M)** -Nanoparticles colour filter	**Optical interconnects (S)** - Link with wafer-level source **Datacom/telecom (S)** - Transceiver with integrated source **Imaging (M)** - Nanostructured colour filter
Nanoparticles in glass or polymer	**Datacom/telecom (S)** - Nanoparticle doped active fibres – 1st generation - Nanoparticle doped active fibres – 2nd generation **Lighting (M)** - White LED via nanoparticle phosphor	**Datacom/telecom (S)** - Nanoparticle doped active fibres – 3rd generation
Left-handed meta-materials	None	None

Table 3: emergence of nanophotonic-based devices in 2011 and 2015

5.2. *Impact of nanomaterials per nanophotonic applications*

The Figure 4 and Figure 5 below show what will be the technical impact of the nanomaterials for the different applications ranked in $ sales.

For example, it shows that CNT will have a strong impact for FPD application. Although only a few % of FPDs would use CNT for backlighting, the very large size of the FPD market would automatically bring large sales volume for CNTs (the total CNT market has been estimated to be $220M in 2010 for all applications).

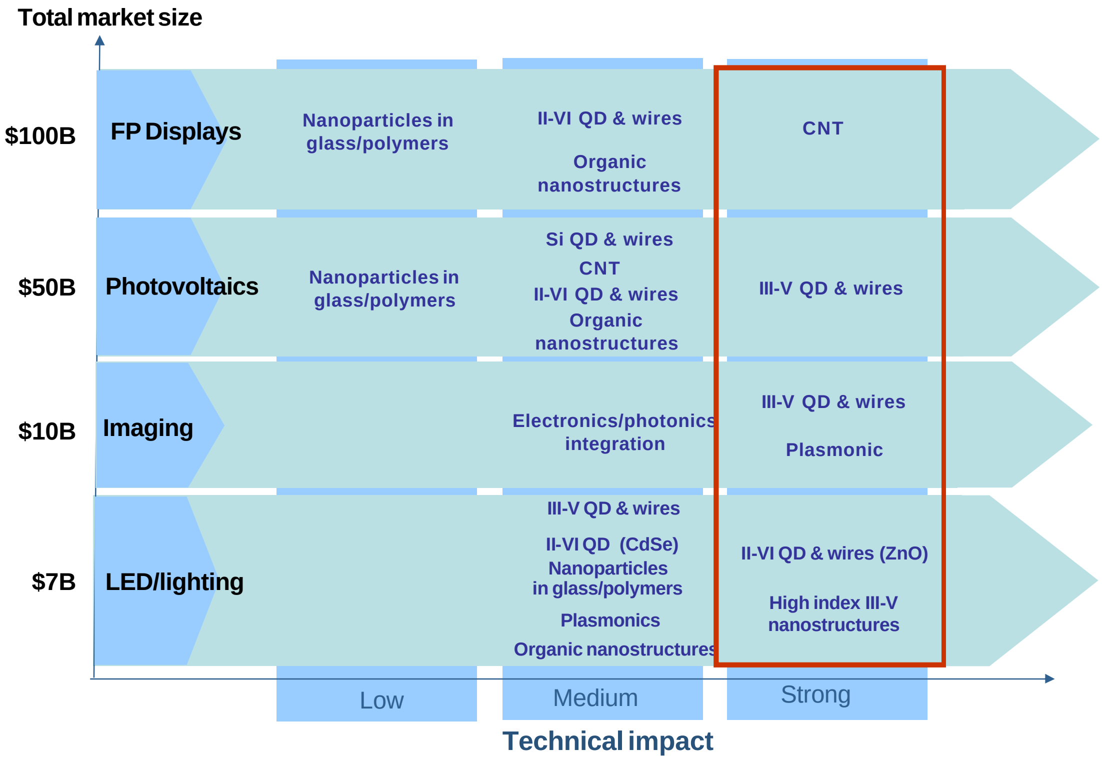


Figure 4: Technical impact of nanomaterials for nanophotonic applications

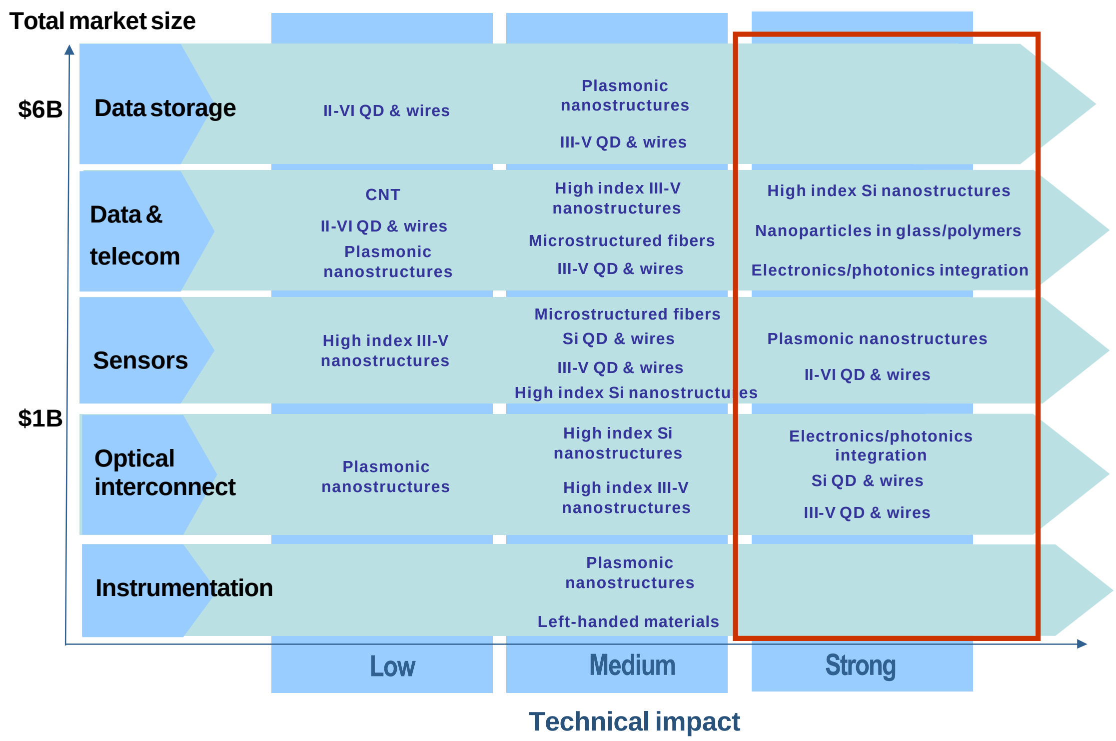


Figure 5: Technical impact of nanomaterials for nanophotonic applications

5.3. Nanomaterials challenges

We have identified challenges for nanomaterials. The table below shows what different experts perceive as identified: to increase fundamental R&D, production scaling and cost reduction, to have foundry access and to set up industrial standards.

	Fundamental R&D	Production scaling and cost reduction	Foundry access	Industry standards
Semiconductor quantum dots & wires in :				
- silicon in colloidal nanostructures	X			
- III-V including colloidal nanostructures	X			
- II-VI including colloidal nanostructures	X	X		
Plasmonics/metallic nanostructures including nanostructures (metal)	X			X (optical interconnects)
Photonic crystals/High index contrast nanostructures in :				
- silicon		X	X	X
- III-V		X	X	X
- other materials (microstructured fibres)		X		
Organic nanostructures	X	X		
Carbon nanotubes (CNT)		X		
Integration of nanophotonic materials/structures with electronic ICs/Silicon Photonics	X	X	X	X
Nanoparticles in glass or polymer		X		
Left-handed meta-materials	X			

Table 4: challenges for nanophotonics

Generally, the most important challenges for the development of nanomaterials are technical and the development efforts required are different depending on the maturity of the nanomaterials:

- Fundamental research in order to have a complete understanding and control of the nanostructures. This is the case for quantum dots, plasmonic, organic, integration and left handed nanomaterials.
- Production scaling and cost reduction for nanomaterials that are more technologically advanced: this is the case for QD II VI, high index contrast structures, organic nanostructure, carbon nanotubes, optics and electronics integration and nanoparticles.

In few cases, other topics are considered as roadblocks on the development path of the nanomaterials:

- Foundry access: highly desirable for high index contrast structures to industrialize the nanomaterials.
- Standards: high index contrast and plasmonic structures need the definition of standards to switch to an industrial phase.

Toxicity is also a general issue for nanomaterials. For III-V and II-VI nanocrystals for example, toxicity arises from their small size and from the constituting materials (Cd, Te…).

6. Nanophotonics equipment: challenges and impact

Equipment and processes are closely linked with the performance of nanophotonic devices, and much of the progress in nanophotonics is enabled by new developments in the equipment sector. Furthermore, novel nanophotonic concepts will stimulate new equipment and process developments. For nanophotonics, we have split the equipment in two kinds: bottom-up and top-down. In general, nanophotonic equipment is the same as used in micro-nanoelectronics industry. This is a very strong driver and process converge could play a role for bringing nanophotonics to a mature industrial level.

Bottom-up technologies are those that deposit any material actively in order to form nanostructures. In the simplest case such technologies are used just to form a thin film which requires later top-down nanostructuring techniques. However, the more sophisticated ones include ways to form the nanostructure directly. The bottom-up technologies were extracted from all sub-roadmaps focusing on specific nanomaterials for specific applications. Furthermore, the bottom-up technologies were also examined independently from specific applications. Many of the technologies exist already as non-nanotechnologies. However, it was found that specific requirements have to be met in order to produce nanostructures.

The technologies analyzed are the following:

- MOCVD (Metalorganic Chemical Vapour Deposition)
- MBE (Molecular Beam Epitaxy)
- Other CVD processes:
  - Carbon nanotube CVD,
  - SiO_x CVD
  - Si nanowire CVD
  - HVPE (Hydrid Vapour Phase Epitaxy)
- Miscellaneous processes:
  - Direct nanoparticle deposition
  - Colloidal chemical synthesis
  - Laser ablation
  - Nanophosphor fabrication
  - Sol-gel synthesis
  - Pyrolysis
  - TiO_2 nanoparticle formation
  - Electrodeposition
  - Vapour phase deposition of ZnO
  - Spin coating
  - Ink jet printing
  - OVPD (Organic Vapour Phase Deposition)
  - PECVD (Plasma Enhanced CVD)
  - Pulsed laser ablation

Top-down technologies are those that define a nanostructure without actively depositing a material. This means that usually a thin film that has been deposited before is laterally structured. The approach chosen to analyze the top-down technologies is equivalent to the bottom-up segment. The technologies were extracted from all sub-roadmaps focusing on specific nanomaterials for specific applications. Furthermore, they were also examined independent from particular applications. Like bottom-up, many of the technologies already exist as non-nanotechnologies. However, it was found that specific requirements have to be met in order to produce nanostructures.

The technologies analyzed are the following:

- Lithography:
  - Optical lithography
  - Deep UV
  - EUV
  - X-ray lithography
  - Electron beam lithography
  - Nanoimprint lithography
  - Focused ion beam lithography
- Etching

From the graph below (Figure 6), it is shown that the technologies that have the highest potential impact on nanophotonics and at the same time have potential for mass production are the following:

- 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 the following:

- MOCVD, MBE and colloidal chemistry as bottom-up technologies and UV litho, e-beam and nanoimprint as top-down technologies

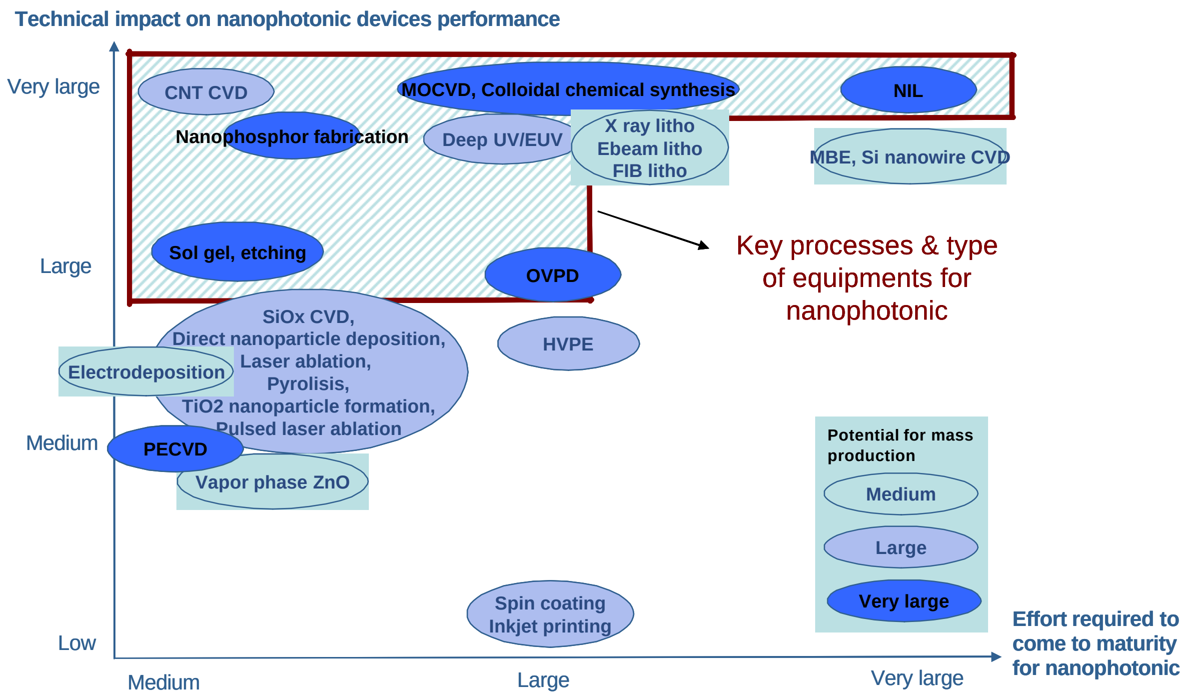


Figure 6: processes and types of equipment with high technical impact for nanophotonics

7. Synthesis of each application

In order to have a general overview of the different applications linked with the nanomaterials and types of equipment for nanophotonics, the following figures (Table 5 to Table 13) show the roadmap synthesis for the application for the nanophotonic materials and types of equipment. Only nanomaterials and devices which will have the largest technical impact are shown (red box). When several generations of devices with increasing complexity are foreseen, only the first generation is mentioned. The related equipment is mentioned only if a specific development is needed.

- Basic R&D
- Applied R&D
- First applications
- Mass production

The object of this document is to provide a synthesis of the outputs of the MONA project and to provide recommendations to support nanophotonics in Europe. This means we use the information from the segment roadmaps, established in the MONA project.

Application	Flat panel displays (FPDs)		
Market forecast	The total FPD market is forecast to be $90B in 2009 (source BCC/DisplaySearch)		
Impact value	Low	Medium	Strong
Nanophotonic materials/devices *Key required type of equipment process*	1. Nanoparticles in glass/polymers for AR coatings *Sol-gel*	1.II-VI QD OLEDs for active FPD *Pyrolysis* 2.OLEDs *Printing* 3.II-VI QD nanophosphors	1.CNT for FED, LCD backlighting & SED *CVD*
Timelines for key nanomaterials/devices	CNT FED (low complexity) : 2007 2008 2009 2010 2011 2012 2013 2014 2015 CNT for LCD backlighting : 2007 2008 2009 2010 2011 2012 2013 2014 2015 CNT for SED : 2007 2008 2009 2010 2011 2012 2013 2014 2015		

Table 5: synthesis for the application: FPDs

Application	**Photovoltaics**		
Market forecast	The market is forecast to be $50B in 2009 (source Yole Développement))		
Impact value	**Low**	**Medium**	**Strong**
Nanophotonic materials/devices *Key required type of equipment process*	1.Nanoparticles in glass/polymers for dye-sensitized solar cells	1.II-VI QD for hybrid solar cells and wavelength conversion *Spin coating* 2.Si-QD solar cell *CVD* 3.Small-molecule and polymer organic solar cells *OVPD* 4.CNT solar cell	1.III-V QD solar cells *MOCVD* *MBE*
Timelines for key nanomaterials/devices	*III-V QD solar cells:* 2007 2008 2009 2010 2011 2012 2013 2014 2015		

Table 6: synthesis for the application: photovoltaics

Application	**Imaging**		
Market forecast	The market is forecast to be $12.4B in 2009 (source Maxtech/WSTS/Yole Développement)		
Impact value	**Low**	**Medium**	**Strong**
Nanophotonic materials/devices *Key required type of equipment process*	None	1.Nanoparticles colour filters 2.Nanostructured colour filters (electronic/photonic integration for improved detector performance)	1.III-V QD infrared detector 2.Plasmonic nanostructured lenses
Timelines for key nanomaterials/devices	*III-V QD infrared detector :* 2007 2008 2009 2010 2011 2012 2013 2014 2015 *Plasmonic nanostructured lenses :* 2007 2008 2009 2010 2011 2012 2013 2014 2015		

Table 7: synthesis for the application: imaging (NB: although both QDIP and plasmonics will have strong impact, one should consider that the IR market is smaller than the visible one)

<table>
<tr><td>Application</td><td colspan="3">Lighting</td></tr>
<tr><td>Market forecast</td><td colspan="3">The market is forecast to be $6.8B in 2009
(source BCC)</td></tr>
<tr><td>Impact value</td><td>Low</td><td>Medium</td><td>Strong</td></tr>
<tr><td>Nanophotonic materials/devices
Key required type of equipment process</td><td>None</td><td>1.II-VI QD (CdSe) nanophosphors for LEDs
2.III-V QD for LEDs
MOCVD
MBE
HVPE
Ebeam lithography
3.Plasmonic nanostructures for SP enhancement for GaN LED/OLEDs
UV lithography
4.Nanoparticles in glass/polymer
5.Organic nanostructures for QD OLEDS
OVPD</td><td>1.ZnO nanowires LEDs
MOCVD
ZnO vapour phase & electrodeposition
2.Photonic crystals in III-V for LEDs
e-beam litho
NIL
Dry etching</td></tr>
<tr><td>Timelines for key nanomaterials/devices</td><td colspan="3"><u>ZnO nanowires LEDs</u> :
2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015
<u>Photonic crystals in III-V for LEDs</u> :
2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015</td></tr>
</table>

Table 8: synthesis for the application: lighting

Application	Data storage		
Market forecast	The market is forecast to be $6.5B in 2009 (source BCC/Strategies Unlimited)		
Impact value	Low	Medium	Strong
Nanophotonic materials/devices *Key required type of equipment process*	1. II-VI QD & wires	1.III-V QD laser *MOCVD* *MBE* 2.Plasmonics for near-field storage systems (SuperRens or SIL)	None

Table 9: synthesis for the application: data storage

Application	Datacoms & Telecoms		
Market forecast	The market is forecast to be $4.4B in 2009 (source BCC/Strategies Unlimited)		
Impact value	Low	Medium	Strong
Nanophotonic materials/devices *Key required type of equipment process*	1.CNT *Laser ablation* 2.II-VI QD & wires 3.Plasmonics	1.III-V QD & wires for semiconductor lasers *MOCVD* *MBE* *UV lithography* 2.Microstructured fibres for FTTH application 3.PhC & high index contrast nanostructures in Si/III-V	1.Electronic/photonic integration for transceivers *UV lithography* 2.PhC & high index contrast nanostructures in Si *UV lithography* *e-beam lithography* *NIL* *Dry etching* 3.Nanoparticles in glass or polymer

Timelines for key nanomaterials/devices

Electronics / Photonic integration for transceivers (no WDM) :

2007	2008	2009	2010	2011	2012	2013	2014	2015

Electronics / Photonic integration for transceivers (with WDM) :

2007	2008	2009	2010	2011	2012	2013	2014	2015

Electronics / Photonic integration for transceivers with integrated source:

2007	2008	2009	2010	2011	2012	2013	2014	2015

Passive photonic integrated circuits :

2007	2008	2009	2010	2011	2012	2013	2014	2015

Micro/nano-cavity laser sources :

2007	2008	2009	2010	2011	2012	2013	2014	2015

Slow switching/tuning functions :

2007	2008	2009	2010	2011	2012	2013	2014	2015

Electro-optical devices :

2007	2008	2009	2010	2011	2012	2013	2014	2015

All-optical devices :

2007	2008	2009	2010	2011	2012	2013	2014	2015

Nanoparticles for active fibers (1st generation) :

2007	2008	2009	2010	2011	2012	2013	2014	2015

Nanoparticles for active fibers (2nd generation) :

2007	2008	2009	2010	2011	2012	2013	2014	2015

Nanoparticles for active fibers (3rd generation) :

2007	2008	2009	2010	2011	2012	2013	2014	2015

Table 10: synthesis for the application: data & telecoms

<table>
<tr><th>Application</th><th colspan="3">Sensors</th></tr>
<tr><td>Market forecast</td><td colspan="3">The market is forecast to be $4.2B in 2009
(source Frost & Sullivan)</td></tr>
<tr><td>Impact value</td><td>Low</td><td>Medium</td><td>Strong</td></tr>
<tr><td>Nanophotonic materials/devices
Key required type of equipment process</td><td>1.III-V PhC & high contrast nanostructures
E-beam lithography</td><td>1.Si QD for UV sensors
2.Si PhC & high contrast nanostructures for biomolecule, strain/pressure, gas/liquid concentration sensors and integrated spectrum analyzer
UV lithography
NIL
Dry etching
3.Microstructured fibre sensors
4.III-V QD & wires</td><td>1.QD and wires II-VI for functionalized fluorescent nanoparticles
Colloidal synthesis
2.Plasmonic nanostructures for biomolecule/refractive index sensors
DEUV/EUV lithography</td></tr>
<tr><td>Timelines for key nanomaterials/devices</td><td colspan="3"><u>QD functionalized fluorescent nanoparticle</u> :
2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015
<u>QD functionalized fluorescent nanoparticle for single molecule observation</u> :
2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015
<u>Plasmonics for specific biomolecules sensing</u> :
2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015
<u>Plasmonics for refractive index sensor</u> :
2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015</td></tr>
</table>

Table 11: synthesis for the application: sensors

Application	Optical interconnects		
Market forecast	The market is forecast to be $800M in 2009 (source BCC)		
Impact value	Low	Medium	Strong
Nanophotonic materials/devices *Key required type of equipment process*	1.Plasmonics – metallic nanostructures	1.PhC & high index contrast nanostructures in Si/III-V for chip-to-chip/intra-chip interconnects and board/backplane interconnects	1.Si QD & wires 2.III-V QD & wires for laser sources *MOCVD* *MBE* 3.Electronic/photonic integration (chip to chip, hybrid, all-Si)

Timelines for key nanomaterials/devices

Laser source based on III-V QD bonded on Si :

2007	2008	2009	2010	2011	2012	2013	2014	2015

Laser source based on III-V QD grown on Si :

2007	2008	2009	2010	2011	2012	2013	2014	2015

Si laser (Si nanocrystals based on Si QD or Er doped Si QD :

2007	2008	2009	2010	2011	2012	2013	2014	2015

Chip to chip link with flip-chipped source :

2007	2008	2009	2010	2011	2012	2013	2014	2015

Link with hybrid integrated source :

2007	2008	2009	2010	2011	2012	2013	2014	2015

All Si link :

2007	2008	2009	2010	2011	2012	2013	2014	2015

Table 12: synthesis for the application: optical interconnects

Application	**Instrumentation**		
Market forecast	The market is forecast to be $2M in 2009 (source Yole Développement)		
Impact value	**Low**	**Medium**	**Strong**
Nanophotonic materials/devices ***Key required type of equipment process***	None	1.Left handed materials *e-beam lithography* *FIB lithography* 2.Plasmonic nanostructures 3.Si QD and wires for SNOM	None

Table 13: synthesis for the application: instrumentation

8. Recommendations for European Science and Industry

8.1. *Most important nanophotonic devices*

Our analysis highlights the most important devices that European industry should focus on for the different applications of nanophotonics. In Table 14, we show the devices which have been identified as having a strong impact for the considered application (however, for data storage and instrumentation, no nanophotonic device will have a strong impact). For displays, the nanophotonic devices which 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 which 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)	Devices
Displays ($ 90 B)	FED, LCD backlighting with CNT
	OLEDs
Photovoltaics ($50B)	Quantum dots III-V solar cells
Imaging ($10 B)	CMOS imager with plasmonics
	IR imager with III-V quantum dots
Lighting ($6.8B)	LEDs with QD II-VI (ZnO) and high index III-V nanostructures
	II-VI QD OLEDs
Datacom/Telecom ($ 4.5B)	High index Si photonic devices (laser, waveguide, switches, detectors)
	Active fibre (amplifier) with nanoparticles
	Electronic/ photonic integrated devices (flip-chip source, integrated source, all Si)
Sensors ($4.2 B)	Fluorescent markers with QD (II-VI)
	Plasmonic biosensors
Optical Interconnects ($ 0.8 B)	Laser sources and gates with Si nanocrystals
	Electronic/ photonic integrated devices (flip-chip source, integrated source, all Si)
	Laser with quantum dots III-V

Table 14: Key nanophotonic devices for European research, development and commercial exploitation

8.2. The technical recommendations

For the different nanophotonic applications and devices, MONA project has highlighted the technical recommendations to be taken.

8.2.1. Displays

The possible role for Europe: Although there is only one European player in Europe (Thales LCD), Europe is well positioned to provide support services such as R&D and process equipment (CVD for CNT for example), as strong European competencies exist in the field of CNT, 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 are not yet industrialized.

Recommendations:

- For CNT, a process is needed today to manufacture low cost, robust, uniform CNTs with a high reproducibility and high purity. This process should also be able to cover large size displays (> 40").
- For OLEDs, the low-lifetime issue must be solved. Encapsulation with organic/inorganic multilayers to solve the issue of lifetime is worth investigating. Moreover, new concepts such as photonic crystals or plasmonics are also a promising way to increase the light extraction.

8.2.2. Photovoltaics

The possible role for Europe: Photovoltaics is growing. Quantum-dot technology offers more flexibility in the management of bandgap, current and strain in order to achieve higher conversion efficiencies. III-V quantum dots can also be used to generate intermediate-band solar cell materials.

Recommendations:

- For QD III-V based solar cells the main challenges are a better control of uniformity in size, form and symmetries of quantum dots and wires.
- Two major research axes are to push the limits of conventional Stranski-Krastanow growth techniques, as well as to develop novel growth modes. In particular, the combination of top-down and bottom-up approaches for better control of quantum dots and wires may provide new material opportunities.

8.2.3. Imaging

The possible role for Europe: Due to the importance of visible and IR-sensing in various application areas, European research should be kept strong in this field. There are industrial players in Europe (STM, e2v) and Europe must stay competitive. Moreover, in the IR sensing, Europe has key players like Sofradir, who are interested in III-V QDs as an alternative to MCT and conventional QWIPs.

Recommendations:

- R&D is needed on III-V QDs for a better control of size, form and symmetries.
- CMOS visible sensors with plasmonic is also a research direction to be investigated. With the reduction of the pixel size, refractive lenses have limited performance. One solution to decrease the focal spot size is to use optical field confinement devices as plasmonic devices.

8.2.4. Lighting

The possible role for Europe: Lighting is a large market for nanophotonics, so securing a successful industrial development appears as an important objective: Intensified R&D is clearly required. Moreover, the presence of two major players (Osram, Philips) will contribute to Europe's competitive position.

Recommendations:

- Accurate control of size distribution and production up-scaling for II-VI QD (ZnO) is needed as well as better lifetime, temperature stability, higher conversion efficiency and better control of emission/absorption overlap. Improvement of the output coupling by a factor of 50% through the use of a photonic-scale surface patterning is one interesting approach.
- QD toxicity issues must also be considered.
- For efficient white LEDs with good colour rendering, one needs quantum efficiencies larger than 85% (for phosphors absorbing in the near-UV) at operating temperatures above 150°C (for phosphors in intimate contact with the LED). New materials are required, e.g. for the binder matrix, to achieve temperature, radiation and mechanical stability.
- For Olds used for lighting, the recommendations are the same as those for displays.

8.2.5. Data Storage

The possible role for Europe: While the drive and disc productions are now largely based in Asia, optical data storage is still providing huge revenues to the patent owners and format founders in Europe (Thomson, Philips). Europe has also major industries in the field of production or test equipment (Singulus, Unaxis, Steag, Audiodev) and in the field of materials (Ciba, Clariant, Umicore). This position is supported by top-level academic research activity in most of the related areas. Innovation and research are strategic components for the health of optical data storage industries in Europe.

Recommendations:

- Although no strong impact of nanophotonic for data storage has been identified, the following research axis will have a medium impact: R&D should be done on III-V QD for a better uniformity in size, form and symmetries. Plasmonics must be investigated as one possible way to overcome the diffraction limit and thus to increase the storage density. SNOM is another research way for high-density optical memories.

8.2.6. Datacom & Telecom

The possible role for Europe: There are still industrial players in Europe (Bookham, Ericsson, 3S Photonics and many start-ups) and Europe has strong R&D skills. R&D should continue to maintain and strengthen the position of Europe, specifically for further integration of optical and electronic chips.

Recommendations:

- Integration of CMOS and photonics raises materials, processing and packaging issues. The following issues must be addressed:
  - Heat dissipation issue.
  - Low cost packaging solutions.
  - Robust, low-loss, standardized coupling structures to interface between chip and fibre are needed.
  - High-throughput, low-cost bonding of III-V to Si wafers as a first approach, then new materials approach (Ge)
  - Good control of feature size and sidewall roughness, in a mass production context.

  - Polarization dependent losses must be controlled.
- Focus development on 2D photonic crystals in III-V for the datacom market.
- Active fibre manufacturing is challenging today. The main methods are ex-situ processes (the nanoparticles are synthesized first and introduced in glass afterwards). The issue is to control the nanoparticle properties throughout the process of introducing them into the fibre. The methods are very difficult to control (gas or aerosol flow, pressure, temperature etc.). Collection of the particles should be efficient, while agglomeration needs to be avoided.

8.2.7. Sensors

The possible role for Europe: Biology is the main application for nanophotonic-based sensors. Europe should maintain its R&D on microstructured fibres, QD II-VI and plasmonics for sensing applications (SPR instrumentation has been successfully commercialized by Biacore in Sweden for example).

Recommendations:

- The use of microstructured fibre for low-cost and sensitive sensors is a relatively unexplored area. Fibre sensors including photonic crystal fibres have been tested without too much industrial success so far. One way should be to fill the holes with gases or other materials having the specific index dispersion properties etc ...
- Regarding II-VI QDs, accurate control of size distribution and production up-scaling is needed as well as better lifetime, temperature stability, higher conversion efficiency and better control of emission/absorption overlap.
- Plasmonics is a powerful technique for molecular sensing. SPR-based sensing is a suitable and widespread method in biotech labs for the ultra-sensitive detection of biochemical binding interactions of molecules to target structures tagged to a functionalized metallic surface. There is a need for standardization and controlling the sensitivity of photon-plasmon coupling.

8.2.8. Optical Interconnects

The possible role for Europe: Europe has strong competencies in R&D. The 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.

Recommendations:

- CMOS integration is the way for cost reduction. The integration can be done at the front end level, with an above IC approach or through bonding of the photonic chip to the IC. Optical interconnects need totally new approaches with different types of micro-cavities and materials, such as quantum dots.

8.2.9. Instrumentation

The possible role for European science and technology: although it is the smallest market for nanophotonic technologies, Europe is at the forefront of this fundamental research topic, with industrial players.

Recommendations:

- Although no strong impact of nanophotonic for instrumentation has been identified, the following research direction will have a medium impact. A challenge to obtain practical devices is the unavoidable appearance of losses. This is also associated with the limited number of usable metals, lacking the desired properties for visible light meta-materials. Moreover, to construct meta-materials for infrared and optical frequencies, one will require nanoscale fabrication methods.

The table below (**Table 15**) shows what the position of Europe and the recommendations for these different devices are.

	KEY DEVICES	EUROPE POSITION		EXAMPLES OF EU PLAYERS (R&D and companies)	TECHNICAL RECOMMENDATIONS
		R&D	Industrial		
Displays ($ 90 B)	FED, LCD backlighting with CNT	+++	+	CEA Leti (FR), Philips (NL), CDT (GB), Thales LCD (FR) …	• Improved manufacturability for CNT (low cost, high reproducibility and purity, large size deposition). • For OLEDs, R&D must focus on low lifetime, encapsulation and light extraction improvement issues.
	OLEDs	++	+		
Photovoltaics ($50 B)	Quantum dots III-V solar cells	+++	+	Material suppliers: Bayer (PEDOT), Merck (bought Covion in 2005) for MDMO-PPPV. Equipment: Aixtron (DE) for the OVPD process. Strong R&D: ECN (NL), University of Eindhoven (NL), Fraunhofer ISE (DE), IMEC and IMOMEC (BE), CEA (FR), LIOS (DE), University of Groningen (NL), University of Linköping (SE) …	• Achieve better control of uniformity in size, form and symmetries of quantum dots and wires.
Imaging ($10 B)	CMOS imager with plasmonics	+++	++	STMicroelectronics (FR), e2v (FR), Sofradir (FR), Ulis (FR), TUBerlin (DE), Univ. of Sheffield (GB), Alcatel-Thales (FR), Acreo (SE) …	• Achieve better uniformity in size, form and symmetries of QD.
	IR imager with III-V QDs	+++	+++		
Lighting ($6.8B)	LEDs with QD II-VI, high index III-V PhC and plasmonics	+++	+++	Osram (DE), Philips (NL), Novaled (DE), CDT (GB)	• Better lifetime, temperature stability, higher conversion efficiency, better control of emission/absorption overlap, accurate control of size distribution and production up scaling for II-VI QD. • QD toxicity issue. • For OLEDs, the recommendations are the same than for displays.
	QD OLEDs	++	++		

	KEY DEVICES	EUROPE POSITION		EXAMPLES OF EU PLAYERS (R&D and companies)	TECHNICAL RECOMMENDATIONS
		R&D	Industrial		
Datacoms/ Telecoms ($ 4.5B)	High index Si/ III-V photonic devices (laser, waveguide, switches, detectors)	+++	+	Bookham (GB), 3S Photonics (FR), Heinrich-Hertz Institute (GE), U2t (DE), Alcatel-Thales III-V Lab (FR), CIP (GB), Draka (NL), Technische Universität Berlin (DE), CEA/LETI (FR), IMEC (BE), Ericsson (SE), Avago (IT), Pirelli (IT) …	• Integration of CMOS and photonics raises materials, processing and packaging issues which are: o Heat dissipation, low cost packaging, robust, low-loss, standardized coupling structures. o High-throughput, low-cost bonding of III-V to Si wafers. o Monolithic new materials approach (Ge). • 2D photonic crystals in III-V for the datacom market. • Active fibre manufacturability.
	Active fibre (amplifier) with nanoparticles	++	++		
	Electronic/ photonic integrated devices (flip-chip source, integrated source, all Si)	+++	++		
Sensors ($4.2 B)	Fluorescent markers with QD II VI	++	+	Biacore (SE)	• Microstructured fibre approach. • Accurate control of size distribution and production up scaling for II-VI QD is needed as well as better lifetime, temperature stability, higher conversion efficiency and better control of emission/absorption overlap. • Plasmonics approach.
	Plasmonics biosensors	++	+		
Optical Interconnects ($ 0.8 B)	Laser sources and gates with Si nanocrystals	+++	+	Technische Universität Berlin (DE), CEA Leti (FR), IMEC (BE), FhG IZM (DE) …	• CMOS integration: the recommendations are the same than for data and telecoms.
	Electronic/ photonic integrated devices (flip-chip source, integrated source, all Si)	+++	++		
	Laser with Quantum dots III-V	++	++		

Table 15: European position on key devices (Legend: + Low; ++ Medium; +++ High) and recommendations summary

The technical recommendations have been organized according to the perceived risk and nanophotonics benefits (**Table 16**).

Definition of the risk: The risk is directly correlated to the devices timelines. We consider that the risk will be high if the time before mass production will be long (that means we are only today at the basic R&D level). On the other hand, the risk will be low if, from 2007, we are close to mass production and most of the basic/applied R&D work has been done already.

- Low: first applications in less than 2 years and mass production starting in 2010
- Medium: mass production will start between 2010 and 2014
- High: mass production will really start in 2015 or after.

Definition of the benefits: the benefits are the improvements that nanophotonics will bring to the considered devices.

	KEY DEVICES	RISKS	TECHNICAL RECOMMENDATIONS	BENEFITS
Displays ($90 B)	CNT for field emission display, LCD backlighting	**H**	• Improved manufacturability for CNT (low cost, high reproducibility and purity, large size deposition): this is more engineering than R&D challenge.	• CNT will give less power consumption, better image quality • CNT is a better electron emitter than standard microtips (silicon or tungsten) • CNT are well adapted to field emission due to their very high aspect ratio (lower threshold of field emission). The current density is one of the key parameter for display application.
	Organic LED	**L**	• Biggest issues are to increase lifetime and display size of the device. • Sensitivity to water and oxygen contamination must be reduced to improve lifetime. • For flexible displays, encapsulation is a bottleneck and flexible encapsulation technique are being developed	• OLEDs allows manufacturing of flexible and thinner displays
Photovoltaics ($50 B)	Quantum dots III-V based solar cell	**M**	• Low defect density for low carrier recombination. • Precise and exact formation of the quantum dot structure as part of epitaxial layers; reproducibility • Process & equipment challenges: strain management - low defect density. QD growth requires special growth conditions. These conditions must be monitored, e.g. by novel in situ methods	• The absorption spectrum of the quantum dots can be tuned to optimise the overall performance of multiple-band cells. • The use of quantum dots may also reduce recombination ("photon bottleneck"), and thus further improve efficiency.
Imaging ($10 B)	CMOS image sensors with plasmonics	**H**	• The main challenge is the sensitivity of photon-plasmon coupling. Thus, there is a considerable disturbing influence by environmental effects or temperature stability. • Another issue is the poor availability of good metals and alloys	• Increased sensitivity in VIS
	III-V QD infra red imager	**L**	• Responsivity is still low compared to other infrared sensors, in particular due to the small volume available for detection. Responsivity can be enhanced by using photonic crystal structures. The main challenges are related to growth, and in particular to create small dots (lateral dimension) with high density	• The main advantages of QDIR are: 1. Lower dark current due to the 3D-confinement of carriers 2. Possibilities for higher operating temperature (~77-100 K), which consequently will lead to a cheaper camera system. 3. Absorption of radiation at all angles of incidence, since the electrons are confined in all directions, which will lead to simpler fabrication process. • Longer lifetime of excited carriers than in quantum wells, which will increase the probability for an excited electron to contribute to the photocurrent and will therefore increase responsivity

	KEY DEVICES	RISKS	TECHNICAL RECOMMENDATIONS	BENEFITS
Lighting ($6.8B)	ZnO nanowires-based LED	**M**	• For LED emitting at 385 nm 1. p-doping is still extremely difficult (maximum doping level achieved is about 10^17, where more than 10^18 is required for the application). Thus homojunction LED have not been demonstrated yet. A potential solution is to make an heterojunction diode, using ZnO as n-doped material associated with another p-doped material (e.g GaN, polymer) 2. Carrier injection in the nanowire. Contacting the top of the nanowire could be done by planarisation + metal deposition 3. Reproducibility of growth, control of dimensions and control of orientation of the nanowires is difficult.	• The major benefit of ZnO nanowires is the excellent quality of material on any kind of crystalline or non-crystalline substrates. Main benefits: 1. Superior crystalline quality 2. Better electrical/optical quality 3. Freedom to chose substrate
	LED with III-V photonic crystal	**M**	• As LED must be cheap enough to compete with other existing solutions, a process for producing the photonic pattern at low cost is mandatory. Obviously the e-beam lithography technique used in the first demonstrations is not suitable. Two other techniques are investigated: the nanoimprint approach and the optical interferometric (holographic) approach. • The real challenges are related to the low cost targeted in this potentially high volume application, which is how to produce this photonic pattern at the surface of full wafers at marginal cost. • This is even more challenging as "simple" surface roughening is probably sufficient.	• A PhC structure is a way to optimize light extraction. Methods used so far are basically a roughening of the LED surface which results in a reduction of losses due to light reflection at the interface. • The PhC approach, however, promises (from theoretical calculations) to yield even higher extraction efficiencies, but this has not been demonstrated so far. • PhCs consist of a periodical pattern (2 dimensional) close to the active MQW region of the LED. The PhC pattern is much shallower (a few 100s nm) than in usual PhC structures.

	KEY DEVICES	RISKS	TECHNICAL RECOMMENDATIONS	BENEFITS
Datacoms/ Telecoms ($4.5B)	High index contrast Si photonic devices (passive PICs, laser source, switch, electro-optical devices, all-optical device)	**H**	• For PICs, the main issues are packaging and coupling. On the fabrication side, one desires processes suitable for mass-production, such as optical or nanoimprint lithography. In order to profit from WDM, there is a challenge to reduce channel cross-talk, such as in arrayed-waveguide gratings. • A main challenge for nanophotonic sources is to prove their advantage over solutions with conventional VCSELs: scattering losses are a big issue in micro- and nanoscale cavities. • Integration of sources with silicon photonics. • For liquid crystal switching devices, the control of molecular orientation is a challenge. • For detectors in germanium or III-V materials the issue is how to integrate these into the silicon platform. • All-optical devices (switches, frequency converters). It is a challenge to demonstrate useful, cascaded circuits with low power, fast switching. For a practical device, getting the right wavelength will need some tuning. • Generic technology allowing for a broad range of functionalities (passive and active).	• Lower cost • More compact devices
	Active fibre (amplifier) with nanoparticles	**M**	• Active fibre manufacturability and performance.	• Low losses
	Electronic/ photonic integrated devices for transceivers	**M**	• Low cost, wafer-scale approaches to incorporate III-V devices on to the silicon. • To lower packaging costs. • Heat dissipation.	• The convergence of photonics and electronics on the silicon platform would create low-cost, high performance optical links for many different applications. • A low cost optical transceiver will be one of the key devices to drive networks into using more optical links.
	All Si link	**H**	• Manufacturing issues (CMOS compatibility)	• Compactness and high performance

	KEY DEVICES	RISKS	TECHNICAL RECOMMENDATIONS	BENEFITS
Sensors ($4.2 B)	Fluorescent markers with QD II-VI	**L**	• Accurate control of size distribution and production up scaling for II-VI QD is needed as well as better lifetime, temperature stability, higher conversion efficiency and better control of emission/absorption overlap. • Regulations issues.	• Enhanced sensitivity for biosensors • Higher photostability, wider optical absorption (i.e. excitation) range, narrow emission spectra as well as less optical cross-talk between excitation and fluorescence. • Lifetime is much longer with nanoparticles than with organic dyes
	Plasmonic biosensors	**M**	• Many different fabrication methods. • Very tight control necessary, (1nm). • Influence of environment. • Integration of these particles with existing technologies (e.g. Si-platform), integration on chip (-> problem of coupling between dielectric and plasmonic modes). • Study of nonlinear properties. • Increase performance of top-down fabricated particles. • Poor availability of good metals. • Specific chemical functionalisation of plasmonic nanostructures is one of the key challenges for health applications	• Enhanced sensitivity • Ultra-small sensors, allowing for dense sensor arrays. • Tailoring of particle size and shape for various functionalities (e.g. different resonance wavelengths). • Access to reaction kinetics • Great processing flexibility, good synthesis schemes exist, with sub-nm size control. • Plasmonic sensing has potential in health applications
Optical Interconnects ($0.8 B)	QD III-V laser source	**M**	• Manufacturing and temperature stability • III-V laser: bonding of III-V membrane at industrial scale has to be developed (e.g. high throughput bonding equipment). III-V processes must be made compatible with CMOS processes. • Cost of III-V bonding and non-standard manufacturing steps could be an issue.	• Compact devices for lasers: QD active medium may offer advantages in terms of gain, threshold current density, thermal stability, growth on "low-cost" GaAs substrate. But when it comes to low current, micro-lasers (small cavity) are what are really needed. • High performance (high data rate) • Microelectronics manufacturing equipment can be used
	Si QD-based laser source	**H**	• Si laser with Si nanocrystals: size and density of Si nanocrystals should be separately controlled. • Si laser with Erbium doped Si nanocrystals: size distribution has to be controlled. The role of non-linear losses, such as confined carrier absorption, excited states absorption, up conversion, should be minimized. Auger processes between Er ions and carriers should be controlled. • Optical gate/ size distribution has to be controlled. Higher density of small size Si-nc gives higher FOM by keeping scattering effects low.	• Compactness and high performance • The introduction of nanomaterials is one of the only solutions to get light emission from silicon • Si-nc (SiOx) provides mainly lower band-offsets with Si (in comparison with pure SiO2) and increased conductivity. • Kerr coefficient is much larger in Si-nc than in bulk materials (respectively 100 times larger than Si, 10000 times larger than SiO2).
	Chip to chip link with flip chip source	**L**	• Flip-chip of laser sources is a short term solution but is not cost effective for high volume.	• Mature process
	Link with hybrid integrated source	**M**	• Manufacturing issues (CMOS compatibility) • Performance issues: power is still too low for Si-based sources, even if some applications may not necessarily need a lot of power).	• Compactness and high performance
	All Si link	**H**	• Manufacturing issues (CMOS compatibility)	• Compactness and high performance

Table 16: Table showing the technical recommendations, the risks and benefits for nanophotonic devices

9. Conclusions

The MONA project has highlighted the major challenges in nanophotonics for European science, technology and industry. For each of the key devices, actions would need to be taken to:

1. Improve the European industrial position by supporting the technological transfer from labs to industry (entrepreneurs and start-up support, access to venture capital, funding of device development projects with R&D labs, SME, large companies….).
2. Answer the nanomaterial challenges: fundamental research, production scaling, toxicity, foundry access, industry standards.
3. Support the key related equipment.

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 doing common work for nanophotonic devices which 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 Field emission displays
- OLED

That means that future developments efforts on those 3 devices will benefit both applications fields. Europe has a strong industrial position on lighting with two major players (Osram and Philips). Although the display market is currently mainly dominated by Asian players, LCD manufacturers could be addressed by Europe through the growing light source business and the development of flexible displays. 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 identified synergy is for optical interconnects and data telecom. In both applications indeed, photonics have been substituted or aimed to be substituted 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, 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 plays 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 applications 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. cm² range for device, dm² for the wafer).

Although the situation in Europe for 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, but also for equipment that is required for more exotic processes. European players are among the top ones for:

- MOCVD with Aixtron (Germany)
- MBE with Riber (France)
- CVD/PVD with Oerlikon (Switzerland)
- Photolithography with ASML (Netherlands)
- NIL with Obducat (Sweden)
- (Deep) etching with STS (GB), Adixen (France)
- ALD with ASM (Finland)

Photonics [21] has validated the final MONA roadmap synthesis. To strengthen the Europe position in nanophotonics, actions could be taken through Photonics [21] and the European Commission. However, since the funding from the European Commission represents less than 5% of all European R+D+I spending, a serious effort is needed to convince industry and national/regional commissions to read and implement the MONA roadmap.

To be useful, a roadmap has to be alive and evolving. The MONA roadmap has been regularly updated through the MONA website (www.ist-mona.org). It will allow the nanophotonics community to stay informed for the R&D and industrial evolutions of nanophotonics.

Annexes A: Report on the 5 to 10-year roadmap on materials

A.1. Introduction

The object of this document is to provide a synthesis from the viewpoint of materials development. This means we use the information from the roadmaps, established in the MONA project, to identify the main challenges and the most promising applications for each material. Furthermore, we try to compare the different materials with respect to their potential impact.

The structure of the discussion is as follows. In the next section we examine each material in series. Every subsection is divided in four parts. The first part describes the particular material. Then we identify the main application areas and discuss their potential. We also provide a table indicating the expected impact of the nanomaterial in the various application areas. This impact is defined as the *technical impact*, which means the expected influence on performance and/or cost of devices if the nanomaterial is implemented, irrespective of the application market size. Next we review the main challenges or obstacles for the material. Finally, we discuss its European position, outlook and recommendations.

The final section of this document provides some comparing insights into the expected development level of the nanomaterials. We provide a synthesis that shows for each nanomaterial which applications are estimated to reach mass production maturity by 2011 and 2015, respectively. The particular devices and the technical impact levels are indicated. To aid these statements we gather the timelines of the proposed devices per material in the annex. This gives a graphic illustration of current and future levels of development.

A.2. Materials synthesis

A.2.1. Quantum dots and wires in silicon

Introduction

In contrast to bulk material the dimensionality of quantum dots and quantum wires is shrunk in three or two spatial directions, respectively. The confinement to sizes below the de Broglie wavelength of the electron causes shifts of the band gap structure and splits of the energy levels. In this section, the semiconductor material consists of silicon only. Compound semiconductor quantum dots and wires, are discussed in other sections.

Applications

The use of silicon quantum dots and wires is envisaged for a range of applications. The nanostructure dramatically changes the electro-optic properties, in contrast to the bulk properties. Silicon is a well established material for many applications. Therefore it is advantageous to use the same material in new quantum-confined structures for enhanced functionalities.
However, most applications are still in a basic research stage. Quantum dots from compound semiconductors seem to be more developed. Nonetheless, the silicon advantage makes it a well-researched subject, and there are good device opportunities.
Silicon nanocrystals are employed to overcome the indirect bandgap and achieve silicon lasers. If output powers increase, these devices would be very useful in a silicon photonics context, e.g. for optical interconnects. In addition, quantum dot solar cells have the potential to increase the efficiency in comparison with standard crystalline silicon cells. At the same time the cost might be lower than for the competing III-V cells. As a final example, silicon nanostructured probes for scanning near-field optical microscopy (SNOM) may offer significant advantages in terms of manufacturability.

Technical impact	
Optical interconnects	Strong
Sensors	Medium
Photovoltaics	Medium
Instrumentation/Metrology	Medium

R&D challenges

One needs a good control of both the size and density of the nanocrystals. The size distribution should be as narrow as possible. For many devices a very high density of small sized crystals is desired. The appearance of losses (scattering, nonlinear, etc.) needs to be minimized. For solar cells an issue is to obtain uniform quantum dots over a large area. Furthermore, the role of the dielectric matrix and dopants, such as rare earth materials, should be elucidated with respect to reliability, creation of defects, etc. Finally, one still has to demonstrate an electrically excited silicon laser.

European position

In the field of silicon photonics and quantum dots Europe has world recognized research teams. Silicon devices in general are of high interest for future components in which photonic and electronic functions are integrated together. Laser sources and nonlinear devices are key building blocks here.

The silicon quantum dot solar cell technology is in a very early stage, with strong research in the USA and Australia. With respect to the demand for alternative energy there should be research carried out in Europe regarding this topic.
For the nanostructured probes Japan is leading, with the US and Europe behind. There are several European SNOM manufacturers, however. Furthermore, these techniques might be applied to high density optical memories.

A.2.2. Quantum dots and wires in III-V materials

Introduction

Quantum dots and wires are semiconductor nanostructures that spatially confine the motion of electrons, holes or excitons. Spatial confinement leads to improved performance and novel quantum effects that may be exploited to develop advanced optoelectronics devices (lasers, detectors, amplifiers, modulators, etc.). Different III-V materials are considered mainly based on GaN, GaAs (including antimonides) and InP materials systems. Self-assembly is the most common technique to grow quantum dots and wires.

Applications

The range of applications for quantum dots and wires in III-V materials is very wide. Most of the R&D efforts have been dedicated to efficient light sources for optical interconnects, datacom/telecom, lighting and data storage, as well as low-noise photodetectors for imaging, sensing and photovoltaic applications. Besides advantages of quantum dots and wires in terms of efficiency, temperature stability (light sources) or low dark currents (photodetectors), the possibility to grow lattice-mismatched materials on top of each other offers new opportunities of material combinations and bandgap engineering.
While the first quantum dot and wires components are being commercialized now, the technology is still in its infancy. Many novel concepts and effects remain to be fully exploited, in particular in the field of photovoltaics, data storage and lighting.

Technical impact	
Optical interconnects	Strong
Datacom/Telecom	Medium
Lighting	Medium
Data storage	Medium - strong
Imaging	Strong
Sensors	Medium
Photovoltaics	Strong

R&D challenges

The main challenges are related to a better control of uniformity in size, form and symmetries of quantum dots and wires, which currently reduce the device performance. Two major research axes are to push the limits of conventional Stranski-Krastanow growth techniques, as well as to develop novel growth modes. In particular, the combination of top-down and bottom-up approaches for better control of quantum dots and wires may provide new material opportunities. In addition, the study of colloidal synthesis could offer a path towards low-cost mass fabrication.

European position

Europe has very strong players at the R&D level of this field, but so far very little industrial involvement.

A.2.3. Quantum dots and wires in II-VI

Introduction

The main type of nanomaterial considered here is II-VI nanoparticles (quantum dots) that can be used for their fluorescence/photoluminescence, electroluminescence or absorption properties. The particular position of emission or absorption is selectable by choice of semiconductor material (coarse adjustment) and size of the dots (fine adjustment). II-VI nanoparticles promise better stability and efficiency compared to conventional solutions. They exhibit broadband absorption spectra, with observable peaks due to individual energy states, and narrow “bell curved” emission spectra. For applications such as biosensors, more complex structures consisting of a core, a shell and a coating have been developed.
Another type of nanomaterial is zinc oxide nanowires that can be used for making UV LEDs.

Applications

Quantum dot nanophosphor technology has been developed for years and is rather mature now. These nanomaterials are manufactured and commercialized by companies such as Evident. Biological sensing (e.g. fluorescence microscopy) is the most mature application field, followed by lighting and displays where nanophosphors are expected to replace conventional phosphors based on rare earth doped materials. In photovoltaics, II-VI nanoparticles have a potential to increase solar cell efficiency at a relatively low cost. For other markets such as data storage, datacom/telecom or image sensors, only very prospective applications are foreseen in the long term. Zinc oxide nanowires should exhibit better structural quality than 2D thin films, and lower cost, non-crystalline, large area substrates can be used.

Technical impact	
Lighting (ZnO nanowires)	Strong
Lighting (CdSe QD)	Medium
Data storage	Low
Sensors	Strong
Displays	Medium
Photovoltaics	Medium – strong

R&D challenges

Wet chemical processes are the main fabrication method for nanoparticles (multiple steps required for core-shell systems), with standard chemical processing equipment. As for other types of nanoparticles, the accurate control of size distribution as well as upscaling from small volume (several grams per batch) to high volume production are the main issues. There is still a need for better lifetimes and temperature stability, higher conversion efficiency and better control of emission/absorption overlap. Some more challenging topics include the design of multifunctional nanocrystals combining for example fluorescence and magnetism, with different emission lifetimes.
The toxicity of the nanocrystals arising from their small size and/or from the constituting materials (Cd, Te, organic surface coating, etc.) or degradation products has to be assessed. As hazardous materials are used (e.g. phosphine or organic solvents such as toluene, hexane, heptane or chloroform) the environmental impact of the fabrication process and waste treatments have to be taken into account. Alternative solutions, using e.g. aqueous solvents, are under development.

European position

Generally speaking, European research laboratories are well positioned compared to US and Asia based R&D centres. At the industrial level, the situation strongly depends on the application field:

- QD-biosensors have been developed mainly in the US, although there has been research in Europe. Commercialization is already made by small and midsized US-companies. It should be analyzed whether there are market possibilities for European companies in the future.
- In the case of lighting further research is required, as it is an important application in the EU. On top of that, the research so far is mainly carried out in the US which makes European efforts even more desirable. The strong lighting industry in the EU should encourage further R&D in these areas.
- In displays, II-VI quantum dot nanophosphors are only a change of existing display technologies, which are dominated by Asia. Presumably there are only little chances for Europe. In contrast, QD-based active flat panel displays depend on the OLED technology. The scope is long-term so that Europe may have a chance in the Asia-dominated display market.

A.2.4. Plasmonics in metallic nanostructures

Introduction

Quantized oscillations of charged particles are called “plasmons”. Plasmonic effects are of particular interest in nanophotonics. They are based on the interaction of light with free electrons in metallic surfaces. Depending on surface structuring, wavelength, angle of incidence and polarization of the light the coupling of photons and surface plasmon resonances (SPR) may be very efficient. Hence, the behaviour of SPRs is very sensitive to modifications of and interferences with the surface and thus makes them appropriate for (bio-) chemical sensing.
The data transfer capacity of plasmons is similar to that of light, i.e. much larger compared to electronic based transfer. The spatial extent on the other hand is considerably below the diffraction limit. With several tens of nanometers, it is similar to the integration scale of future electronic circuits. However, depending on the metal, plasmon propagation is rapidly decaying and their range is limited to several 10 to 100 µm.
Currently, nanostructured plasmonic metal surfaces are intensively investigated as photonic elements. Their potential may be seen in sub-wavelength optics.

Applications

A prominent application of plasmonics is in the area of molecular sensing. SPR-based sensing is a suitable and widespread method in biotech labs for the ultra sensitive detection of biochemical binding interactions of molecules to target structures tagged to a functionalized metallic surface. Appropriate instrumentation has been commercialized and is available on the market.
In other areas, plasmonics is predominantly in a stage of basic research. Good possibilities for short term application can be seen in the lighting sector, where solid state based lighting devices (LED and OLED) gain increasing applicability. These devices can be assumed to obtain widespread usage in the near future. With the commercial distribution of LEDs and OLEDs, light efficiency losses caused by electrode contacts to the emissive layers become an increasing issue. Plasmonic structuring of electrodes has the potential to increase light emission efficiency considerably.
The time range of further applications extends more into the future: Plasmonics is discussed for integrated structures in microelectronics, as it could be a means for combining high-capacity optical data transfer with the integration density of CMOS electronics. However, the spatial range of SPRs is low, thus usage of plasmonic elements is worthwhile only for complex tasks in highly integrated (short range) chip devices.

The same holds for applications in optical data storage, where plasmonics is discussed to overcome the diffraction limit and thus to increase the storage density.

Technical impact	
Optical interconnect	Low
Datacom/Telecom	Low - medium
Lighting	Medium
Data storage	Medium
Sensors	Strong
Instrumentation/Metrology	Medium

R&D challenges

As plasmonics is still in basic research, the challenges concerning stable applications are manifold. In general there is a need for standardization and a definition of standard operating procedures.
In the sensor area the main challenge is the sensitivity of photon-plasmon coupling. Thus, there is a considerable disturbing influence by environmental effects or temperature stability. In data storage as well as in SP-lithography one of the key problems is to control the distance of the front end optical elements to the rotating disk or to the photoresist which is below 40 nm. The key trade-off for electronic applications is the short range of SPRs as well as the tight fabrication control in the range of ~1 nm.
Another issue is the poor availability of good metals and alloys. Indeed, because of the metal parameters many effects such as extraordinary transmission are mainly observable in the visible range. In the important infrared region the design of plasmonic devices is more difficult.

European position

Europe has a strong position in the plasmonics area. A series of research institutions are working in this field. There are industrial players observing these basic research activities with interest, and performing their own research. The position strength depends on the application sector. Europe is in a leading position concerning optical storage, lighting and photovoltaics. On the other hand, the situation is different for SP-lithography, where activities are mainly US or Asia based. Concerning microelectronic applications, the European research level is quite high but the commercialization aspect is missing so far. Enhanced industrial engagement is desirable.

A.2.5. High index-contrast nanostructures in silicon

Introduction

Optical and/or optoelectronic devices made of silicon in which the performance and/or functionality is strongly based on high index contrast nanostructures (photonic wires, photonic crystals, etc.). For some devices one combines the silicon with III-V semiconductors for active functionality.

Applications

This nanomaterial has a high potential impact, especially in the data communication and interconnects sectors. Fibre to the home for example is actively deployed nowadays. For these applications a number of components (lasers, modulators, detectors, etc.) receive much attention, and are in an advanced development stage. In addition, the advantages of compactness and low cost mass production are now examined intensely for use in sensors. The strong interest in lab-on-a-chip approaches will accelerate these developments.

Technical impact	
Intra-chip interconnects	Medium
Chip-to-chip interconnects	Medium
Datacom/Telecom	Strong
Sensors	Medium

R&D challenges

To obtain affordable chips with a good performance, it is imperative to develop high-throughput, high-resolution manufacturing processes. Another cost related issue is the packaging and coupling of these devices to external sources or fibres. In addition, it is very hard for a fabricated component to hit the right wavelength without some form of tuning. For sensors e.g. one needs to cancel or control the temperature influence. Furthermore, for some components there are still many possibilities to improve the designs and materials. A main challenge for interconnect nanophotonic devices is to prove their advantage over solutions with conventional VCSELs. For biosensors one needs to chemically activate the optical structure in order to sense particular molecules. Another issue of pure silicon structures for sensing is the transparency window, as only wavelengths above 1.1µm are guided. For many applications the visible or near IR light is more attractive.

European position

Europe has strong players at the R&D level of this field. However, the key challenge will be to involve industrial players (established or start-up) at the earliest possible stage. This is difficult as many major (electronics) companies are non-European. Furthermore, these industrial collaborations are required in order to develop standards. In addition, a foundry-like access to industrial manufacturing capability in silicon (or III-V) photonics will prove advantageous.

A.2.6. High-index-contrast nanostructures in III-V

Introduction

Optical and/or optoelectronic devices made of III-V materials in which the performance and/or functionality is strongly based on high index contrast nanostructures (photonic wires, photonic crystals, etc.). For some devices one combines silicon and III-V structures, so there is a strong connection with the previous section.

Applications

One expects that III-V photonic chips will have a large impact for data communications and optical interconnect applications. Product applied research is conducted towards complete III-V devices and integration with other materials such as silicon. Thus, both active and passive components can be fabricated. Furthermore, the material is already broadly used for communication and lighting sources such as VCSELs and LEDs. Therefore, the next step is to incorporate nanophotonic features, such as 2D photonic crystals, in these designs.

Technical impact	
Optical interconnect	Medium
Datacom/Telecom	Medium
Lighting	Strong
Sensors	Low

R&D challenges

Similar challenges as for the previous nanomaterials apply. There is a need for low-cost, high-resolution manufacturing methods. For LED devices one still needs to prove that the addition of nanophotonic features is effective, both for performance and cost. In the datacom and interconnect sectors there is a competition with silicon-based devices. The latter have the integration edge with CMOS electronics. However, III-V devices will be necessary, e.g. for sources, in the first generation of hybrid products. Sources for these hybrid devices will need wavelengths above 1.2μm, because of the silicon transparency window.

European position

As the lighting market is very promising and Europe has a good position in various facets of this topic (GaN LEDs, imprint lithography, etc.) it is important to secure a successful industrial development. For the III-V photonic chip applications Europe has a strong research position. However, there is a need for initiatives leading to standardization and foundry-like access to industrial manufacturing capability.

A.2.7. Microstructured fibres

Introduction

Microstructured fibres exhibit modal characteristics that are strong functions of wavelength. As such they can be engineered to realize desired dispersion properties. Furthermore, fibres with large or small effective mode area can be designed and fabricated for various applications such as high-power transmission, sensing or nonlinear applications.

Applications

The main application areas that are identified by the consortium are datacom/telecom and sensors. The devices in the datacom/telecom sector are expected to develop slightly faster than the sensors. Indeed devices such as super continuum sources and Raman amplifiers are well suited for implementation with microstructured fibres. In addition, these fibres can have low-loss small-radius bends, which makes them very suitable for FTTH deployment. The particular applications for sensors and their packaging/coupling issues are less well studied. However, there is a large interest from e.g. the biotechnology field.

Technical impact	
Datacom/Telecom	Medium
Sensors	Medium

R&D challenges

The main issues are the following:

- Manufacturing: As the starting rods for drawing are not perfect, some roughness appears at the hole surfaces after the fibre is drawn. Presently, this is setting a lower limit to the propagation loss.

It also implies a variation in properties like birefringence, chromatic dispersion, etc. that may make the fibre unusable. For datacom/telecom purposes achieving low cost is an important issue.

- Applications: The research into microstructured fibres has to move towards practical implementations. One needs to determine designs and methods for industrialization. At the same time more applications should be explored.

European position

In Europe there is a very strong track record in the research of microstructured fibres. Moreover, these fibres are envisaged for a wealth of applications in diverse fields (telecommunications, medical applications, sensing etc.). It is evident that the position of Europe should be maintained and expanded towards development and production (see e.g. the European IST project NextGenPCF).

A.2.8. Organic nanostructures

Introduction

In this section we consider devices with organic layers developed for light emission (OLEDs) or absorption (photovoltaics). In OLEDs the organic part is composed of a series of layers. At least a conductive and an emissive layer are needed. Other nanophotonic elements (quantum dots, photonic crystals etc.) are investigated to increase the efficiency.
For photovoltaic applications there are generally two classes of organic materials available. The first are the so-called small molecules, which are deposited on a substrate by thermal evaporation or, more recently, by organic vapour phase deposition (OVPD). The second are polymers, which are produced by spin coating or printing.

Applications

Roadmaps were established for organic nanostructures in the application areas of lighting, displays and photovoltaics. The market for these applications is very large or grows rapidly. Therefore, there is a large interest in new developments for OLEDs and organic solar cells. Many other technologies are explored or already commercialized however, such as LCD displays. Nonetheless, commercialization of OLEDs seems imminent. Organic solar cells with polymers are expected to go to market somewhat later. Small molecule OLEDs and cells may provide for the next generation.

Technical impact	
Lighting	Medium
Displays	Medium
Photovoltaics	Medium

R&D challenges

Key issues for OLEDs are lifetime (sensitivity to oxygen and moisture, degradation mechanisms), efficiency (carrier injection) and cost. For lighting it is a challenge to obtain a ‘warm’ white colour. For displays an issue is to increase the display size and to obtain flexible screens. With current materials one expects incremental advances. However, new materials may offer more substantial performance increases. Light extraction methods, based for example on photonic crystal or plasmon concepts, can also improve the efficiency of OLEDs. One needs to prove that these effects give a substantial improvement in a cost-effective way.
The organic photovoltaic devices are still in a relatively basic status of development. Main problems are the limited efficiency due to high recombination rates and the limited lifetime due to oxygen or moisture

contamination. Encapsulation solutions using organic/inorganic multilayers are under development with promising performance. The small molecule devices show fabrication challenges, as some dimensions need to be controlled on the nm scale.

European position

Commercialization of OLEDs for lighting and displays should start soon. Some major players are located in the US (e.g. Universal Display) and Asia (e.g. Ritek). However, Europe has a good position with Osram and Philips, and various start-ups, such as Novaled and CDT. This creates a strong R&D base.
The OLED market for rigid displays seems quite crowded and dominated by Asian manufacturers, whose priority is to reduce the cost and increase the size of the devices. Europe could benefit from OLED rigid display development by providing R&D services, materials and equipment. There is more room for innovation on flexible displays, which are not industrialized yet. For example, the European project Flexidis targets the development of flexible OLED displays.
Polymer solar cells are still in the research phase. The only industrial player known is Konarka (US). In Europe there are key material (e.g. Bayer, Merck) and process (e.g. Aixtron) suppliers. In addition, Europe has a strong R&D world leadership, which should be strengthened. Polymer solar cell technology is an attractive opportunity for Europe. However, at the beginning the applications will be in the field of consumer products due to the limited device lifetimes. Small molecules based cells experience a rapid development and are promising for next generation applications.

A.2.9. Carbon nanotubes

Introduction

Both single- and multi-wall carbon nanotubes (CNTs) are considered here. The single-wall nanotubes help to improve the photovoltaic characteristics in polymer cells, whereas the multi-wall variety is used as an electron source for field emission displays.

Applications

The impact in the datacom/telecom sector should be considered as a side product of CNT development. The use in solar cells draws interest, as there is a broad consensus that photovoltaics is an important technology. Here, CNTs can help to improve efficiency and lower the cost. The main application is for displays, where the ultimate target is to create large, high-quality flat panel screens.

Technical impact	
Datacom/Telecom	Low
Displays	Strong
Photovoltaics	Medium

R&D challenges

Some of the main challenges are linked to industrialization. There is no conventional manufacturing method that creates low cost CNTs. Desirable properties are robustness, reproducibility, uniformity and purity. For displays an important issue is to increase the screen size to 40”. CNT growth on a large surface has never been demonstrated. There are no fundamental limits however. In photovoltaics the main issue is related to the lifetime of the cell. Similar to OLEDs, the devices are very sensitive to moisture and oxygen. Better encapsulation solutions are under development.

European position

Main industrial players for field effect displays are in Asia (Samsung, Canon, Toshiba, Mitsubishi, Sony, Ise Electronics) or USA (Motorola, CDream, Applied Nanotech). The flat panel display industry is highly concentrated, capitalistic and concentrated in Asia. Therefore it is very difficult for new players to enter this field (Motorola chose to license its technology to an Asian company). However, there are strong R&D skills in Europe, e.g. CEA Leti on CVD techniques. It seems the main interest for Europe in that segment will be to provide support services such as R&D and process equipment. Another opportunity may be to focus on flexible large size displays.
Currently Europe has a leading role in the development and, to some extent, in the manufacturing of photovoltaic applications. Europe should try to maintain and even strengthen this R&D role. In addition, the focus must be on manufacturability, in order to compete with Asian competitors.

A.2.10. Integration of electronics and photonics

Introduction

No particular material is considered, but rather the integration issues of nanophotonic functions on electronic ICs. This includes the fabrication of nanophotonic devices using CMOS compatible processes, and the combination of electronic and nanophotonic elements in the same chip. The devices considered are the key building blocks of optical links, i.e. laser sources, modulators, waveguides and passive functions, detectors and coupling/packaging. In addition, CMOS sensors with nanophotonic enhancements are examined.

Applications

There are strong anticipations for this technology in the field of optical interconnect and datacom/telecom. Electronics is expected to hit a speed time distance bottleneck, which can be handled by nanophotonic solutions. The use of CMOS compatible processes to fabricate photonic chips ensures a low-cost, mass-production environment. The complete integration of photonics and electronics is a challenging next evolution. These devices have a large potential for mass applications such as fibre-to-the-home or server interconnects. Therefore, many developments in applied research are reported.
The use of nanophotonic elements in CMOS image sensors is another suitable, though less developed, application. The use of compact colour filters in micromodules for cell phones or medical applications is suggested.

Technical impact	
Optical interconnect	Strong
Datacom/Telecom	Strong
Imaging	Medium - strong

R&D challenges

The following challenges need an intensive research effort:

- An important difficulty for the integration of CMOS with photonics is heat dissipation. A high speed CMOS circuit is a hostile environment for photonics. These chips run very hot, with large differences in place and time, which is problematic if the photonic circuit is in close contact. In addition, in image sensors one needs to use materials that offer very limited ageing effects under strong and/or permanent illumination.

- Low cost packaging solutions, as used in microelectronics, have to be developed. This is still one of the major issues. One needs robust, low-loss, standardized coupling structures to interface between chip and fibre.
- There are materials and processing related issues that need to be addressed. As the power of pure Si lasers is still too small for many applications, there is a lot of development towards hybrid lasers with III-V materials. For detectors e.g. one examines structures with Ge. In this respect one can understand that one of the main manufacturing issues is to develop the processing so that an electronics step does not poison or disrupt an optical step and vice versa. The compatibility with mass production CMOS processes in view of materials and temperature is crucial, even more so as the equipment is very expensive. High-throughput, low-cost bonding of III-V to Si wafers could be important.
- To obtain chips with a high performance one needs to have good control of feature size and sidewall roughness, in a mass production context. Polarization dependent losses are an issue here.

The previous challenges become more complex if WDM is envisaged (different source wavelengths, (de)multiplexers, etc.).

European position

Integration of photonic functions with electronics is one of the major challenges for photonics and electronics in the next decades. Photonics will contribute to the evolution of microelectronics by bringing new functionalities on a CMOS chip and/or by overcoming some of the “red brick walls” of the ITRS roadmap. Europe is well positioned in this domain with several leading institutes. Silicon photonics is also strongly investigated in the US by federal agencies (DARPA with the EPIC project, DoD with the MURI project on silicon lasers), microelectronics companies (INTEL, IBM) and start-up companies (Luxtera, Kotura). The European companies should aim to decrease the gap with the American industry. In addition, the European industry is relatively segmented between “photonics” and other advanced sectors, such as semiconductors. Improved coordination and joint development at the research stage should help to combine these functions more easily. Finally, foundry-like access would be beneficial for academia and industry to advance the state-of-the-art in this field.

A.2.11. Nanoparticles in glass or polymer

Introduction

A number of different devices, based on nanoparticles from various materials, are discussed in this section. Nanoparticles with Er, or other active ions, are introduced in fibres to create active fibres, used e.g. as optical amplifiers. To create white LEDs one employs a blue or UV LED with a converter sheet. This converter may consist of nanosized crystals of a phosphor, e.g. Ce-doped YAG, embedded in a matrix. For flat panel displays one can use nanoparticles, generally made of silica, to fabricate good anti-reflective and anti-glare coatings. Finally, in dye-sensitized solar cells (DSSC) one employs TiO_2 nanoparticles to increase the interaction between light and dye.

Applications

The amplification of optical signals in telecommunications is dominated by rare-earth doped active fibre devices, particularly the erbium-doped fibre amplifiers (EDFAs). The control of doped nanoparticles introduced in fibres is expected to lead to new generations of active devices. Other wavelength ranges will be covered and the gain shape can be engineered. These fibre amplifiers will be a very important technology around 2010. At this time, however, there will also be a significant share of Raman fibre amplifiers, planar waveguide optical amplifiers and semiconductor optical amplifiers.
With respect to white LED phosphors and display coatings there is obviously a good opportunity. The nanophotonic impact of these solutions is more difficult to estimate.
In the field of solar cells new designs, such as DSSC, are expected to obtain a large portion of the market. These new concepts will compete with the traditional crystalline silicon cells.

Technical impact	
Datacom/Telecom	Strong
Lighting	Medium
Displays	Low
Photovoltaics	Low

R&D challenges

The main challenge for the active fibre lies in the manufacturing. The main methods are ex-situ processes, meaning that the nanoparticles are synthesized first and introduced in glass afterwards. The issue is to control the nanoparticle properties throughout the process of introducing them into the fibre. The methods are very difficult to control (gas or aerosol flow, pressure, temperature etc.). Collection of the particles should be efficient, while agglomeration needs to be avoided.
For efficient white LEDs with good colour rendering one needs quantum efficiencies larger than 85% (for phosphors absorbing in the near-UV) at operating temperatures above 150°C (for phosphors in intimate contact with the LED). New materials may be required, e.g. for the binder matrix, to achieve temperature, radiation and mechanical stability.
With respect to anti-reflective coatings for displays, there are commercially available products. The main issue is to reduce the cost (about $100/kg of coating) to be competitive with anti-glare coatings. A core challenge is that any improvement of the anti-reflective properties of the surface by nanostructuring must not interfere with its mechanical stability.
DSSCs are now in an applied R&D phase. Pilot production is under development. Several technical challenges need to be addressed before commercialization (longer stability, higher efficiency). Those improvements are not related to the nanoparticles however.

European position

The position of Europe is not strong with respect to telecommunication fibres and related products. However, there is Draka Comteq and OFS in Denmark (daughter of a Japanese company). So, for the inventor of the DND (direct nanoparticle deposition) active fibres, a start-up company in Finland, there are possible European partners to work with. To make this activity a focus of European nano-optics, however, an initiative to make optical communications a focus area has to be developed.
The strong position of the European lighting industry and the already existing commitment of a number of big companies to go ahead with the development of white LEDs provide a powerful basis for sustainable research in this area.
For the flat panel displays, the main polarizer manufacturers that could use anti-reflection coatings are based in Asia (Nitto, Sumitomo, LG Chem, Optimax). The most interesting opportunity for Europe will be to sell coating R&D services, e.g. from German research centres, to Asian manufacturers.

There are numerous R&D, materials and industrialization players in Europe for DSSC. Japan is also very active in this field with major industrial players. We note however that nanophotonics is not the main issue for this device to go to commercialization.

A.2.12. Left-handed meta-materials

Introduction

Theoretical and experimental arguments have shown that certain materials can effectively be described by a negative electric permittivity and/or a negative magnetic permeability. This may happen in artificial meta-materials, where the composing elements are much smaller than the used wavelength. The peculiar character of the electromagnetic fields around such resonances has spurred an intense research activity.

Applications

A potential application that is often associated in this context is the creation of a superlens, where the diffraction limit is overcome by amplifying the evanescent near-field. Such a device would have very useful properties for microscopy, data storage, lithography, etc. However, it is difficult to imagine commercial applications of these ideas in the near future. Research is still very basic, and there are fundamental arguments, that will hamper the usefulness of these materials.

Technical impact	
Instrumentation/Metrology	Medium

R&D challenges

A challenge to obtain practical devices is the unavoidable appearance of losses. This is also associated with the limited number of usable metals, lacking the desired properties for visible light meta-materials. In addition, some devices are extremely sensitive to dimensions, such as the film width. Finally, to construct meta-materials for infrared and optical frequencies one requires nanoscale fabrication methods.

European position

European institutes are at the forefront of this fundamental research subject. Europe has several SNOM (Scanning Near-field Optical Microscopy) manufacturers. Meta-material techniques developed for SNOM might also be applicable to high-density optical memories.

A.3. Analysis

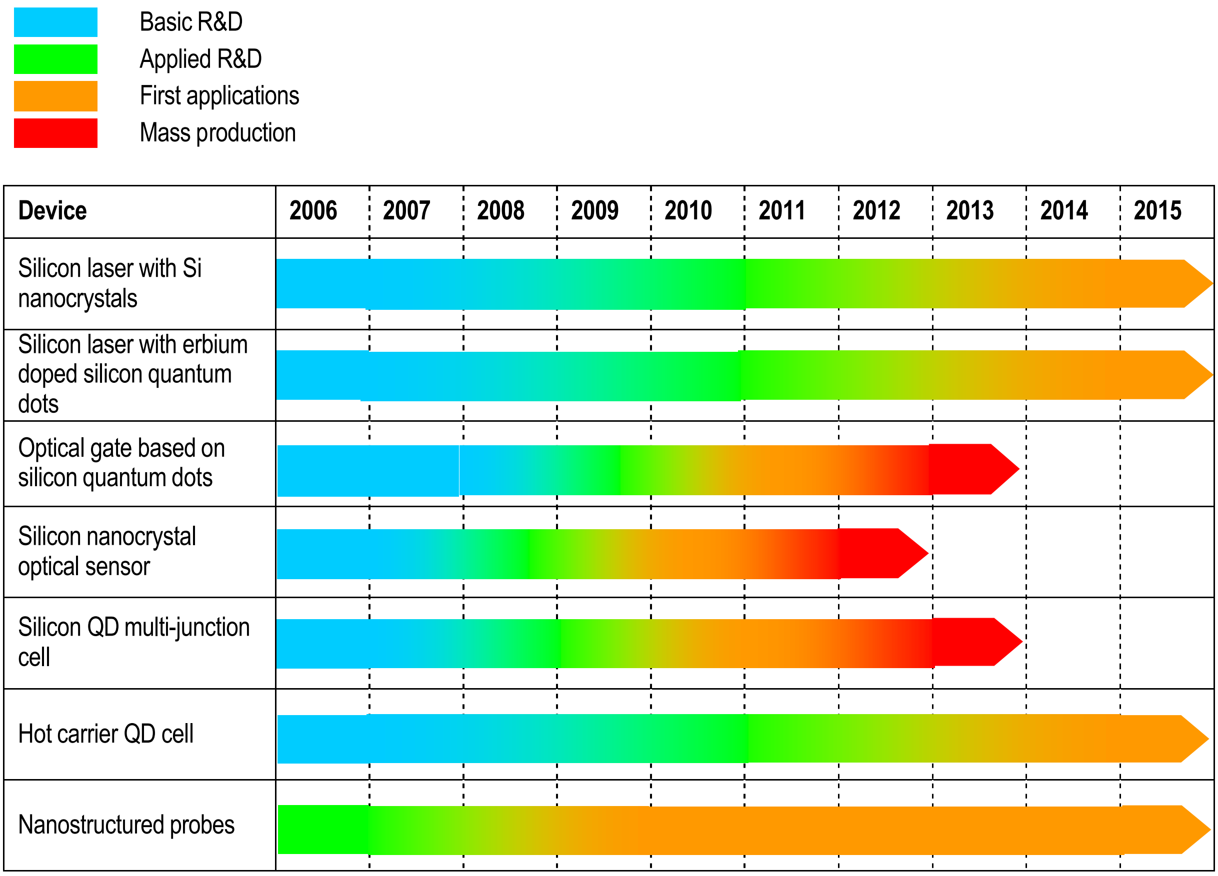
The purpose of this section is to present a comparative synthesis of the different nanomaterials under examination. We extract the data from the timelines in the roadmaps, which are gathered in the annex after this section. For each nanomaterial we show the application areas with devices that are estimated to reach mass production maturity in 2011 and 2015, respectively. The particular promising devices are also listed.
The technical impact of the material for the application area is indicated: We write the application name in red (black) if the impact is estimated as strong (medium). This is also shown with (S) for strong and (M) for medium.
In this way one can observe which nanomaterials have devices that are close to maturity and may provide a strong technical impact. These materials could then be strong drivers for growth. For information and analysis with respect to application market sizes we refer to the MONA deliverables D4.2 and D5.1.

Material system	2011	2015
Quantum dots and wires in silicon	-	**Optical interconnects** (S) - Si QD gate **Photovoltaics** (M) - Si QD multi-junction cell **Sensors** (M) - Si QD UV sensor
Quantum dots and wires in III-V	**Imaging** (S) - QD IR detector **Photovoltaics** (S) - QD cell - QD intermediate band cell **Datacom/telecom** (M) - Improved semiconductor lasers	**Optical interconnects** (S) - III-V QD laser bonded on Si **Data storage** (M-S) - III-N QD laser for data storage - QD memory **Datacom/telecom** (M) - Narrow spectral width lasers - SOA **Lighting** (M) - III-N based LED with nanoconcepts
Quantum dots and wires in II-VI	**Lighting** (M) - GaN LED with QD nanophosphor **Sensors** (S) - Functionalized fluorescent II-VI nanoparticles **Displays** (M) - Nanophosphors based on II-VI QD	**Lighting** (S) - ZnO LED **Photovoltaics** (M-S) - Organic solar cell with QD materials
Plasmonic nanostructures	**Sensors** (S) - (Bio)molecule sensor - Refractive index sensor **Lighting** (M) - GaN based LEDs with surface plasmon enhancement	**Lighting** (M) - OLEDs with surface plasmon enhancement **Data storage** (M) - Near-field storage with SIL - SuperRens storage
High contrast Si nanostructures	**Datacom/telecom** (S) - Passive photonic integrated circuits - Slow switching/tuning functions - Electro-optic devices	**Datacom/telecom** (S) - Micro/nano-cavity laser sources - All-optical devices **Optical interconnects (chip-to-chip)** (M) - Coupling structures/low cost packaging - Laser sources (silicon or III-V based) **Optical interconnects (intra-chip)** (M) - Passive devices **Sensors** (M) - Biomolecule sensor - Strain/pressure sensor - Gas/liquid concentration sensor - Integrated spectrum analyzer

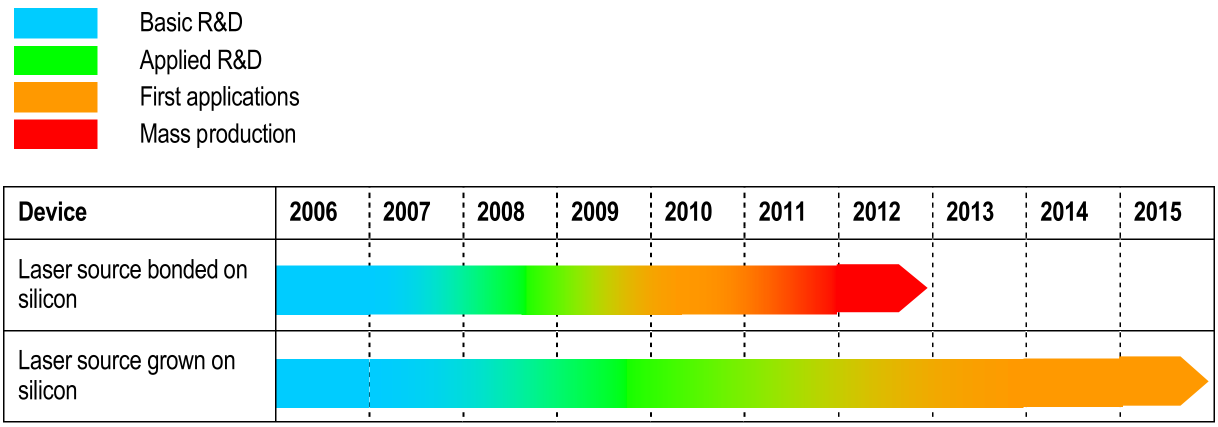
High contrast III-V nanostructures	**Lighting** (S) - White LED (GaN) with photonic crystal structure - GaN & AlGaInP LEDs with improved output beam **Datacom/telecom** (M) - Passive photonic integrated circuits - 1D photonic crystal reflector	**Lighting** (S) - Other LEDs (AlGaInP) with photonic crystal structure **Optical interconnects (chip-to-chip)** (M) - Laser sources **Datacom/telecom** (M) - 2D photonic crystal devices
Microstructured fibres	-	**Datacom/telecom** (M) - Microstructured fibres for FTTH or domestic applications - Microstructured fibres for long-haul transmission - Microstructured fibre for other applications (lasers, amplifiers…) **Sensors** (M) - Microstructured fibre sensors
Organic nanostructures	**Displays** (M) - OLED **Photovoltaics** (M) - Small molecule based bulk heterojunction solar cells - Small molecule based planar heterojunction solar cells - Small molecule/C60 based solar cell	**Photovoltaics** (M) - Fullerene (C60) bulk heterojunction solar cells - Multi-junction cells based on small molecules - QD based organic solar cells using small molecules
Carbon nanotubes	**Displays** (S) - Field Emission Display - small area, low complexity	**Displays** (S) - Field Emission Display – large area - Field emission backlighting for LCD - Surface-conduction Electron-Emitter Displays (SEDs) **Photovoltaics** (M) - Organic solar cell with single wall CNTs
Integration electronics/photonics	**Optical interconnects** (S) - Chip-to-chip link with flip-chipped source **Datacom/telecom** (S) - Transceiver (no WDM) with flip-chip source - Transceiver (with WDM) with flip-chip source **Imaging** (M) -Nanoparticles colour filter	**Optical interconnects** (S) - Link with hybrid integrated source **Datacom/telecom** (S) - Transceiver with integrated source **Imaging** (M) - Nanostructured colour filter
Nanoparticles in glass or polymer	**Datacom/telecom** (S) - Nanoparticle doped active fibres – 1st generation - Nanoparticle doped active fibres – 2nd generation **Lighting** (M) - White LED via nanoparticle phosphor	**Datacom/telecom** (S) - Nanoparticle doped active fibres – 3rd generation
Left-handed meta-materials	-	-

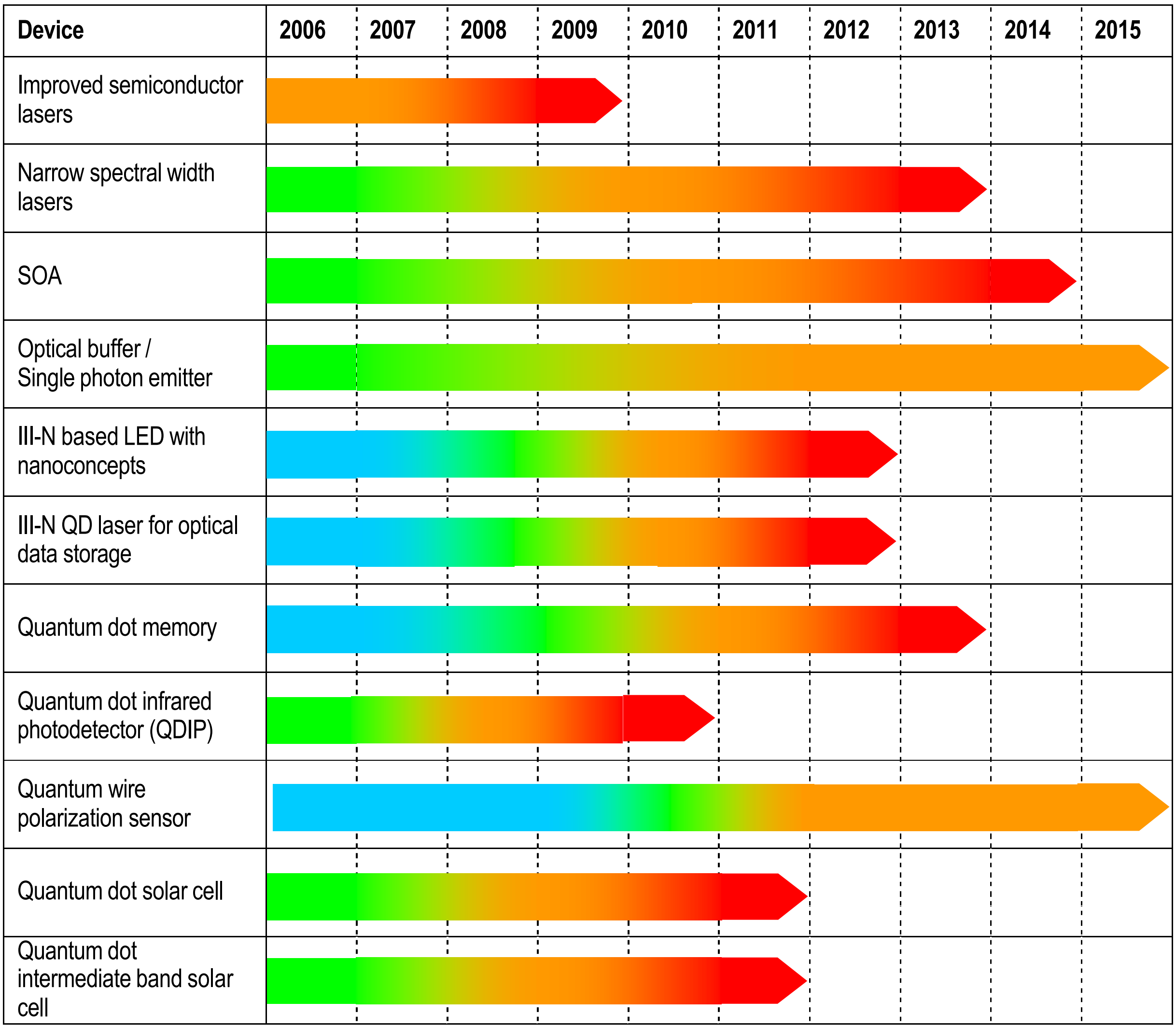
A.4. Timelines for each material

Quantum dots and wires in silicon



Quantum dots and wires in III-V





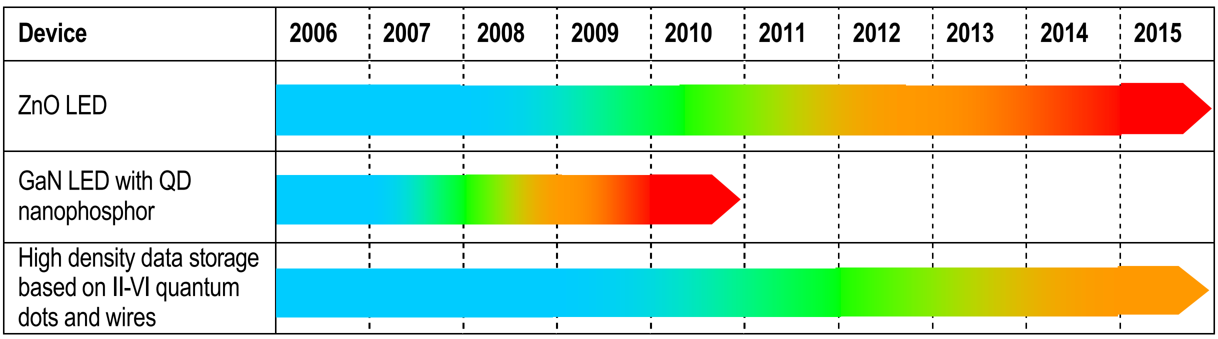
Quantum dots and wires in II-VI

Basic R&D

Applied R&D

First applications

Mass production

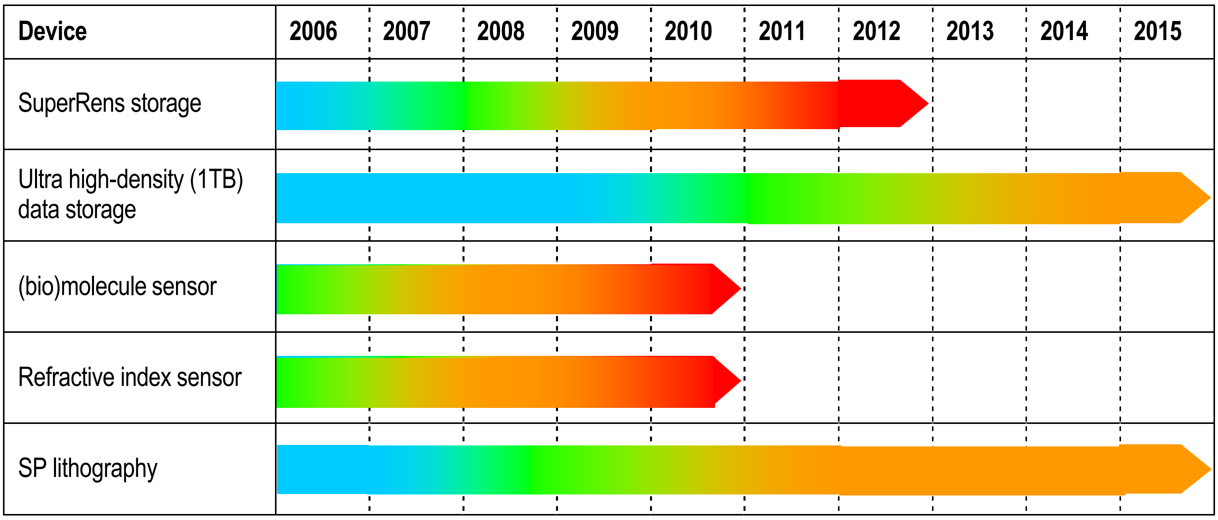


Device	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Functionalized fluorescent II-VI nanoparticles										
Functionalized fluorescent nanoparticles for single molecule observation										
Nanophosphors based on II-VI QD										
Active Flat Panel Displays based on II-VI										
Organic solar cell with QD materials										
Hybrid solar cell based on II-VI materials										
Wavelength conversion devices based on II–VI materials										
Active junction in multijunction solar cells based on II-VI materials										

Plasmonics in metallic nanostructures

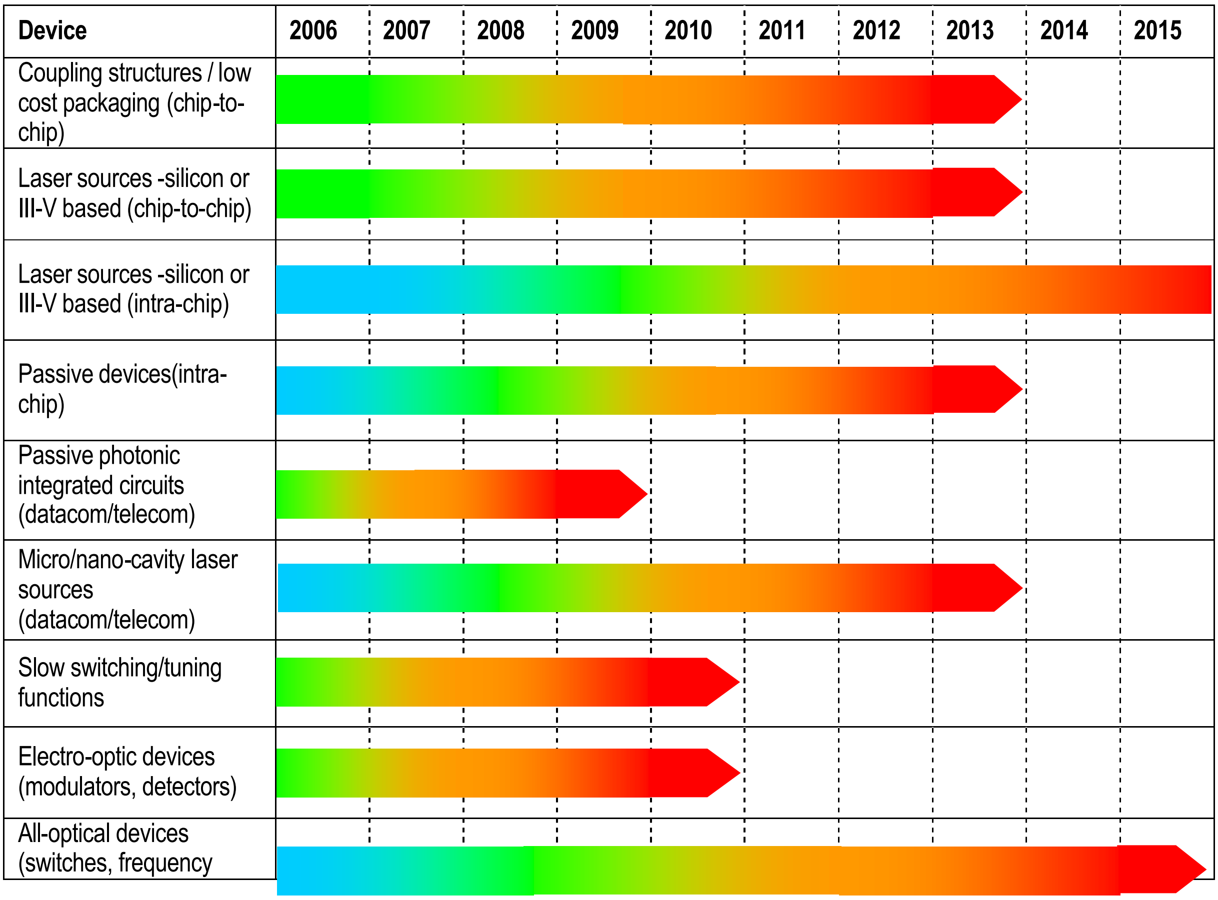
- Basic R&D
- Applied R&D
- First applications
- Mass production

Device	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Active/all-optical nanodevices										
Passive ultra-compact components										
GaN based LEDs with surface plasmon enhancement										
Organic LEDs with surface plasmon enhancement										
Near-field storage with SIL										



High index contrast nanostructures in silicon

Basic R&D
Applied R&D
First applications
Mass production



Device	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
converters).										
Biomolecule sensor										
Strain/pressure sensor										
Gas/liquid concentration sensor										
Integrated spectrum analyzer										

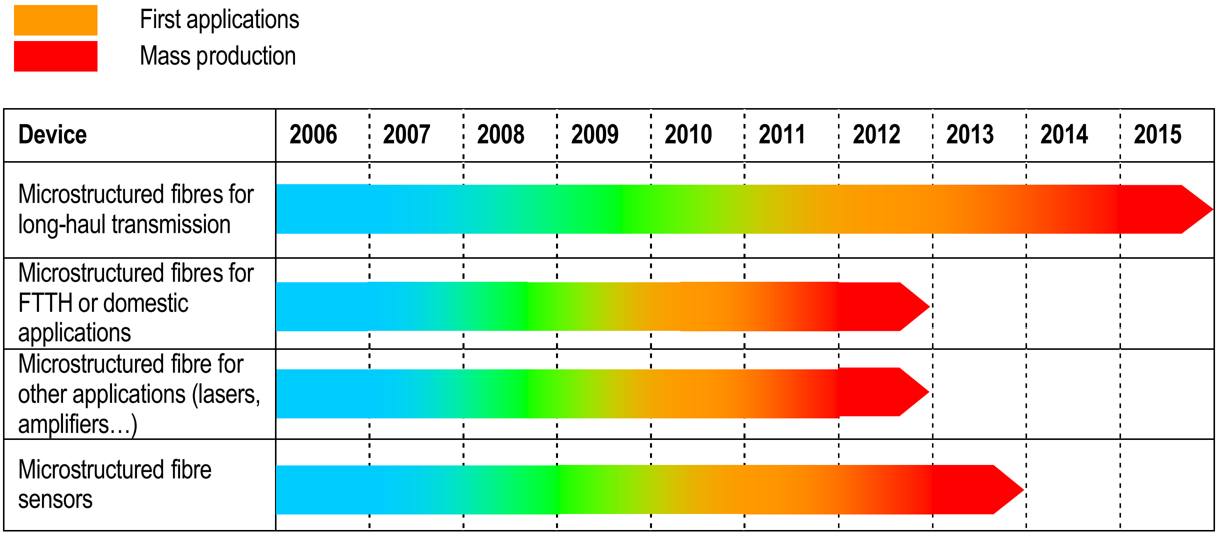
High index contrast nanostructures in III-V

Basic R&D
Applied R&D
First applications
Mass production

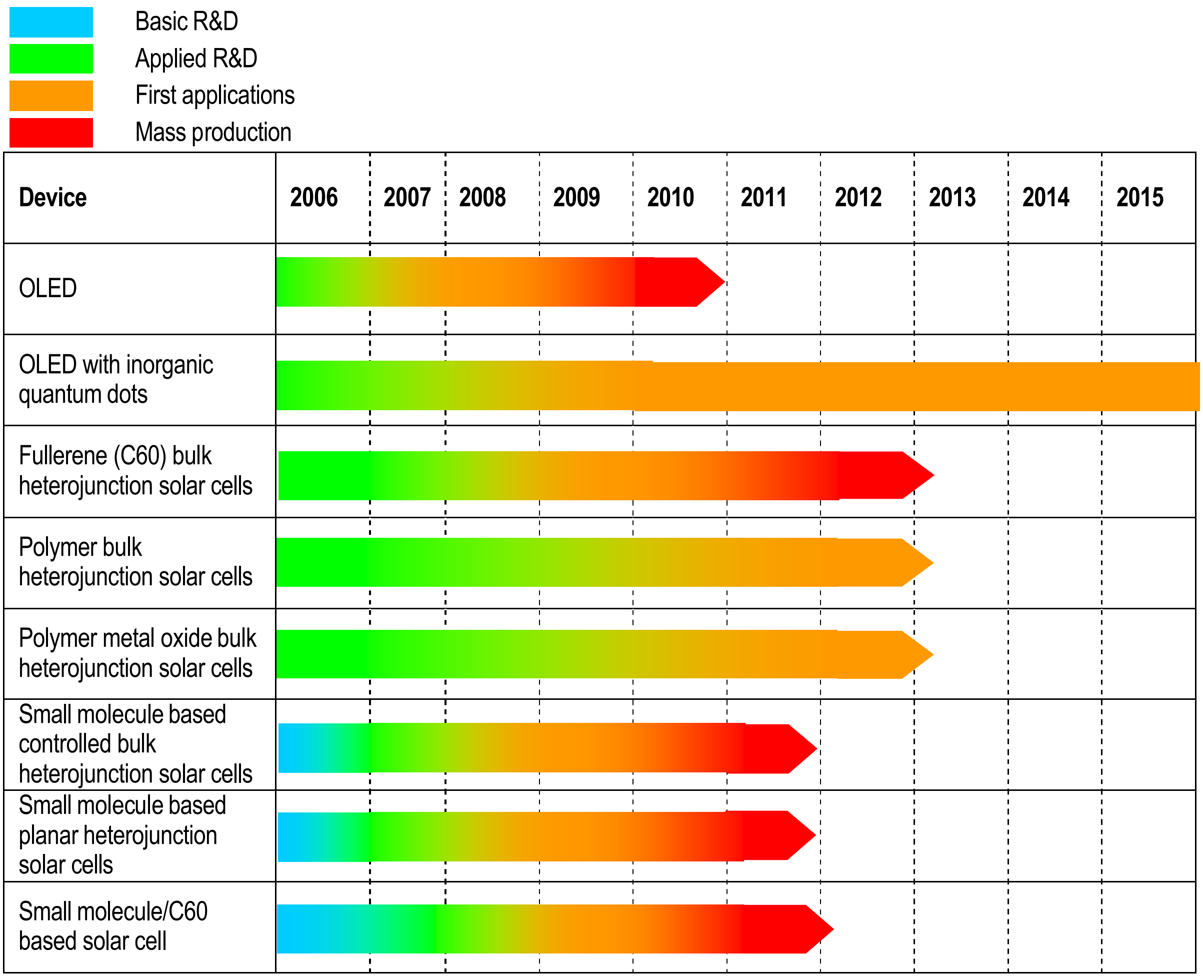
Device	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Laser sources (chip-to-chip)										
Passive photonic integrated circuits										
1D photonic crystal reflector										
2D photonic crystal devices										
White LED (GaN) with photonic crystal structure										
Other LEDs (AlGaInP) with photonic crystal structure										
GaN & AlGaInP LEDs with improved output beam										
PhC cavity laser for sensing										

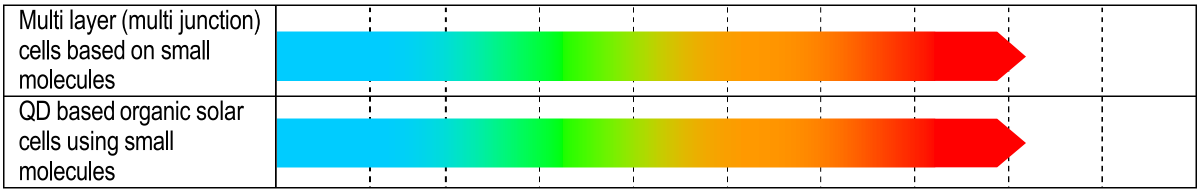
Microstructured fibres

Basic R&D
Applied R&D



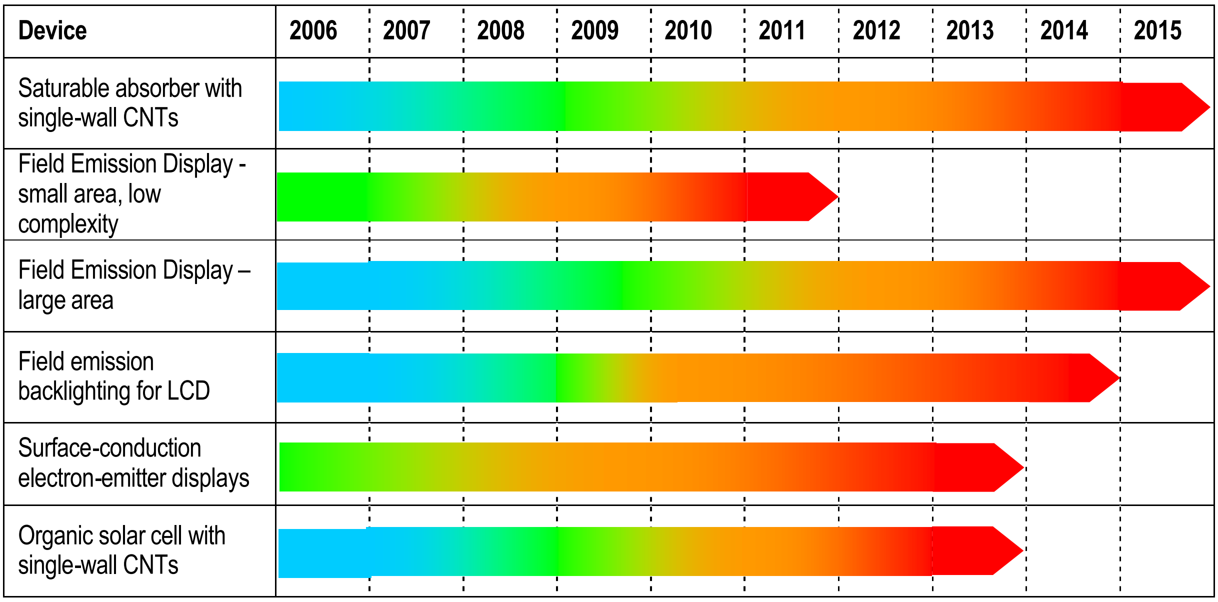
Organic nanostructures





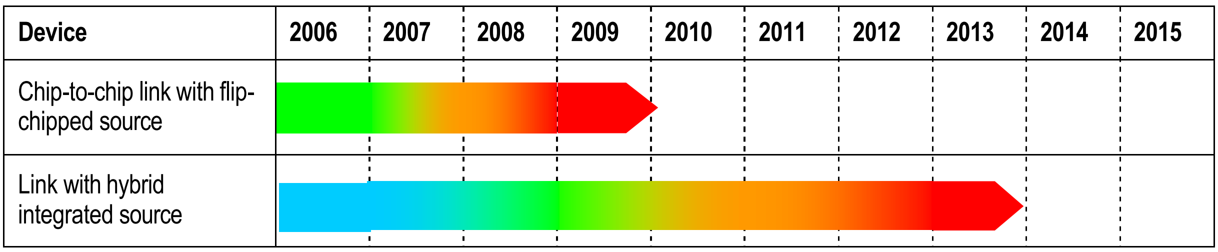
Carbon nanotubes

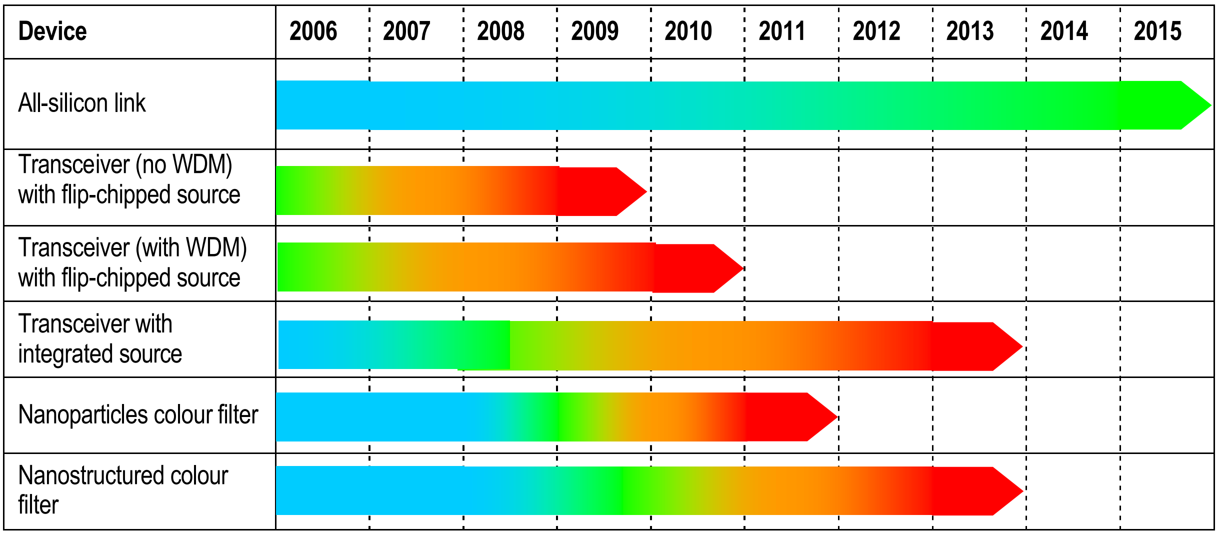
- Basic R&D
- Applied R&D
- First applications
- Mass production



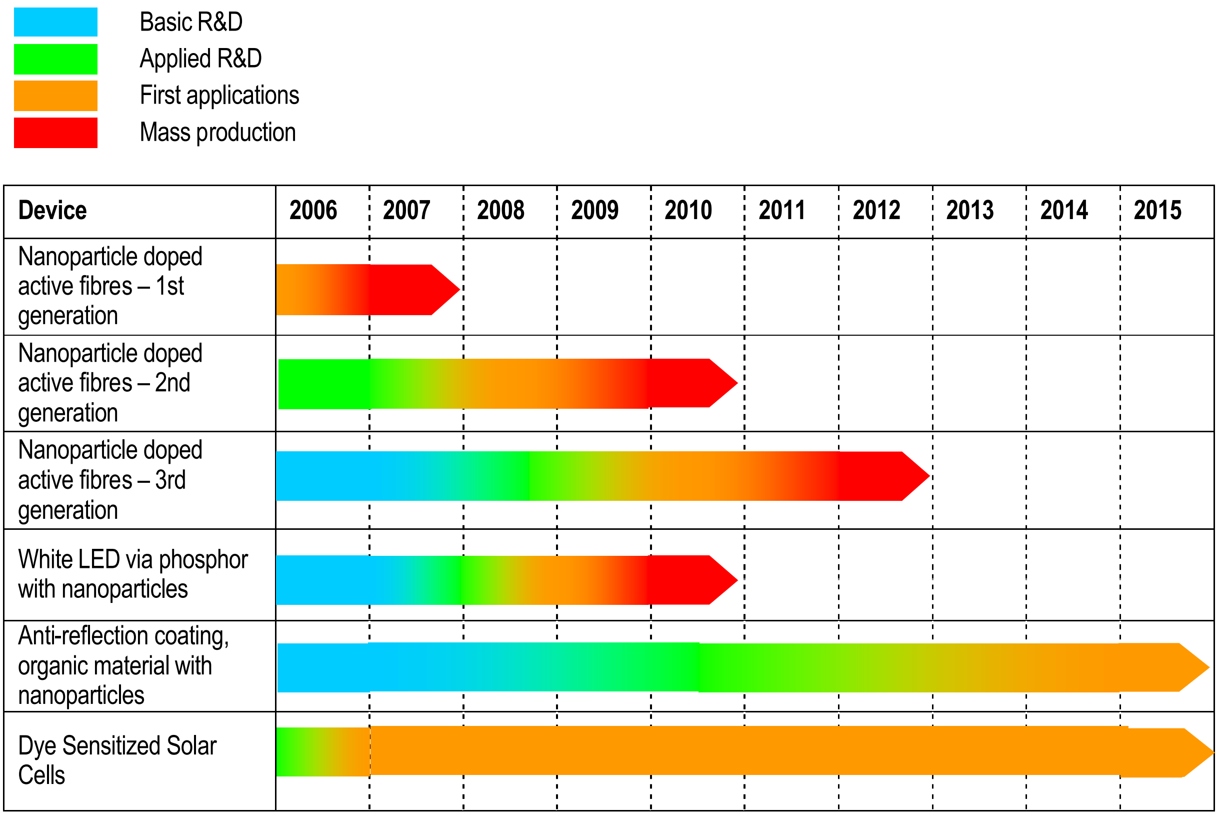
Integration of electronics and photonics

- Basic R&D
- Applied R&D
- First applications
- Mass production

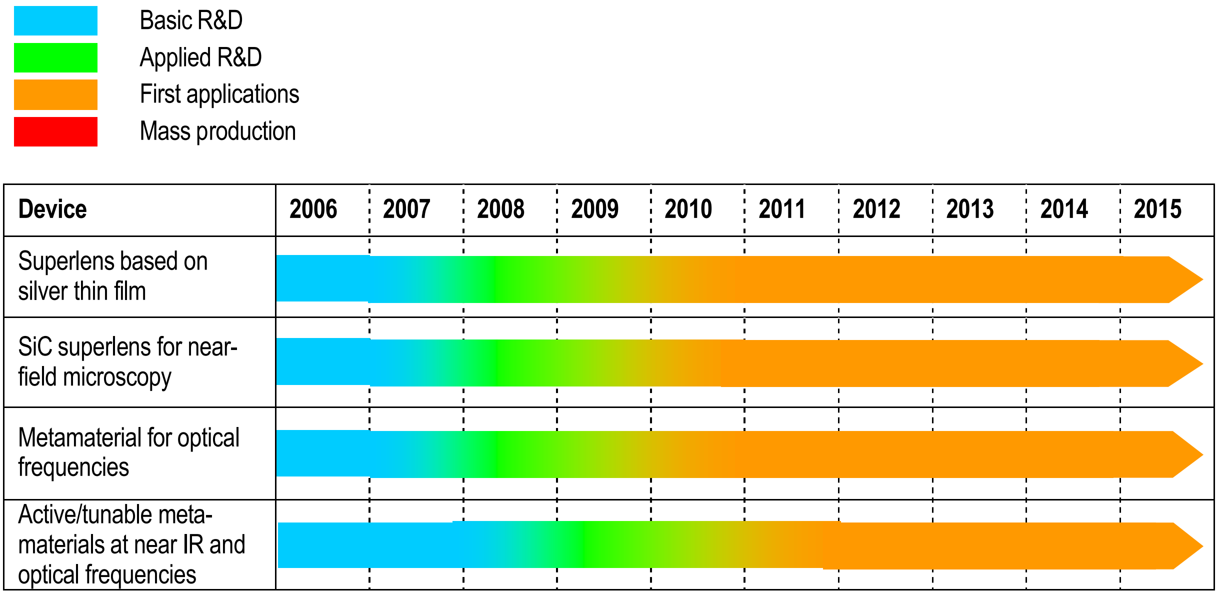




Nanoparticles in glass or polymer



Left-handed meta-materials



Annexes B: 5 to10-year roadmap for equipment and processes

B.1. Introduction

This document summarizes the MONA roadmapping activities with respect to equipment and processes. The information provided herein was collected within the MONA consortium, by studying external sources, through expert interviews and, most important, within the two workshops in Strasbourg and Grenoble.

Equipment and processes are closely linked with the performance of nanophotonic devices, and much of the progress in nanophotonics is enabled by new developments in the equipment sector. Furthermore, novel nanophotonic concepts will stimulate new equipment and process developments. Thus the three segments of the MONA roadmap, which are also revealed by separate workpackages, strongly interact. Because of this, the three deliverables 4.2, 2.1 and 3.1 have many commonalities.

This document consists of three parts. The first part extracts all equipment and process related information from the roadmapping discussions, the two workshops and the roadmap templates that were used as a basis for the collection of information. It is grouped by equipment categories and then subdivided into nanomaterials/applications sections, thus providing the full information related to equipment. Additionally, it contains information about the maturity stage of all equipment/process/nanomaterial/applications combinations. This part of the document is closely linked with the deliverables 4.2 and 2.1, and part of the information will appear in the other documents as well.

The second part focuses completely on equipment and processes. It summarizes the maturity of equipment and processes independent of the maturity of nanophotonic applications. An analysis of the impact that certain equipment may have on the nanophotonic application is given as well as a quantification of the potential of an equipment or process to reach the mass production stage for a certain nanophotonic application. Furthermore, the effort that is required to reach the desired maturity level for nanophotonic applications is quantified. As a conclusion, a first attempt is made to give some recommendations from a European perspective. These recommendations reflect statements made by various experts during the roadmapping process.

The annex shows in a more condensed way the development of equipment and applications versus time. In a graphical format, it extracts all information from the first part that is related to the progress of the technologies in the future. It shows how closely the progress in equipment and processes is related to the progress on nanophotonic concepts and applications.

B.2. Equipment and process analysis

In the first part of the document, all “top-down” and “bottom-up” types of equipment and processes are considered. All equipment is analyzed with respect to the different materials and applications, in a way that the current technological status is described (“state of the art”) as well as the targeted performance (“target”). The actual status of the equipment, its forecast status in 2012, and its entry into mass production are listed. It is important to note that the technological status and the maturity of the equipment or process are analyzed with respect to the *nanophotonic application*. Most of the equipment and processes are well established for non-nanophotonic device manufacturing; thus, the roadmaps always refer to the defined manufacturing of nanophotonic devices. This is the case for equipment types like MBE, MOCVD, dry etching etc. However, there are also specific types of equipment that have not played any role in conventional photonics as they are designed for nanostructure purposes. A typical example is the nanoimprint technology.

Initial data were collected in the course of the project by literature studies, expert interviews, workshops and comments. These data were compiled for each nanomaterial/application combination using the roadmap templates. As they included detailed information about equipment and processes, this information was then used to perform the analysis presented in this section.

After the first analysis of collected information, it turned out that two equipment types were by far the most relevant ones with the highest impact on the performance of nanophotonic devices. These were the deposition techniques MBE and MOCVD. As a consequence of this, these two technologies were additionally analyzed, including separate expert consultations and sessions during the workshops.

In order to generate tangible development targets for the equipment and processes required in nanophotonic applications, for the majority of equipment types a table is presented that reveals the current performance vs. the targeted performance of the equipment. The target performance is defined, as the performance that is assumed required for using the equipment in a volume production process.

B.3. Bottom-up technologies

Bottom-up technologies are those that deposit any material actively in order to form nanostructures. In the simplest case, such technologies just form a thin film, which requires later top-down nanostructuring techniques. However, the more sophisticated ones include ways to form the nanostructure directly.

The bottom-up technologies were extracted from all sub-roadmaps focusing on specific nanomaterials for specific applications. Furthermore, the bottom-up technologies were also examined independent from particular applications. Many of the technologies already exist as non-nano technologies. However, it was found that specific requirements have to be met in order to produce nanostructures.

The technologies discussed are the following:

MOCVD (Metalorganic chemical vapour deposition)

MBE (Molecular beam epitaxy)

Other CVD processes:

- Carbon nanotube CVD,
- SiO_x CVD
- Si nanowire CVD
- HVPE (hydride vapour phase epitaxy)

Miscellaneous processes:

- Direct nanoparticle deposition
- Colloidal chemical synthesis
- Laser ablation
- Nanophosphor fabrication
- Sol-gel synthesis
- Pyrolysis
- TiO_2 nanoparticle formation
- Electrodeposition
- Vapour phase deposition of ZnO
- Spin coating
- Ink jet printing
- OVPD (Organic vapour phase deposition)
- PECVD
- Pulsed laser ablation

Most of the technologies have been described in the document “Frame of Reference” (Deliverable 1.1). Thus, only a brief introduction will be given for each technology. Only if required, some more detailed information will be provided.

B.4. MOCVD

General

MOCVD exists as a mass production technology for the manufacturing of III-V compounds for a long time. Production of high brightness LEDs, lasers, detectors and many other photonic devices use this technology. Both R&D-type equipment as well as production equipment is available. High throughput MOCVD reactors can simultaneously grow on up to 49 x 2” wafers, and wafer sizes range from 2” to 6” (in case of Si substrates even up to 300 mm). Besides III-V compounds, II-VI alloys, oxide-based materials or pure metals are also deposited.

Nanophotonic applications

For nanophotonic applications there are many different ways to employ MOCVD. The simplest approach is to deposit very thin layers that undergo nanostructuring later on. Besides this, many true nano approaches are used. A lot of work has been done on self-organized nano structure growth (e.g. Stranski-Krastanow growth mode), where a proper adjustment of growth parameters leads to the formation of three-dimensional nanostructures without any further definition of lateral structures. Another way to produce nanostructures is catalyst induced growth, where very small droplets of metals catalyze a growth reaction that usually leads to the formation of nanorods or nanowires. Finally, there is a huge number of processes that are based on the MOCVD growth on pre-structured substrates. In this case, masks with openings that are defined by lithography are used to grow laterally confined structures.

Looking at the detailed analysis, MOCVD is a deposition technology that is widely used for nanophotonic applications and devices. As the technology is commonly available, a lot of initial R&D is performed. Without or only with small modification of the equipment, nanophotonic approaches are realized. However, there are improvements required in order to implement the MOCVD technology for nanophotonic applications. For self-assembled growth, a better control of the deposition regarding size, density and distribution of quantum structures is desired. Nearly all processes need improved temperature control, as many of the nano processes are more sensitive to temperature effects than the standard processes. This will require the use of sophisticated in situ metrology giving information about growth conditions during the growth.

The maturity status of MOCVD for nanophotonic applications today is high. For many nanophotonic concepts (self assembled QDs) it is suited for mass production. Other nanomaterials like ZnO or GaN nanorods will require more development work.

Nanomaterial/Application	Performance	Current Status	2012 Status	Mass Production
Self-organized III-V quantum dots for telecom applications	**State of the art:** MOCVD allows using self-assembled growth mechanisms, such as the Stranski-Krastanow growth mode. Various devices based on QD concepts have been demonstrated and in many cases brought to commercial maturity. **Target:** Control and uniformity of QD location and size should be improved. A better control of active species is required to achieve this. Optimized or novel in situ monitoring methods have to be developed allowing more controlled growth of QDs. Temperature control down to 1 K is required	First applications	Mass Production	2008
Self-organized III-V quantum dots for infrared detector applications	**State of the art:** MOCVD allows using self-assembled growth mechanisms for detector applications. Quantum dot infrared photodetectors are successfully produced by MOCVD. **Target:** Control and uniformity of QD location and size should be improved. A better control of active species is required to achieve this. Optimized or novel in situ monitoring methods have to be developed allowing more controlled growth of QDs. In some cases, purity has to be improved.	Applied R&D	Mass production	2010
III-V quantum dots for solar cell applications	**State of the art:** MOCVD is a well-proven mass production technology for III-V solar cells on very large areas. For conventional cells (i.e. with nanophotonic components), equipment and processes are well controlled. **Target:** Using QDs in III-V solar cells will require much better control of parameters such as temperature that affect QD formation. The ability to manage and control strain will become important and low dislocation densities will be required. These properties must be monitored in situ and adjusted if necessary. Suited in situ tools for this purpose have to be developed.	Applied R&D	Mass production	2011
III-V quantum dots/wires for lighting applications	**State of the art:** MOCVD is the well-established technology for mass production of high brightness LEDs based on GaN and AlGaInP. Highest wafer throughputs (42 wafer/run) and uniformities (1%, 1 nm) are achieved today. However, there are no specific nanophotonic concepts implemented as of today. **Target:** MOCVD processes for lighting (LED) applications involving QDs will require a	Basic R & D	First applications	2012

Nanomaterial/Application	Performance	Current Status	2012 Status	Mass Production
	combination of high throughput, low cost manufacturing and precise control of the low dimensional features. Processes may be optimized separately for low dislocation density buffers and QD/QW based active structures. Yield figures above 90% must be obtained. Suited in situ measurement and control methods thus need to be developed. Concepts like GaN nano-wire or nano-rod based LED may require completely new MOCVD processes. Key issue will be the precise control of such structures.			
III-V quantum dots for data storage applications (lasers and QD memories)	**State of the art:** MOCVD equipment and processes are available for lasers emitting red and blue (405 nm) **Target:** Special equipment and processes for the use of QDs in laser structures. Control of size and distribution of QDs is crucial.	Basic R & D	First Applications	2012
III-V quantum dots for optical interconnects (QD lasers grown on III-V or Si)	**State of the art:** MOCVD processes for QD lasers in III-V substrates are available. **Target:** Better control and higher throughput in production of QD lasers. MOCVD processes for QD lasers on Si need to be developed. Focus must be on buffer layers and other methods to reduce dislocation densities and on control and monitoring.	Basic R & D	First applications	2013
High contrast III-V nanostructures, in plane laser sources for intra-chip interconnects	**State of the art:** Standard MOCVD technology available today for growth on III-Vs **Target:** Processes for growth on Si	Basic R & D	First applications	2013
High contrast III-V nanostructures, in plane laser sources for data storage	**State of the art:** Standard MOCVD technology available today for growth on III-Vs **Target:** Processes for growth on Si	Basic R & D	Applied R & D	2016
II-VI quantum dots/wires for Lighting applications (ZnO)	**State of the art:** Experimental MOCVD equipment and processes for bulk and nanostructured ZnO is available. P-type doping still is the major challenge. **Target:** Large-scale MOCVD equipment and processes for ZnO production is required. Optimization in terms of precursor choice, p-type doping and equipment hardware is required.	Basic R & D	First Applications	2015

Table 1: MOCVD technology for different nanophotonic materials for various applications

Equipment characteristics	Current performance	Target performance
Temperature control	2-3 °C	1°C with feedback
Wafer capacity	42/49x2”, max.7x 6”	300 mm
QD uniformity & distribution (emission wavelength)	Several nm	1 nm
ZnO p-type doping	n.a.	1e17
Run to run reproducibility	2%	1%

Table 2: Performance targets for MOCVD

B.5. MBE

General

MBE is, besides MOCVD, the second big mass production technology for III-V compounds. However, due to its technological limitations, only a few products are commercially manufactured with MBE. These are AlGaAs based high frequency transistors (HEMTs, HBTs) and some type of lasers. Commercial MBE machines have multi 6” capability. For phosphorus containing or nitride based compounds MBE does not play a role in mass production.

The strength of MBE is clearly in R&D and pilot production. MBE allows a fast implementation of novel device concepts, and many new materials or structures were first grown by MBE before they were transferred to an MOCVD process. In the R&D environment, nearly all materials can be grown by MBE.

Nanophotonic applications

Similar to MOCVD, also MBE is used for a variety of nanostructure growth methods. Both self-organized growth and growth on pre-structured substrates is possible. Like MOCVD, MBE is well proven as a technology providing controlled thin layers.

On an R&D scale, MBE is used for many different nanophotonics approaches and devices. It also plays a role in small scale commercial production of quantum dot based lasers. The technology is widely available. For nanophotonic applications, in situ metrology is regarded as a key issue. MBE uses RHEED as such a tool. In the longer term, additional methods for more precise control of size and distribution of quantum structures are required. Thus in situ temperature measurement or control might help to improve the reproducibility.

However, MBE will remain to be limited in terms of mass production capabilities. Only for specific devices, it may be the right production technique. This is because certain materials cannot be grown in a larger scale and that the throughput is limited by maintenance requirements.

The maturity stage of MBE for nanophotonic applications today is on a medium level. For a few applications like QD lasers, it is already used in first applications. It is difficult to predict when its entrance into mass production due to the relatively high cost of producing devices with MBE.

Nanomaterial/Application	Performance	Current Status	2012 Status	Mass Production
Self-organized III-V quantum dots for telecom applications	**State of the art:** MBE allows using self-assembled growth mechanisms, such as the Stranski-Krastanow growth mode. First commercial products based on MBE grown QD structures are available **Target:** Control and uniformity of QD location and size should be improved. A better control of active species is required to achieve this. Optimized in situ monitoring methods have to be developed allowing more controlled growth of QDs.	First applications	Mass Production	2008
Self-organized III-V quantum dots for infrared detector applications	**State of the art:** MBE allows using self-assembled growth mechanisms for detector applications. Material purity is good. Quantum dot infrared photodetectors can be grown by MBE, however they are not commercially produced by MBE. **Target:** Control and uniformity of QD location and size should be improved. If possible, MBE could be implemented as a production technology	Applied R & D	Mass production	2012
III-V quantum dots for solar cell applications	**State of the art:** MBE does not play a role in solar cell manufacturing, but is suited for basic studies of novel cell concepts or solar cell physics. **Target:** MBE may be used for initial studies of QD concepts. Key performance targets are controllability of QD size and distribution.	Applied R & D	Mass production	2011
III-V quantum dots/wires for lighting applications	**State of the art:** MBE is to some extent used in R&D in order to investigate basic physical properties of GaN. In volume production, MBE does not play any role. **Target:** There might be some need to develop specific MBE processes for QD based LED structures. Higher throughput and better control are desirable.	Basic R & D	First applications	??

Nanomaterial/Application	Performance	Current Status	2012 Status	Mass Production
III-V quantum dots for data storage applications (lasers and QD memories)	**State of the art:** MBE is used for R&D purposes **Target:** Better control of quantum dot size and distribution. Implementation of in situ methods for better control.	Basic R & D	First Applications	2012
III-V quantum dots for optical interconnects (QD lasers grown on III-V or Si)	**State of the art:** Standard MBE is available. The key equipment associated with MBE growth is RHEED for accurate growth rate measurement and QD control. First QD lasers on Si are demonstrated. **Target:** MBE is not well suited for volume production. Size dispersion has to be carefully controlled: better uniformity is necessary to fully benefit from the advantages of quantum dots. Temperature and composition homogeneity is critical.	Applied R & D	First applications	2013
High contrast III-V nanostructures, in plane laser sources for intra-chip interconnects	**State of the art:** Standard MBE technology available today for growth on III-Vs **Target:** Processes for growth on Si	Applied R & D	First applications	2013
High contrast III-V nanostructures, in plane laser sources for data storage	**State of the art:** Standard MBE technology available today for growth on III-Vs **Target:** Processes for growth on Si	Basic R & D	Applied R&D	2016

Table 3: MBE technology for different nanophotonic materials for various applications

Equipment characteristics	Current performance	Target performance
Temperature control	up to 5 °C	2°C with feedback
QD uniformity & distribution (emission wavelength)	Several nm	1 nm
Run to run reproducibility	Several %	2 %

Table 4: Performance targets for MBE

B.6. Other CVD processes

General

There is a variety of CVD processes (besides MOCVD) that are used in microelectronics and photonics or that are already in use for nanophotonic applications. This broad field of CVD technologies takes advantage of the fact that gas phase-based processes are usually well controllable and thus are most promising for the production of quantum size structures. It includes well-established CVD processes like PECVD, which only have to be adjusted for nanophotonic applications as well as novel ones like carbon nanotube CVD, which have been designed for a specific nanophotonic material.

Nanophotonic applications

The general maturity of Si CVD is high due to its wide use in the semiconductor industry. For more nano-specific applications like Si nanowire growth, dedicated equipment has to be developed. Thus, this process currently has a low maturity level. CNT CVD exists on a laboratory level, but currently no industrial equipment is available. HVPE exists as a small-scale industrial technology; however, it has to be further developed for large-scale use in nanophotonic applications.

Nanomaterial/Application	Performance	Current Status	2012 Status	Mass Production
Carbon Nanotubes CVD for displays	**State of the art:** CVD for CNT exists as hot filament equipment, plasma assisted or thermal CVD. Deposition area today is a few inch. **Target:** CNT density up to 1e9 cm-2; deposition area up to 40 inch for large displays. Low temperature growth (< 600 °C and lower) is desired for deposition on non-glass substrates.	Applied R&D	First applications	2015
SiOx CVD for Si quantum dots (application: interconnects)	**State of the art:** Use of standard microelectronics equipment and processes. **Target:** No major modification is expected	Basic R & D	First applications	2013
CVD of Si nanowires	**State of the art:** Standard Si tools are available; however, they are not well suited for the type of R&D that is currently done. **Target:** A special cluster tool consisting of metal catalyst deposition and CVD	Basic R & D	Applied R&D	n.a.

Nanomaterial/Application	Performance	Current Status	2012 Status	Mass Production
	is required. There must be a chance to integrate new techniques into this environment without breaking the vacuum. The replacement of Au by Al (as a catalyst) will require UHV CDV. The control of the catalyst particles needs to be improved.			
HVPE of III-V quantum dot materials for lighting applications	**State of the art:** Most of the equipment is single wafer equipment on a R&D scale (1x2”). No commercial multi wafer equipment available. Has been demonstrated to grow nano-wires. **Target:** Process control needs to be improved (run to run reproducibility better than 5%; Temperature stability 3°C). Reproducibility of processes and upscaling has to be investigated (target for upscaling: 6x2”). Some limitations in terms of materials (Al-containing materials) need to be solved. In situ measurement methods need to be applied.	Basic R&D	Mass production	2012
CVD of Si QDs for photovoltaics	**State of the art:** Well established technology **Target:** To be adopted for QDs	Basic R&D	First applications	2013

Table 5: Other CVD technologies for different nanophotonic materials for various applications

Equipment characteristics	Current performance	Target performance
Deposition temperature	> 600 °C	< 600 °C
CNT density		1e9 cm^{-2}
Deposition area	Few inch	> 40 inch

Table 6: Performance targets for CNT CVD

Equipment characteristics	Current performance	Target performance
Reactor capacity	1x2“	> 5x2“
Run to run reproducibility	> 5%	< 5%
Temperature stability	Indirectly measured, 5°C?	< 3 °C, feedback

Table 7: Performance targets for HVPE

B.7. Miscellaneous deposition processes

General

This chapter deals with all those processes that deposit material, but are not CVD or MBE processes. As these processes cover a very broad range, there are some additional information provided (column Process details/performance). If possible, development targets are given similar to the previous chapters.

Nanophotonic applications

Like in the previous chapters, there are technologies that have been well established for non-nano applications, which only need to be qualified for nanophotonics, and others that are developed for nanophotonic use exclusively. Some of them are very specific solutions created to meet requirements of nanostructure fabrication. Thus, it is difficult to give some overall judgement of their maturity for nanophotonic applications. However, a detailed description of their individual maturity stage is given in the table.

Equipment/process/application	Process details/performance	Current Status	2012 Status	Mass Production
Direct nanoparticle deposition (DND) for active fibres (telecom application)	**State of the art:** The nanoparticles are manufactured by the reaction of gases, a subsequent condensation to spherical droplets, which after rapid cooling lead to the nanoparticles. The challenges include the thermal and hydro/aerodynamic processing parameter (temperature etc.) distribution. Agglomeration of droplets has to be avoided. In general the issue is to anticipate the nanoparticle characteristics evolution during the thermal treatment <u>The active fibre</u>:Manufactured with the active ions introduced within a nanoparticle matrix, e.g. using direct nanoparticle deposition <u>Manufacturing of the fibre pre-form</u>: - outside vapour/aerosol deposition on an alumina mandrel **Target:** The challenge is to control the nanoparticles properties throughout the process of introducing them into the glass fibre. This is particularly an issue for DND. Outside deposition methods are very difficult to control (gas or aerosol flow, pressure, temperature). They imply the removal	First applications	Mass Production	2008

Equipment/process/application	Process details/performance	Current Status	2012 Status	Mass Production
	of a mandrel at the end of the process. Because of this, inside deposition processes are preferred for fibre pre-form fabrication by some manufacturers.			
Colloidal chemistry for nanostructure based optical interconnects, data/telecom, sensors	**State of the art:** Many different approaches; sub-nm size achieved. **Target:** Control of position of particles. Control of 3D particle shape.	?	?	?
Drawing kit for microstructured fibres	**Target**: Well controlled process, no impurities.	Basic R&D	First applications	2015
CNT fabrication by laser ablation (telecom application)	**Target:** Introduction as production process, control	Basic R&D	First applications	2015
Fabrication of nanophosphors for lighting (LED) applications	**State of the art:** Basic processes exist: Spray or slurry deposition of milled phosphor particles with binder; Embedding of phosphor particles in an inorganic matrix **Target:** Dedicated equipment and processes need to be developed	Basic R&D	Mass production	2010
Sol-gel synthesis for nanoparticles in polymers (display applications)	**State of the art**: Well understood process **Target:** Implementation for mass production	Basic R&D	Applied R&D	2015
Colloidal chemistry for II-VI nanoparticles (lighting)	**State of the art:** The technology is broadly used for the fabrication of quasi-spherical and rod-like particles. The particles are produced by precipitation reactions from metallic and not-metallic brought to reaction within organic solvents. Size dispersion is about a few percents **Target:** Elimination of hazardous materials. Alternative solutions, e.g. with aqueous solvents. Fabrication of large quantities.	Basic R&D	Mass production	2010
Colloidal chemistry for II-VI nanoparticles (display)	**State of the art:** See above **Target:** See above	Applied R&D	Mass production	2009
Colloidal chemistry for II-VI nanoparticles (photovoltaic)	**State of the art:** See above **Target:** See above	Basic R&D	Mass production	2012

Equipment/process/application	Process details/performance	Current Status	2012 Status	Mass Production
Pyrolysis process for II-VI quantum dots in flat panel displays	**State of the art:** The QDs are prepared by pyrolysis of organometallic compounds and then dispersed in a TPD matrix. Both are dispersed in a suitable solvent and then spin-coated on a transparent substrate **Target:** n.a.	Basic R&D	Applied R&D	2015
TiO2 nanoparticle production for solar cells	**State of the art:** Standard process **Target:** n.a.	n.a.	n.a.	n.a.
Electrodeposition of ZnO for Lighting applications (LEDs)	**State of the art:** R&D process exists; the principle is a galvanostatic cathodic deposition on an Au/Si substrate. Zn sheets act as the anode and the electrolyte is zinc nitrate aqueous solution. Deposition temperature is 355 K **Target:** Main challenges are controlled doping and to achieve the desired orientation of the wire.	Basic R&D	Applied R&D	>2015
Vapour phase deposition of ZnO (Zn evapouration under O2)	**State of the art:** Existing process **Target:** Doping (p-type)	Basic R&D	Applied R&D	> 2015
Colloidal synthesis of II-VI nanoparticles for sensors	**State of the art:** Wet chemical process are mainly used (multiple steps required for core-shell-systems), with standard equipment. The particles are produced by precipitation reactions from metallic and not metallic brought to reaction within organic solvents. Size dispersion is about a few percents. **Target:** Assurance of particle homogeneity Proper surface functionalization Hazardous materials are used (e.g. phosphine or organic solvents as toluene, hexane, heptane or chloroform). Alternative solutions using for example aqueous solvents are under development	First applications	Mass production	2009
Spin coating of polymers for organic solar cells	**State of the art:** Standard equipment of thin layers deposition by wet process. During the annealing step, demiction between the polymer and fullerenes nanocrystals occurs. **Target:** No particular ones.	n.a.	n.a.	n.a.

Equipment/process/application	Process details/performance	Current Status	2012 Status	Mass Production
Ink jet printing of organic semiconductors for displays	**State of the art:** Established technology Only used for polymers **Target:** Better control	First applications	Mass production	2010
Organic vapour phase deposition of small molecule based organic semiconductors for photovoltaics and lighting	**State of the art:** Process is understood and controlled for small scale. OVPD can be better controlled than evapouration (upscaling may be easier, better precision for thin layers). **Target:** Upscaling, larger scale process and production of very thin layers.	Applied R&D	First applications	2015
Dielectric deposition for photonic crystal reflector devices	**State of the art:** PECVD and related equipment is suited **Target:** n.a.	n.a.	n.a.	n.a.
Pulsed laser deposition and RF co-sputtering for Si nanocrystal optical sensors	**State of the art:** Well developed equipment **Target:** n.a.	n.a.	n.a.	n.a.

Table 8: Miscellaneous deposition technologies for different nanophotonic materials for various applications

B.8. Top-down technologies

Top-down technologies are those that define a nanostructure without actively depositing a material. This means that usually a thin film that has been deposited before is laterally structured.

The approach chosen to analyze the top-down technologies is equivalent to the bottom-up segment. The technologies were extracted from all sub-roadmaps focusing on specific nanomaterials for specific applications. Furthermore, they were also examined independent from particular applications. Many of the technologies already exist as non-nano technologies. However, it was found that specific requirements have to be met in order to produce nanostructures.

The technologies discussed are the following:

Lithography:

- Optical lithography
- Deep UV
- EUV
- X-ray lithography
- Electron beam lithography
- Nanoimprint lithography
- Focused ion beam lithography

Etching

Most of the technologies have been described in the document “Frame of Reference” (Deliverable 1.1). Thus, only a brief introduction will be given for each technology. Only if required, some more detailed information will be provided.

B.9. Photolithography including deep UV and EUV

General

Photolithography is one of the most developed technologies as it is a standard in any semiconductor process. Mass production processes are available for standard feature sizes.

Nanophotonic applications

Specific nanophotonic applications however will require much smaller structures than usually defined in standard CMOS processes. Small features will require EUV, which means that special light sources and optics have to be used. The main challenges are precision and accuracy improvement, upscaling to a mass production level and the reduction of the related manufacturing cost.

The maturity level of photolithography and its progress is completely defined by the mainstream semiconductor industry. Compared to that, nanophotonic applications are still very small in volume, which means they cannot stimulate the development of equipment. In terms of industrial use of photolithography its maturity is of course very high.

Nanomaterial/Application	Performance	Current Status	2012 Status	Mass Production
Plasmonics/metallic nanostructures for optical interconnects, data/telecom, sensors	**State of the art:** proven technology for semiconductors, cost efficient technology **Target:** Adoption for metallic structures. A combination of very high resolution (nm scale) and cost efficient production is required. High throughput and reproducibility	Basic R & D	n.a.	n.a.
Integration of nanophotonic materials with electronic ICs for datacom/telecom: transceivers	**State of the art:** The technology is well suited for large area processes. **Target:** The extreme cost of equipment is the main challenge, as this technology is quite complex (lens systems, UV source). Furthermore, there is a need to increase the accuracy and reproducibility for nanophotonic devices	First applications	Mass production	2009
High index contrast nanostructures in silicon/III-V for datacom/telecom	**State of the art:** The technology is well suited for large area processes. **Target:** The extreme cost of equipment is the main challenge, as this technology is	First applications	Mass production	2010

Nanomaterial/Application	Performance	Current Status	2012 Status	Mass Production
	quite complex (lens systems, UV source). Furthermore, there is a need to increase the accuracy and reproducibility for nanophotonic devices.			
High index contrast nanostructures in silicon/III-V for sensors	**State of the art:** See above **Target:** See above	Basic R&D	First applications	2013
Plasmonic/metallic nanostructures for lighting applications	**State of the art:** Well established technology **Targets:** Improve reliability, scaling up to mass production level	Applied R&D	Mass production	2011
III-V quantum dots for telecom/datacom	**State of the art:** On a laboratory scale, lithography for site-controlled QDs is available. **Target:** Mainly reproducibility and cost improvement	Applied R&D	First applications	2013
Photonic crystals in III-V for Datacom/Telecom	**State of the art:** Patterns are obtained through a variety of techniques including conventional optical lithography and e-beam, with an inorganic transfer layer used as mask for the semiconductor etching. **Target:** Improve efficiency of the process	First applications	Mass production	2010

Table 9: Photolithography / UV technologies for different nanophotonic materials for various applications

Equipment characteristics	**Current performance**	**Target performance**
Structure size	65 nm	< 45 nm
Litho wavelength	193 nm	13.5 nm (EUV)

Table 10: Performance targets for photolithography

B.10. X-ray lithography

General / Nanophotonic applications

X-ray lithography has proven to have the capability to define smallest structures. However, as there are severe limitations with respect to throughput and cost, it is doubtful whether this technology will ever be implemented in mass production. This is also reflected by the fact that most of the sub-roadmaps for different applications and nanomaterials do not consider x-ray lithography as a significant technology.

The technological and industrial maturity is difficult to be judged as the technology development is driven by the mainstream semiconductor industry and not by nanophotonics.

Nanomaterial/Application	Performance	Current Status	2012 Status	Mass Production
Plasmonics/metallic nanostructures for optical interconnects	**State of the art:** High resolution method. **Target:** Scalability, reduction of investment cost	Basic R&D	n.a.	n.a.

Table 11: X-ray lithography for nanophotonic materials

B.11. Electron beam lithography

General

E-beam lithography in its various variations (see frame of reference) must be regarded as a proven technology, which is commercially available.

Nanophotonic applications

Besides using e-beam lithography for mask fabrication, its real strength is in direct writing of smallest structures. Numerous tools are used for the fabrication of nanostructures. However, its use is limited to R&D purposes so far. The main challenge is to apply this technology for larger structures, large substrate areas and high substrate throughput. At the same time the overall cost of using such equipment has to be dramatically reduced.

The technology has a high technological maturity. However, progress has to be made to implement it as a mass manufacturing technology.

Nanomaterial/Application	Performance	Current Status	2012 Status	Mass Production
High index contrast nanostructures in silicon/III-V for datacom/telecom	**State of the art:** This serial technique is slow but accurate, and therefore suitable for research purposes. However, it is also applied for the production of masks and templates for other lithography techniques. **Target:** The slowness is the limiting factor, so parallel processing is desirable. Furthermore, care is needed for larger devices (>200x200μm²) because of stitching errors	Applied R&D	First applications	2015
High index contrast nanostructures in silicon/III-V for sensors	**State of the art:** See above **Target:** See above	Basic R&D	First applications	2013
III-V quantum dots for telecom/datacom	**State of the art:** On a laboratory scale, EBL for site-controlled QDs is available. **Target:** Throughput improvement and cost reduction will be required	Applied R&D	First applications	2012
Left-handed meta-materials for Instrumentation/metrology (meta-materials for optical frequencies)	**State of the art:** Well established technology **Target:** Improve reproducibility	Basic R&D	Mass production	> 2015
Photonic crystals in III-V for Datacom/Telecom	**State of the art:** Processes for pattern definition exist. **Target:** Improve efficiency	First applications	Mass production	2010
Photonic crystals in III-V for lighting	**State of the art:** Equipment is available meeting the requirements in terms of resolution, however with very low throughput. **Target:** The challenge in this application is the photonic pattern writing speed: to ensure the high-volume manufacturing capability requested for low-cost, a lithography technique with high throughput is mandatory.	Applied R&D	Mass production	2010

Table 12: E-beam lithography technology for different nanophotonic materials for various applications

B.12. Nanoimprint lithography

General/Nanophotonic applications

Nanoimprint is a new technology that promises to combine high resolution (nm feature size) with low running cost. It is definitely targeting at nano applications. Nanoimprint might be the only cost efficient method for nanostructuring in the future; however, the final proof of its capabilities is still not achieved.

The maturity level of this technology is still low, as it is not yet used in production. Interestingly enough, however, this technology was regarded as a most promising one for photonic crystal fabrication and other nanostructures as it has the potential to overcome the cost and throughput limitations related to e-beam and x-ray lithography.

Nanomaterial/Application	Performance	Current Status	2012 Status	Mass Production
Plasmonics/metallic nanostructures for optical interconnects	**State of the art:** Pre-production processes available **Target:** Low cost, high-resolution process for mass applications. Improve reproducibility and reduce feature size.	Basic R&D	n.a.	n.a.
High index contrast nanostructures in silicon/III-V for datacom/telecom	**State of the art:** A relatively new technology, which can lead to high-resolution, high-throughput and low-cost fabrication of nano-devices. This straightforward process does not need complex optics or sources, so it is even suitable for low to medium production volumes. **Target:** The technology needs to mature in order to reach its potential of high-resolution reproducibility. The production of the template is an issue	Applied R&D	First applications	2015
High index contrast nanostructures in silicon/III-V for sensors	**State of the art:** See above **Target:** See above	Applied R&D	First applications	2013
Photonic crystals in III-V for Datacom/Telecom	**State of the art:** Basic processes are available. **Target:** Implement nanoimprint as a cost efficient alternative to conventional lithography	Basic R&D	First applications	2013
Photonic crystals in III-V for lighting	**State of the art:** The concept is demonstrated; however, there is no proof of production type equipment and process. **Target:** Throughput must meet the demand of high volume LED production. Reproducibility and precision, at the same time, must be as good as e-beam lithography.	Applied R&D	Mass production	2010

Table 13: Nanoimprint technology for different nanophotonic materials for various applications

Equipment characteristics	Current performance	Target performance
Feature size	50 nm	20 nm
Throughput	25 wafers/h @ 4”	> 25 wafers/h
Max. wafer size	300 mm	450 mm

Table 14: Performance targets for nanoimprint lithography

B.13. Focused ion beam lithography

General/Nanophotonic applications

Focused ion beam lithography has a potential similar to electron beam lithography, but might have advantages in reduction of proximity effects and undesired scattering. Potentially many different applications are feasible; however, within the MONA roadmapping process only one example was examined.

Nanomaterial/Application	Performance	Current Status	Status 2012	Mass Production
Left-handed meta-materials for Instrumentation/metrology (meta-materials for optical frequencies)	**State of the art:** Well established technology **Target:** Improve reproducibility	Basic R&D	Mass production	2012

Table 15: FIB technology

B.14. (Dry) Etching

General

There is a variety of well-developed etching processes available. These processes cover all relevant materials. Nearly all photonic devices use such etching processes. The most prominent types of dry etch processes are reactive ion etching (RIE), ion beam or reactive ion beam etching and chemically assisted ion beam etching. As these technologies are quite mature, the table below will not distinguish between these subtypes and focus more on general issues.

Nanophotonic applications

As all dry etching process are based on reactions between single atoms or molecules and the material to be etched, there is no principal difference between standard etching processes and those for nano applications. However, roughening effects become more relevant as the size of the structures is very small compared to the surface roughness.

Generally, dry etching is a very mature technology. Developments have to be made more on the process side than on the hardware side.

Nanomaterial/Application	Performance	Current Status	Status 2012	Mass Production
High index contrast nanostructures in silicon/III-V for datacom/telecom	**State of the art:** Well established technology. Aspect ratio 10 to 20 is feasible. **Target:** To obtain high-quality nanophotonic devices, it is imperative to develop processes that diminish the roughness of vertical walls and horizontal surfaces.	Applied R&D	Mass production	2010
High index contrast nanostructures in silicon/III-V for sensors	**State of the art:** See above **Target:** See above	Basic R&D	First applications	2014
Photonic crystals in III-V for Datacom/Telecom	**State of the art:** Homogeneity is good. Process is well established. Aspect ratio 10 to 20 is feasible. **Target:** The challenge for the process and equipment is mainly to allow etching vertical-walled holes deeper in the III-V structure. Process with vertical walls with minimum roughness (< 2 nm). Process without "lag" effect that leads to different depth depending on the hole diameter.	First applications	First applications	2010
Photonic crystals in III-V for lighting	**State of the art:** Dry etching is the commonly used method to define the PC structure. **Target:** A peculiar characteristic of GaN-based alloys is their low dry-etching speed, which call for some new process developments. ICP-type of etching technique appears the choice one.	Applied R&D	Mass production	2010

Table 16: Etching technologies for different nanophotonic materials for various applications

Equipment characteristics	Current performance	Target performance
Sidewall roughness	>2 nm, depending on material	2 nm
Aspect ratio	10 – 20	> 20

Table 17: Performance targets for etching processes

B.15. Summary and analysis

This section gives a condensed summary of the equipment types, its maturity stage in general and the importance of the equipment and process for the development of nanophotonics. Furthermore, it also lists the expected potential of the equipment types for mass production. The data have been extracted from the materials, applications and equipment sub-roadmaps.

Equipment/process	General technical maturity 2007	Technical Maturity for nanophotonic applications 2007	Effort required to come to maturity	Technical impact on performance of nano-photonic devices	Potential for mass production
MOCVD	++	+	+	++	++
MBE	+	+	++	++	o
Carbon nanotube CVD	o	+	o	++	+
SiOx CVD	++	+	o	+	+
Si nanowire CVD	o	o	++	++	o
HVPE	o	o	+	+	+
Direct nanoparticle deposition	+	+	o	+	+
Colloidal chemical synthesis	+	+	+	++	++
Laser ablation	+	+	o	+	+
Nanophosphor fabrication	+	+	o	++	++
Sol-gel synthesis	+	+	o	+	++
Pyrolysis	+	o	o	+	+
TiO2 nanoparticle formation	+	+	o	+	+
Electrodeposition	o	o	o	+	o
Vapour phase deposition of ZnO	o	o	o	o	o
Spin coating	+	-	+	-	+
Ink jet printing	+	-	+	-	+
OVPD	+	o	+	+	++
PECVD	++	+	o	o	++
Pulsed laser ablation	+	+	o	+	+
Deep UV/EUV	o	+	+	++	+
X-ray lithography	o	++	+	++	o
Electron beam lithography	+	++	+	++	o
Nanoimprint lithography	-	++	++	++	++
Focused ion beam lithography	o	+	+	++	o
Etching	++	+	o	+	++

Table 18: Equipment maturity and potential for mass production

A ranking of the equipment and process technologies is difficult. However, Table 11 allows extracting those technologies that have the highest potential technical impact on nanophotonics and at the same time have a potential for mass production. Using these criteria, the most relevant ones are MOCVD, CNT CVD, colloidal synthesis, nanophosphor fabrication, sol-gel synthesis, OVPD, UV lithography, nanoimprint and etching. The effort that is required to bring these technologies to the desired maturity is different for the technologies; for better understanding, it is also presented in the table. These efforts refer to the applications analyzed and thus may be different for other applications.

Combining the two criteria: “technical impact on performance of nanophotonic devices” and “potential for mass production” (e.g. by multiplying the representative values) yields a figure that shows the overall potential of a process or equipment type. In fig. 19 and 20, this value vs. the effort required to bring this equipment/process to maturity is shown.

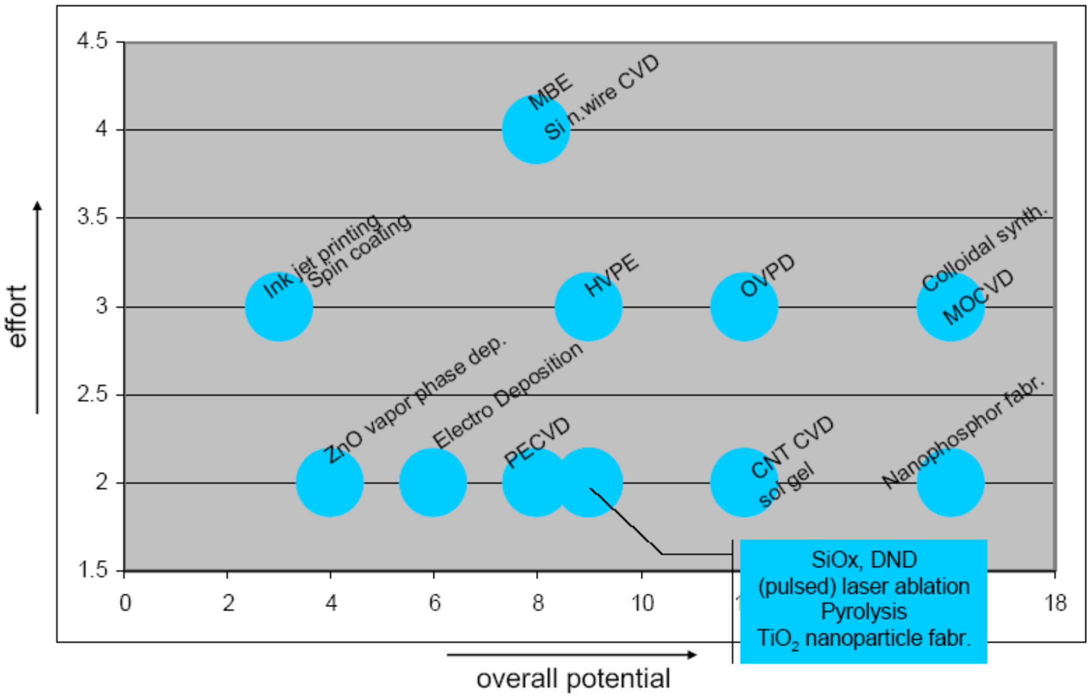


Fig. 1: Overall potential (expected “reward”) of equipment types for nanophotonic applications and effort required to bring this equipment to maturity for all bottom-up technologies

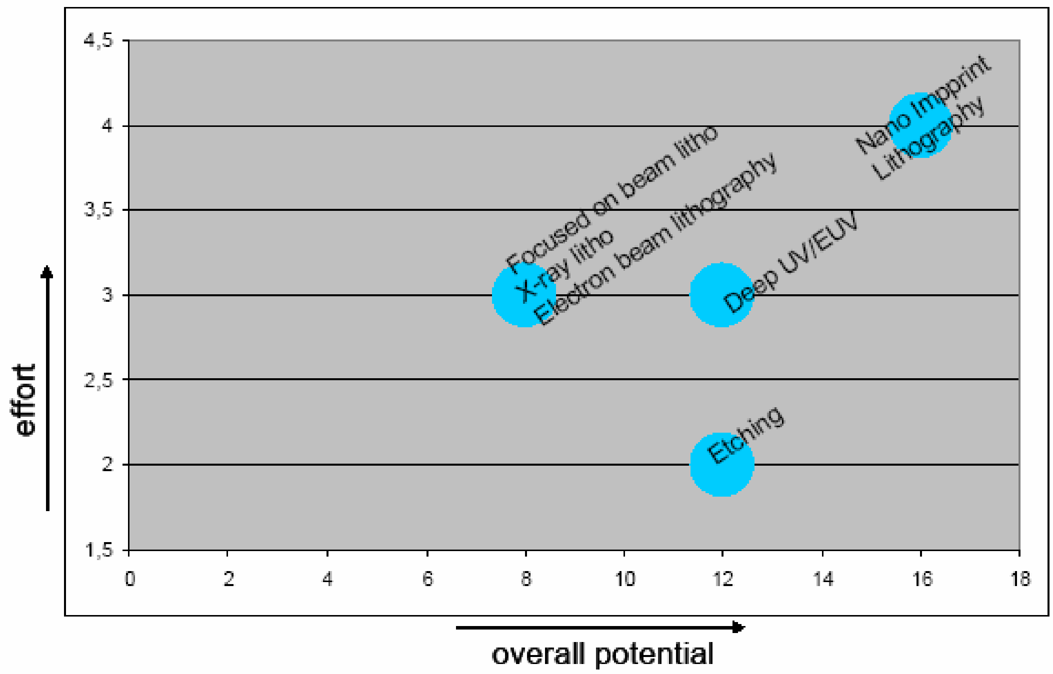


Fig. 2: Overall potential (expected "reward") of equipment types for nanophotonic applications and effort required to bring this equipment to maturity for all top-down technologies

As these two graphs show the expected "reward" vs. the effort that has to be put into the technologies, it is simple to prioritize the required developments.

For the bottom-up technologies, the highest priorities should be given to:

OVPD
CNT deposition
Sol-gel technology
Colloidal synthesis
MOCVD
Nanophosphor fabrication

For top-down technologies, the highest priority thus should be on

UV lithography
Etching processes
NIL

Another important point was to analyze which equipment/processes are relevant for a broader field of applications and which are only mentioned for one or two specific applications. This analysis is summarized in the tables below.

	Telecom/ Datacom	Sensors/ detectors	Optical interc.	Lighting	Photo-voltaics	Displays	Instr./ metrology	Data storage
MOCVD	X	X	X	X	X			X
MBE	X	X	X	X	X			X
CNT CVD						X		
SiOx CVD			X					
HVPE				X				
DND	X							
Colloidal chemistry	X	X	X	X	X	X	X	X
Laser ablation CNT	X							
Nanophosphor fabrication				X				
Sol-gel synthesis						X		
II-VI Pyrolysis						X		
TiOs nanoparticles					X			
Electrodep. ZnO				X				
Vapour phase dep. of ZnO				X				
Spin Coating					X			
In jet printing						X		
OVPD				X	X			
Pulsed laser ablation		X						

Table 19: Applications requiring specific bottom-up equipment/processes

	Telecom/ Datacom	Sensors/ detectors	Optical interc.	Lighting	Photo-voltaics	Displays	Instr./ metrology	Data storage
UV Litho	x	x		x				
X-ray litho			x					
E-beam	x			x			x	
Nanoimprint	x		x	x				
FIB							x	
Etching	x			x				

Table 20: Applications requiring specific top-down equipment/processes

Both tables only show those equipment types that have been regarded as important ones when specific nanophotonic applications where discussed. However, the fact that equipment is not mentioned for an application does not mean that is does not play a role there.

The two tables can be used to achieve another ranking with respect to applications. Those equipment and process types with the broadest field of applications are MOCVD, MBE and colloidal chemistry as bottom-up technologies, and UV litho, e-beam and nanoimprint as top-down technologies. However, the latter ranking appears somewhat doubtful as standard techniques like etching are underrepresented.

B.16. First recommendations in the European context

In the previous chapter, some attempts were made to rank the equipment and process types with respect to their maturity, their potential to enter into mass production of nanophotonic devices and the broadness of application fields. All those technologies that have received a high ranking should be considered to be strengthened through increased R&D. The focus of the development, however, is very much different for all these technologies. The most relevant development targets are the improved process control, mass production scale-up, cost reduction and the elimination of undesired effects that may be harmful to nanophotonic device manufacturing.

Although 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, but also for equipment that is required for more exotic processes. On the application side, one of the most important photonic applications – solid-state lighting – is well represented by two world leading manufacturers in Europe. Photovoltaic applications are traditionally also very strong in Europe with an increasing industrial base. Additionally there are strong R&D activities in many nanophotonic fields.

Because of this, a special focus should be set on joint R&D efforts combining resources of equipment manufacturers, process developers, R&D centers and universities and industrial end users. The focus should be on applications that have certain relevance within Europe, using equipment that is manufactured in Europe, which has a high ranking in this analysis.

B.17. Equipment and process roadmaps

General

This section analyzes the development and maturity of equipment and processes for nanophotonic applications as it is today (2007), in five years from now (2012) and in 2015. The information was collected in the roadmapping process within the MONA project and is based on the technology descriptions in the first section of this report. Equipment and processes are sub-divided into categories for better understanding.

For quick reference a colour code is used. It is important to note, however, that the colour code reflects more the maturity if the device/application manufactured by this technology and less the maturity of the equipment itself. Thus, the maturity levels have to be understood as follows:

Basic R&D:	The process or equipment is mainly used for basic R&D, even if production capability is already given
Applied R&D:	As above, but with more focus on applied research.
First applications:	The equipment or process is used under production conditions; however, the volume is still low. Still the technological performance of the equipment or the process plays an important role.
Mass production:	Production volumes are high. Technological performance gets less important and economical production considerations are getting more important.

In the following section, all relevant equipment categories will be shown in the described way. If no sufficient information could be extracted for a specific equipment/ nanomaterial/ application combination, this was omitted rather than presenting incomplete data.

	Basic R&D
	Applied R&D
	First applications
	Mass production

Table A1: Colour code for Equipment and process roadmaps

An example for one equipment/process roadmap is given below. In this case, the equipment would be expected to be used for basic R&D up to 2009, for applied R&D between 2010 and 2011, first applications would be implemented on this tool type between 2012 and 2014 and mass production would be expected in 2015. In cases where different timelines were given for different devices (however using one nanophotonic concept for one application), the *earliest* dates were chosen per equipment type.

		2007	2008	2009	2010	2011	2012	2013	2014	2015
Equipment/process: nanomaterial	Application									

Table A2: Example for an equipment roadmap

		2007	2008	2009	2010	2011	2012	2013	2014	2015
MOCVD general	All applications									
MOCVD: III-V QD/QW self-organized	Telecom									
MOCVD: III-V QD/QW self-organized	IR detectors									
MOCVD: III-V QD/QW self-organized	Solar cells									
MOCVD: III-V QD/QW self-organized	Lighting									
MOCVD: III-V QD/QW self-organized	Data storage									
MOCVD: III-V QD/QW self-organized	Interconnects									
MOCVD: III-V nano processes on Si	Interconnects									
MOCVD: III-V nano processes on Si	Data storage									
MOCVD: ZnO nanostructures	Lighting									

Table A3: MOCVD roadmap

		2007	2008	2009	2010	2011	2012	2013	2014	2015
MBE: general	All applications									
MBE: III-V QD/QW self-organized	Telecom									
MBE: III-V QD/QW self-organized	IR detectors									
MBE: III-V QD/QW self-organized	Solar cells							??	??	??
MBE: III-V QD/QW self-organized	Lighting							??	??	??
MBE: III-V QD/QW self-organized	Data storage									
MBE: III-V QD/QW self-organized	Interconnects									
MBE: III-V nano processes on Si	Interconnects									
MBE: III-V nano processes on Si	Data storage									

Table A4: MBE roadmap

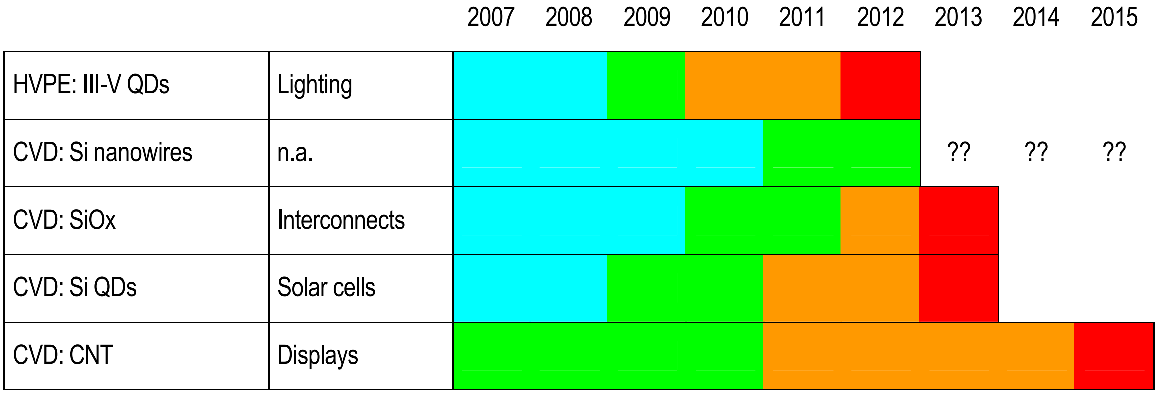


Table A5: Other CVD roadmap

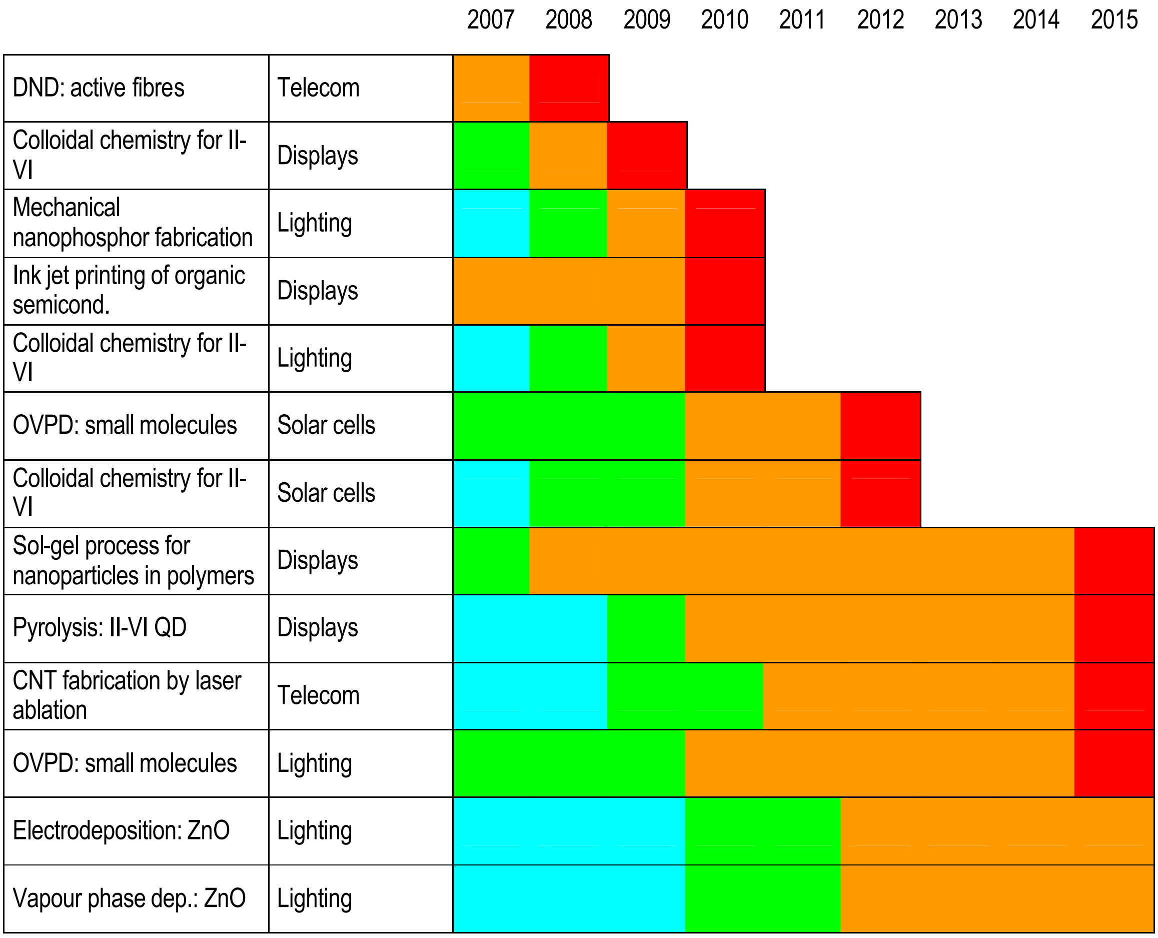


Table A6: Other deposition technologies

		2007	2008	2009	2010	2011	2012	2013	2014	2015
UV lithography: integration in ICs	Telecom									
UV lithography: photonic crystals III-V	Telecom									
UV lithography: nanostr. in Si	Telecom									
UV lithography: plasmonics/metalic nanostr.	Lighting									
UV lithography: III-V QDs	Telecom									
UV lithography: nanostr. in Si	Sensors									

Table A7: UV lithography roadmap

		2007	2008	2009	2010	2011	2012	2013	2014	2015
e-beam lithography: photonic crystals III-V	Lighting									
e-beam lithography: photonic crystals III-V	Telecom									
e-beam lithography: left-handed mater.	Metrology									
e-beam lithography: III-V QDs	Telecom									
e-beam lithography: photonic crystals III-V	Sensors									
e-beam lithography: nanostr. in Si	Telecom									

Table A8: e-beam lithography roadmap

		2007	2008	2009	2010	2011	2012	2013	2014	2015
Nanoimprint: photonic crystals III-V	Lighting									
Nanoimprint: photonic crystals III-V	Telecom									
Nanoimprint: nanostr. in Si	Sensors									
Nanoimprint: nanostr. in Si	Telecom									

Table A9: Nanoimprint lithography roadmap

		2007	2008	2009	2010	2011	2012	2013	2014	2015
FIB lithography: left-handed mat.	Metrology									

Table A10: FIB roadmap

		2007	2008	2009	2010	2011	2012	2013	2014	2015
Dry etching: photonic crystals III-V	Lighting									
Dry etching: photonic crystals III-V	Telecom									
Dry etching: nanostr. in Si	Telecom									
Dry etching: nanostr. in Si	Sensors									

Table A11: Dry etching roadmap

Annexes C: Report on the 5-10 years roadmap on applications and related markets

C.1. Introduction

The goal of the present document is to synthesize all the gathered information related to applications and markets. This information has been extracted from roadmaps related to devices based on given materials and used in applications previously defined by the MONA consortium. In the present report, we concentrate on the devices that emerged from the roadmapping process and are related to one of the applications areas defined by the MONA consortium.

The present report contains an evaluation of more and less mature components/devices as described in the roadmaps, but now related to a given application. For each application, we propose two evaluation milestones: at present (2007) and in 2012. The goal of this time-to-market evaluation process is to assess the degree of maturity of devices and to understand the dynamic of their future development.

C.2. Applications and markets - roadmaps consolidation

C.2.1 General description

In the present chapter, we summarize and show in table format all the devices related to a given application. For each application, all the available devices are listed in Annex 1.

In our methodological approach, we present for each application the devices and materials on which it is based. Two reference points are used for the evaluation of the application: 2007 and 2012, in order to show the present status of each application as well as its evolution in relation to future market penetration.

Four stages are used in order to compare the innovation maturity of the devices considered for each application. They are mainly related to the roadmapping status of the devices. These stages are **Basic R&D**, **Applied R&D, First Applications (FA)** and **Mass Production (MP)**. Devices for which no information is available in 2007 (NA) are considered as being in Basic R&D status.

The roadmaps concerning each application are summarized in Annex 1. There, one can find all the data about the devices based on different materials and having different degrees of maturity.

A more visual presentation of the roadmaps is given in Annex 2 graphics that allow to rank at a glance all the devices for the application.

Concerning the market data, as already exposed in deliverable D4.1, the market sizes related to applications have been extracted from a market study prepared by BCC[1] and correspond to a market projection in 2009.

C.2.2 Applications overview

In the following paragraphs, we present the various applications identified by the MONA consortium and the devices related to these applications. The structure of the description for each application is the following:

- General overview
- Innovation maturity and top devices
- Nanophotonic impact
- European context

C.2.2.1. Optical Interconnects

General overview

Optical Interconnects are of great interest for replacing copper links in short to medium distance data communication field (for data-rates > 10 Gb/s). The corresponding applications are facing severe bottlenecks due to copper links bandwidth limitations:

- In board-to-board and chip-to-chip communications, optical backplanes and optical links on PCB provide higher bandwidth, higher density and lower latency, while reducing the power consumption and the electromagnetic noise.
- Inside the chip, optical interconnects have been identified in the ITRS roadmap as a potential solution for addressing global wiring scaling issues. Clock distribution could be a potential first application.

However, the cost of optical components is still too high for addressing these high volume markets. Silicon photonics is the way to tackle the problem, by extending a massive, low-cost electronics manufacturing platform into the photonics domain.
In this application area, integration with standard CMOS processes is one of the key issues. The photonic layer can be integrated following 3 different ways:

- front end process (the photonic devices are at the same level as the transistors)
- above IC (the photonic devices are fabricated in back end in-between the metallic interconnection layers)
- bonding of photonic IC (the photonic devices are fabricated separately and bonded to the IC)

Innovation maturity level and top devices

This application field is under strong development. No standard has emerged so far (wavelength, single mode or multimode waveguide, PCB coupling interface, etc…). Optical Interconnect applications could be described accordingly as applications for which most of the devices are at present (2007) in a Basic R & D status. It should be noted that three devices/components will reach Mass Production status by 2012:

[1] Business Opportunity Report « GB-314 : Nanotechnology for Photonics », Business Communications Company, Inc., Norwalk, CT, USA, 2005

- Laser sources based on III – V quantum dots bonded on silicon
- Chip to chip link with flip-chipped source
- Link with hybrid integrated source

Nanophotonics impact

According to the material used, the impact of nanophotonics in this application area varies according to the information available as follows:

Impact of nanophotonics	Materials/Technologies
Strong	Silicon quantum dots and wires
Strong	Electronic/photonic integration
Strong	III-V Quantum dots and wires
Medium	Photonic crystals & high index contrast nanostructures in silicon/III-V for intra-chip interconnects
Medium	Photonic crystals & high index contrast nanostructures in silicon/III-V for board/backplane interconnects
Medium	Photonic crystals & high index contrast nanostructures in silicon/III-V for chip-to-chip interconnects
Low	Plasmonics - metallic nanostructures

European position in the area

Europe is well positioned in this area with several leading institutes (to mention only Technische Universität Berlin, CEA/LETI or INTEC). But silicon photonics is also being strongly investigated in the US by federal agencies (DARPA with the EPIC project, DoD with the MURI project on silicon lasers), microelectronics companies (INTEL, IBM) and start-up companies (Luxtera, Kotura).

In the fields of III-V lasers and passive devices large progress is being made in a silicon context. New concepts with different types of micro-cavities and materials, such as quantum dots, are intensively researched. For some designs the study should now move towards development of higher-throughput processes and integration with CMOS electronics. However, it is very difficult to compete with electronic interconnects on the intra-chip level. Therefore, one expects photonics to be introduced first on the chip-to-chip interconnect level. Further on, some compact technologies will be employed on a smaller scale with larger bandwidths.

C.2.2.2. Datacoms & Telecoms

General overview

Voice and data traffic keep increasing at a quite significant rate, in particular owing to the widespread use of internet and mobile telephony, and to the huge amount of exchanged data. In order to face this steady trend, larger data rates are implemented in core, metropolitan and storage networks and optical fibre technologies are now introduced in the access network (e.g. Fibre-to-the-Home).

Optical transmission with wavelength multiplexing has been deployed in the core and metropolitan networks for quite a while for point to point connection, and wavelength agility /transparency is now identified as a main challenge for future network deployments.
Optical devices and circuits used in optical transmission are basically light sources, modulators, transmission fibre, optical amplifiers, wavelength multiplexers and demultiplexers, photodetectors and combinations thereof. All these functions are expected to benefit from nanotechnologies, for instance:

- lasers with low threshold current and low temperature dependence, owing to Quantum Dots containing active regions,
- nanocavity (Photonic Crystal-based) laser arrays with low power consumption,
- add-drop filters and switches for wavelength routing,
- optical fibre amplifiers with nanoparticles or Photonic Crystal transmission fibre,
- quantum information devices.

Innovation maturity level and top devices

The top devices according to their degree of maturity are:

- Improved semiconductor Lasers based on III-V Quantum dots
- High index contrast devices - AWG MMI & ring resonator- based on III – V Photonic Crystals
- Add/Drop filter
- 1D and 2D Photonics Crystal reflector based on III – V Photonic Crystals
- Microstructured fibres for FTTH or domestic applications and for applications like laser, amplifiers, etc.
- Transceivers
- Passive photonic integrated circuits - PIC (waveguides, splitters, filters, (de)multiplexers, delay lines etc.).
- Electro-optic devices (modulators, detectors)
- Nanoparticules doped active fibres 1st, 2nd and 3rd generations

Nanophotonics impact

According to the material used, the impact of the nanophotonics in this application area varies according to the information available as follows:

Impact of nanophotonics	Materials/Technologies
Strong	Electronic/photonic integration
Strong	Photonic Crystals & high index contrast nanostructures in silicon
Strong	Nanoparticles in glass or polymer
Medium	Photonic Crystals & high index contrast nanostructures in III-V
Medium	III-V quantum dots and wires
Medium	Microstructured fibres
Medium/Low	Plasmonics effects
Low	Carbon nanotubes (CNT)
Low	II-VI quantum dots and wires

European position in the area

Concerning the European context, it should be emphasized that 1-D Photonic Crystals are already used in VCSELs production. One can expect an increasing use of VCSELs with the growing datacom market. 2-D Photonic Crystals in III-V are still in their infancy, and in spite of considerable progress in recent years, have not yet produced devices performing better than conventional devices, or demonstrating really new functionalities. However, as this is a new technology and given its likely impact, basic investigations must go on in Europe, to further investigate its potential.
High index contrast waveguide-based devices are worth investigating further, as a solution towards small footprint, low consumption integrated devices suitable for WDM systems.
In Quantum Dots area, it helps improving optoelectronic devices characteristics, and QD will be used in devices for optical fibre transmission. Europe appears to have a strong position in the physics as well as in the fabrication of QD structures and devices, but further progress is still needed to better control QD characteristics and to fully benefit from their potential. Europe together with Japan and USA is leading material development, but might not be as successful in exploiting the unique properties of quantum dots in components and innovative solutions.
The introduction of optical links has been hampered by the high cost of combining and packaging discrete optical components. The integration of these functions on a silicon chip and the combination with CMOS circuits and processing make it possible to obtain fast but low cost transceivers. These transceivers couple to fibres and are useful for many different network services. Because of scalability a profitable roadmap is attained. Many innovations are still possible, however. Therefore the European companies should aim to decrease the gap with the American industry (e.g. Luxtera).

Europe has a very strong tradition in research on microstructured fibres. Moreover, these fibres are envisaged for a wealth of applications in diverse fields (telecommunications, medical applications, sensing etc.). It is evident that the position of Europe should be maintained and expanded towards development and production (see e.g. the European IST project NextGenPCF).

C.2.2.3. Lighting

General overview

There is a strong effort to develop novel solid-state lighting technologies that, compared to conventional lighting technologies, are much more energy efficient, longer lasting, and cost competitive. OLED have been demonstrated as good candidates to replace conventional light sources and provide more efficient lighting in the near future. The performance of OLED can be enhanced by using nanotechnology techniques, such as introducing inorganic quantum dots emitters or nanocomposite electrode coating materials for better carrier transport.

Since their invention in the 1960s, LED have continuously become more efficient and brighter while the manufacturing cost has continuously decreased. Extrapolation of the increase in performance vs. time suggests that LED will be able to compete with conventional lighting (i.e. incandescent or fluorescent) within a few years from now (based on the so-called Haitz' law, similar to Moore's law). The progress in the development of LED is driven by various factors, such as internal quantum efficiency, outcoupling of the emitted light, chip shape, packaging. Future LED may even require new approaches to reduce dislocation densities in the epitaxial structures in order to minimize non-radiative recombination (especially for UV LED). Nanophotonic concepts are considered in many parts of the LED structures, such as templates, buffer layers, active semiconductor structures, chip surfaces and luminescence converting phosphors.

The final application is solid-state lighting, i.e general lighting, backlighting for LCD or DLP displays or automotive. Solid-state lighting using high brightness LED should replace incandescent and fluorescent lighting.
As for Optical Interconnects, Lighting applications appear to be in Basic R & D status at present (2007).

Innovation maturity level and top devices

According to the roadmaps, lighting related devices are in basic R & D status at present. However a strong development of the components related to lighting applications is foreseen. The top devices/components to reach mass production stage will be the following:

- LED emitting at 385 nm based on II-VI materials - GaN based with QD nanophosphors
- White LED - GaN-based LED with Photonic Crystal structure
- Other LEDs – AlGaInP
- GaN based LEDs with SP enhancement based on plasmonics effects
- III-N based LEDs based on nano concepts

Nanophotonics impact

According to the material used, the impact of the nanophotonics in this application area varies according to the information available as follows:

Impact of nanophotonics	Materials/Technologies
Strong	II-VI quantum dots and wires (ZnO LED, QD nanophosphors)
Strong	Photonic crystals & high index nanostructures in III-V materials
Medium	Plasmonics
Medium	III-V quantum dots
Medium	Organic nanostructures (OLED)
Medium	Nanoparticles in glass or polymer

European position in the area

LED based on blue light emission from GaN diodes are developing, with still much progress possible to enhance the internal quantum efficiency. Improvement of the output coupling by a factor of 50% through the use of a Photonic Pattern at their surface may seem to be marginal, but could be very important for future competition. Europe has a good position in the various facets of this topic (GaN lighting, Imprint & Interference Lithography). Given the targeted market which is amongst the most promising ones, securing a successful industrial development appears as an important objective: therefore, intensified R&D is clearly required.

Commercialization should start soon as there is one US company involved in this field (Universal Display Corp.). In Europe, there are two major players: Osram in Germany and Philips in the Netherlands. This creates a strong base for R&D. Besides that, there are various start-up companies with high growth potential (Novaled, CDT).

C.2.2.4. Data Storage

General overview

The techniques considered under "High density optical data storage" are Near-field optical storage and Superrens (Super resolution Near-field Structure) for the 4th generation data storage.

Near-field optics allows a further increase of the numerical aperture of the focusing objective lens by using the evanescent waves coming out of a Solid Immersion Lens (SIL) on the basis of which the light is focused. The use of those evanescent waves is possible if the distance between the solid immersion lens and the disc is a fraction of the wavelength (about 30-40 nm).

Superrens is a clever way to introduce the near-field optics in the disc layer stack itself by using nonlinear properties of a specific thin film, and thus going beyond the diffraction limit. By doing so the disc remains removable and the distance between the disc and the objective lens is comparable to Blu-Ray.

The capacity of SIL and SuperRENS are several hundreds of GB per disk. The two technologies are now competing.

Innovation maturity level and top devices

As for Interconnects and Lighting, data storage devices are at present in Basic R & D status. Concerning the evolution of this application in 2012, the three devices defined as the first to reach mass production stage are:

- 200GB optical storage near-field SIL based on plasmonics effects
- 200GB optical storage SuperRens based on plasmonics effects
- III-V quantum dot laser

According to the material used, the impact of the nanophotonics in this application area varies as follows:

Impact of nanophotonics	Materials/Technologies
Medium	III-V quantum dots and wires (laser)
Medium	Plasmonics materials
Low	II-VI quantum dots and wires

European position in the area

European research institutes and industrial companies are among the leaders in SIL type near-field and superrens data storage. European companies have a strong position in optical data storage research and development. While the drive and disc productions are now largely based in China, Taiwan or India, optical data storage is still providing huge revenues to the patent owners and format founders in Europe (Thomson, Philips). Europe has also major industries in the field of production or test equipment (Singulus, Unaxis, STEAG, Audiodev) and in the field of materials (CIBA, Clariant, Umicore). This position is supported by a top-level academic research activity in most of the related areas. Innovation and research are strategic components for the health of optical data storage industries in Europe.

C.2.2.5. Imaging

General overview

The video and imaging equipment and components category covers devices using video technology to record data. In industrial applications, these products are used for automated inspection and measurement, quality control, image sensing. Micromodules can be used for either mobile phone imaging or medical applications and more precisely in any application requiring very small optical products
CMOS image sensors or optical micromodules are considered in this roadmap.
The main challenge is to find the best compromise between Moore's law and the optical performance of the smallest possible detectors (pixel size < 1.5 µm). Denser chip integration leads to lower chip size, lower chip cost and thus larger use.

Infrared sensors in the range of ~3- ~25 µm are of particular importance for a wide area of applications, ranging from night vision, surveillance, search and rescue, to medical diagnosis.

At present infrared detectors are often based on mercury-cadmium-telluride (MCT) systems and quantum well infrared photodetectors (QWIP). However, due to sensitive bandgap effects in dependence of the material composition, reproducibility of manufacturing of MCT image sensors remains a challenge. In contrast, growth techniques for III-V systems provide accurate control of composition and homogeneity, but performances are lower. The main type of materials used is InAs quantum dots embedded in quantum wells ("dot-in-a-well"). Due to the 3-dimensional confinement quantum dot based detectors may offer substantial advantages, including higher operating temperatures and surface-normal direct absorption. Thus, quantum dot infrared photodetectors (QDIP) and quantum dot-in well detectors (DWELL) are studied extensively.

Concerning image sensors in visible and IR, II-VI materials as Mercury Cadmium Telluride (HgCdTe/MCT) can be used to develop IR detectors in the 1 - 3 µm (SWIR), 3 - 5 µm (MWIR) and 8 - 12 µm (LWIR) atmospheric transmission windows. In that case, a MCT photodiode array is hybriditized on a CMOS readout circuit. No significant development on II-VI nanostructures for imaging has been identified so far. The detection volume, and thus the sensitivity, is much larger in bulk materials than in nanostructures.

Innovation maturity level and top devices

The imaging applications roadmaps are unfortunately poor for the moment as all the devices are in Basic R & D status or even in exploratory research. It appears that in 2012 two devices will be in Mass Production status:

- Quantum dot infrared photodetector (QDIP) based on III-V quantum dots.
- Pixel sized colour filter

According to the material used, the impact of the nanophotonics in this application area varies according to the information available as follows:

Impact of nanophotonics	Materials/Technologies
Strong	III-V quantum dots and wires
Medium	Electronic/photonic integration (detector performance)

European position in the area

There are strong European actors in the field of IR imaging. State-of-the-art of quantum dot growth with MOVPE and MBE is being investigated in several European research facilities (TUB, Univ. of Sheffield, Alcatel-Thales, Acreo...). Due to the importance of IR-sensing in various application areas, European research should be kept strong in this field.
European industry is relatively segmented between photonics and other advanced sectors such as semiconductors: improved coordination and joint developments at the research stage should help to integrate more easily such functions in the future.

C.2.2.6. Sensors

General overview

A sensor is a device that responds to a physical stimulus, such as thermal energy, electromagnetic energy, acoustic energy, pressure, magnetism, or motion, by producing a (usually electrical) signal..

As mentioned by one of the MONA participants, “Optical sensors are immune to electromagnetic interference and can be used in harsh environments. They also provide good sensitivity, linearity and stability. Commercial applications include physical sensing (e.g. strain) and chemical or biological sensing. Currently, most optical sensors are based on fibre optics or free space optics, but some new research deals with integrating the sensor functions on photonic ICs”.

Photonic ICs in SOI (Silicon on Insulator) can integrate many sensor functions or sensor arrays on a small silicon chip to create a multi-parameter sensor. An application of such a multi-parameter sensor is label-free biochemical analysis. An advantage of using SOI is that a wavelength division multiplexing scheme can be used for easy readout of the sensors. In 2005, several research projects started on SOI integrated sensors, both on biochemical sensors and physical sensors.

SOI based nanophotonic sensors offer big advantages for bio-sensing applications. Next to the possibility for low cost mass fabrication, the technology is suitable for sensing (see section Micro- and Nanophotonic components and ICs). Due to the extremely narrow resonance peaks of SOI micro-rings, they are suitable for the measurement of extremely small changes of the surface refractive index, caused by the binding of bio-molecules to the cavity's surface.

Among other techniques, it should be noted that various types of sensing can be realized using plasmonics. In general enhanced sensitivity of plasmonics sensors is based on improved temperature control. Refractive index sensing is not yet done with nanostructures; i.e. there is no point localization possible so far. Thus, there is a need to step over from 2D detection to localized 3D point detection based on nanostructures. Refractive index sensing sensitivity itself may be enhanced by one order of magnitude within one year.
Further application fields of plasmonic sensing may be seen in health applications. Features of advantage are the single molecule sensitivity and a better biocompatibility of metallic nanoparticles compared to more toxic quantum dot markers and some organic dyes. One of the key challenges of plasmonic nanostructures seen for health applications is a specific (bio-) chemical functionalization.

Innovation maturity level and top devices

Sensors applications are in Basic R & D status in 2007. Three devices are expected to reach Mass Production in 2012:

- Functionalized fluorescent nanoparticles based on II-VI quantum dots
- Sensing of specific (bio)molecules based on plasmonics effects
- Refractive-index sensor based on plasmonic effects

According to the material used, the impact of nanophotonics in this application area varies according to the information available as follows:

Impact of nanophotonics	Materials/Technologies
Strong	III-V quantum dots and wires
Strong	II – VI quantum dots and wires
Strong	Plasmonic nanostructures
Medium	Silicon quantum dots based materials
Medium	Photonic crystals & high index contrast nanostructures in silicon
Medium	Microstructured fibres
Low	Photonic crystals & high index contrast nanostructures in III-V

European position in the area

There is a need for more integration between players in the nanoparticle field: for example, at IBM Watson Research Centre, research on nanoparticles is oriented towards applications in many different fields (from magnetic devices to field effect transistors). This is possible only with an integrated, multidisciplinary team.

With the burgeoning fields of life sciences and photonic interconnects, combined with the many advantages of integration, it is evident that the lab-on-a-chip approach will reach fruition. Currently, the design of sensitive, low-cost, proof-of-principle devices is very active. Soon, however, the focus needs to shift towards practical devices, suitable for commercialization.

Using microstructured fibre in sensors is a relatively unexplored area. However, fibre characteristics point towards many device opportunities. We mention e.g. the possibility to fill the holes with gases, the specific dispersion properties etc. It is clear that some of the fibre research in Europe is progressing quickly towards these sensing applications.

C.2.2.7. Displays

General overview

In this area, several technological developments have been observed during the last years. Thus, flat panel display technologies (FPD) are replacing the traditional CRT cathodic technology, the main applications being the TV, laptop and computers.

Many FPD technologies are competing: LCD, plasma, OLED, DLP and FED, SED. LCD is leading the market with 80 % forecast for 2007. Plasma, LCD, FED and SED are competing on large size TV (i.e. 40 inches and up). OLED targets small size displays: MP3, Car audio, mobile phones.

LCD is becoming the FPD standard thanks to its good performance / cost ratio. Nanophotonic devices that might be integrated into this display technology (nanophosphors, backlighting, IC integration) would be promised to a large diffusion with million units sales. However the display market is strongly driven today by cost reduction and it is not expected that nanophotonic could significantly participate to this trend. Hence we consider that the nanophotonic impact gained through a continuous improvement on the LCD technology will not generate significant additional sales.

Nanophotonics could have a more important impact on LCD competitors' technologies: FED, OLED, QLED, SED. Those technologies are all "nanophotonic" based. Their main advantages are generally the low power consumption and sometimes flexibility. FED and SED will compete with plasma on high value large size displays (40") while OLED and QLED are targeting smaller rigid displays (Mobile ...) and flexible new applications.

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According to the available data, the total FPD market is $ 90 billion in 2008. In the same time, OLED sales are forecast to be about $ 5 billion in 2009.

Innovation maturity level and top devices

From the data available in the roadmaps (see the Annexes), displays related devices seem to be all in basic R & D status in 2007.

It appears from the roadmap that the 3 devices that will be in the most advanced innovation status in 2012 are:

- Nanophosphors based on II-VI Quantum Dots
- Field Emission Display small area, low complexity using tiny electron emitters made of CNT, FED or NED (nano emissive display) based on Carbon Nanotubes
- Organic Light Emitting Diodes (OLED) and pLED: solid state semi conductor device that contains a 100 to 500 nanometre thick organic light emitting layer

The nanotechnology impact in the area is evaluated by the MONA experts as follows:

Impact of nanophotonics	Materials/Technologies
Strong	Carbon nanotubes (CNT)

Medium	Organic nanostructures
Medium	II – VI quantum dots and wires
Low	Nanoparticles in glass or polymer

European position in the area

Main industrial players for FED are in Asia (Samsung, Canon, Toshiba, Mitsubishi, Sony, Ise Electronics ...) or USA (Motorola, CDream, Applied Nanotech). Flat panel display industry is highly concentrated and capitalistic and most of it is located in Japan, Korea and Taiwan. Therefore it is very difficult for new players to enter into the field (Motorola chose to licence its technology to an Asian player).

However, there are strong R&D skills in Europe: for instance, CEA Leti on CVD techniques. It seems that the main interest for Europe in that segment will be to provide support services such as R&D and process equipment (CVD techniques).

Another possible opportunity would be to focus on a new field of application: flexible large size displays. A European project called Nanopage has aimed to develop CNT flexible displays for 2007.

Many of the leading laboratories in the domain are European. There is no longer any European industrial production of displays. Strong European industrial players exist in the field of CNT, glass substrates and display systems. It may be an opportunity to bring display fabrication back to Europe

Concerning the players in the area, Kodak (US) and Cambridge Display Technology (GB) licensed their technologies to Asian manufacturers: Samsung (30% market share), Rit Display, Pioneer, Univision, and LGE (source: Display Search).
Philips (NL) exited the pLED market in 2005 and OTB (NL) purchased the business to strenghten its OLED manufacturing equipment offer.

OSRAM (DE) and Novaled (DE) are the only OLED European manufacturers. Merck (DE) has bought the OLED material supplier Covion in 2005.

OLED market for rigid display seems already crowded and dominated by Asian manufacturers whose priority is to reduce the cost and increase the size of the devices. However Europe could benefit from OLED rigid display development by providing R&D services, materials and equipment.

There is more room for innovation on flexible displays which are not industrialized yet. A European project Flexidis targets to develop flexible display which will use OLED, one of the two display technologies investigated (the other one is electrophoretic (EP) monochrome displays).

C.2.2.8. Photovoltaics

General overview

Photovoltaic solar cells offer the potential to develop flexible, lightweight solar cells based on organic and hybrid materials. One of the main advantages of these materials is their compatibility with low cost, high throughput printing based on vapour phase process techniques.
Two current trends in the development of photovoltaic cells have emerged: low-cost (low efficiency) approaches and high-efficiency (high-cost) techniques. While today most of the commercially available cells

are made of bulk silicon, other thin film materials (Si, CIS and others) have been introduced to improve cell performance.

Triple-junction solar cells represent state-of-the-art photovoltaics, today mainly used for space applications. Lattice-matched layers are grown on top of each other and are designed to absorb different parts of the solar spectrum. Quantum well structures can be grown to engineer the absorption bandgap of each layer.

Quantum dots offer more flexibility to bandgap, current and strain management to achieve higher conversion efficiencies. III-V quantum dots can also be used to generate intermediate band solar cell material.

Innovation maturity level and top devices

Photovoltaic applications are presently in an advanced research status, in comparison with other applications. In 2012, photovoltaics components will appear and enter into Mass Production status:

- Quantum dot solar cells and intermediate band solar cells
- Organic solar cells with QD materials
- Hybrid solar cells based on II-VI materials
- Polymer - fullerene (C60) bulk heterojunction solar cells
- Small molecules based on control bulk or planar heterojunction and C60 based solar cells

According to the roadmaps the impact of nanotechnologies in this domain is the following:

Impact of nanophotonics	Materials/Technologies
Strong	III-V quantum dots
Medium/Strong	II–VI quantum dots
Medium	Carbon Nanotubes (CNT)
Medium	Silicon quantum dots based materials
Medium	Organic Nanostructures
Low	Nanoparticles in glass or polymer

European position in the area

Polymer solar cells are still in a primary status of development. Therefore the only industrial player known is Konarka (US) that develops an organic solar cell process.
There are key material suppliers in Europe: Bayer for the PEDOT and Merck (bought Covion in 2005) for MDMO-PPPV.

Aixtron is the worldwide leader for the OVPD process. Europe has also a strong R&D leadership with the following active players: ECN (NL), University of Eindhoven (NL), Fraunhofer ISE (DE), IMEC and IMOCMEC (BE), CEA (FR), LIOS (DE), University of Groningen (NL), University of Linköping (SE).
Polymer solar cells are therefore an attractive opportunity for Europe.

The basis for R&D in the field of organic solar cells should become broader. Manufacturing technologies should be investigated at an early stage in order to compete with Asia.

C.2.2.9. Instrumentation and equipment

General overview

In this application several techniques seem to be used for characterizing nanophotonics components or materials. In scanning near-field optical microscopy (SNOM), light fields very close to the sample, at a distance much less than the wavelength of the light, are observed. Light is illuminated/collected through a sub-wavelength diameter aperture. The resolution achieved is far better than with conventional optical microscopes.
SNOM is a versatile instrument for nanophotonics, since it can be used for example to characterize optical nanomaterials (quantum dots, quantum wires ...) and plasmonics components.
Tapered optical fibres with a small optical aperture are commonly used in SNOM systems to collect near-field information, and are commercially available. However, fibre probes are still difficult to fabricate with high reproducibility, and have low throughputs.
Silicon nanostructured probes for scanning near-field optical microscopy (SNOM) may offer significant advantages in terms of manufacturability. Moreover, the same probe structure can be used for both SNOM and atomic force microscopy (AFM) measurements.

Another type of material seems to have impact in this application area: meta-materials. Negative index materials do not exist in nature. To achieve negative index effects, artificial meta-materials have been created consisting of appropriate sub-wavelength structures. Although left-handedness could be achieved for the RF-range and down to long IR, it has not yet been possible to reach negative refraction based on meta-materials for the optical and UV-range. Several devices used in this application area could be considered. The first device considered is the "superlens" based on silver thin-film (no real metamaterial). It is considered that the first prototypes could achieve optical resolution of 1/3 to 1/5 of a wavelength. Silver shows negative electric permittivity in the optical range. Thus thin films allow for negative refraction and a "superlensing effect". The second one is the SiC "superlens" for Near-Field Microscopy (no real metamaterial). A first prototype achieved resolution of 1/20 of a wavelength.

Plasmonics resonances are used at infrared or visible frequencies in metallic (Au, Ag, Al, Cu) nanostructures or colloid nanoparticles (1-50 nm). Research into potential plasmonics applications is still at an early stage. In principle, it should be possible to use plasmonics to form compact integrated optical circuits, with length scales much smaller than those feasible with other technologies. Surface plasmons are being explored for their potential in subwavelength optics, data storage, light generation, microscopy and biophotonics.

Innovation maturity level and top devices

Today instrumentation and equipment related devices are still in basic research and future applications are at a low development pace.
Five devices/components will enter into **first applications** stage in 2012:

- Nanostructures probes based on Si quantum dots and wires
- SP lithography
- SiC "superlens" for Near-Field Microscopy
- Meta-materials for optical frequencies
- Active/tunable meta-materials for IR/optical frequencies

According to the roadmaps the impact of nanotechnologies in this domain is the following:

Impact of nanophotonics	Materials/Technologies
Medium	Silicon quantum dots based materials
Medium	Left-handed meta-materials
Medium	Plasmonics/metallic nanostructures

European position in the area

There are several European manufacturers of SNOM. However Japan is a leading player for Silicon quantum dots and wires used in the measurement instrumentation applications, as compared to USA and Europe.
Beside instrumentation applications, techniques developed for SNOM might be applied for high-density optical memories.

C.3. Conclusion

In the present document, we have analysed all roadmaps build by the MONA consortium with the support of European experts who participated in public consultations to provide their feedback about the potential of applications and devices.

We have extracted for each application the most promising devices as those which will experience the quickest development (most of them being in Basic R&D status in 2007) as well as the materials and technologies with the highest impact on photonics.

C.4. Devices as mentioned in the roadmaps for each application

Optical Interconnects

Device	Performance	Current Status	2012 Status	Mass Production
Laser source based on III-V quantum dots bonded on silicon	• Targeted power is closely related to the application, i.e. is the mW range for chip to chip or board to board links, lower for intra-chip interconnects • QD lasers emitting in the mW range have already been demonstrated	Basic R & D	Mass Production	2012
Laser source based on III-V quantum dots grown on silicon	NA	Basic R & D	Applied R & D	>2015
In-plane laser sources (silicon or III-V based). – for intra-chip interconnects	The following are desirable characteristics for sources in an intra-chip (but also chip-to-chip) context: • Low power consumption (<mW). The shorter the link, the smaller the power can become. • High speed - at least 10 Gb/s should be achieved. • Compact, parallelizable technology. In a multi-core processor with thousands of cores, each core might need a source.	Basic R & D	First Applications	2015
High index contrast waveguides and passive devices.	• For photonic integrated circuits, the acceptable loss level of waveguides is in the range of 0.1 to 1dB/cm. • Current SOI waveguides show 2-3dB/cm losses, and amorphous Si waveguides show 4-5dB/cm. • For compactness one needs bending radii smaller than about 5μm.	Basic R & D	First Applications	2013
High index contrast detectors	NA	Basic R & D	First Applications	2015
Laser sources (in-plane & out-of-plane) for chip-to-chip interconnects	Designs with extreme modulation speeds (>100GHz) and ultra low thresholds (<10µA) have been reported	Basic R & D	First Applications	2013
Structures to couple light from a chip to an optical fibre or a board-level waveguide (gratings, microtapers).	The important characteristics here are loss and bandwidth.	Applied R&D	First Applications	2013

Device	Performance	Current Status	2012 Status	Mass Production
Silicon laser with Si nanocrystals based on Silicon Quantum dots	Silicon nanocrystals in SiO2 amorphous matrix are used as active materials emitting at 750 nm. Experimental demonstration of gain has been made, as well as LED emission	Basic R & D	Applied R & D	>2015
Silicon laser with Erbium doped silicon quantum dots	Er doped silicon nanocrystals in SiOx matrix are used as active materials emitting at 1530 nm.	Basic R & D	Applied R & D	>2015
Optical gate based on Silicon quantum dots	Optical non linear refraction and absorption are used for all optical logical gates	Basic R & D	First Applications	2013
All-optical active nanodevices. (e.g. nanolaser, modulator, transistor) - based on Plasmonics nanostructures	• Low loss. • Ultra-small size.	Basic R & D	Applied R & D	2015
Metallic waveguides - based on Plasmonics nanostructures	Low losses	Basic R & D	First Applications	2015
Chip to chip link with flip-chipped source	NA	First Applications	Mass Production	2009
Link with hybrid integrated source	NA	Basic R & D	First Applications	2013
All silicon link	NA	Basic R & D	Basic R & D	>2015

Table 4 - Optical interconnects related devices

Datacom & Telecom

Device	Performance	Current Status	2012 Status	Mass Production
Improved semiconductor Lasers based on III-V Quantum dots	• Power almost independent on the temperature • Possible growth on GaAs for lasers emitting at 1,3 µm	First applications	Mass Production	2008
Narrow spectral width lasers based on III-V Quantum dots	Narrow spectral width of the beat note between oscillating modes.	Applied R & D	First Applications	2013
SOA based on III-V Quantum dots	• Large wavelength range, gain efficiency. • Decrease of gain recovery time	Applied R& D	First Applications	2014
Optical buffer & single photon emitter based on III-V Quantum dots	Tuneable slow light.	Basic R& D	First Applications	> 2015
Saturable absorber made from single-wall carbon nanotubes	Very fast relaxation time – 1 ps	Basic R & D	First Applications	2015
High index contrast devices - AWG MMI & ring resonator-based based on III – V Photonic Crystals	• Compact devices • Wavelength selectivity and filtering	First Applications	Mass Production	2010
Add/Drop filter	NA	First Applications	Mass Production	2010
1D-Photonics Crystal reflector based on III – V Photonic Crystals	High reflectivity mirrors obtained by stacking alternate layers of two materials with different optical indices	First applications	Mass Production	2010
2D-Photonics Crystal devices based on III – V Photonic Crystals	Improved performance in terms of: • power, • bandwidth & tunability, • spectral purity. • high Q value	Applied R & D	Mass Production	2013
Microstructured fibres for long-haul transmission – based on Photonic Crystals in other materials	Reported losses for hollow-core: 1.2dB/km, and solid-core: 0.28dB/km.	Applied R & D	First Applications	2015
Microstructured fibres for FTTH or domestic applications – based on Photonic Crystals in other materials	Fibres that do not show bend losses before the breaking point have been demonstrated	Applied R & D	Mass Production	2012

Device	Performance	Current Status	2012 Status	Mass Production
Microstructured fibres for other applications (lasers, amplifiers…) – based on Photonic Crystals in other materials	While the low transmission loss is not a primary concern, the properties that are exploited remain similar.	Applied R & D	Mass Production	2012
Transceivers (no WDM)	Two very important characteristics: • Speed- optical transceivers will provide bandwidths starting at 10Gb/s • Cost - because of wafer-scale processing prices should drop below 100 $ / transceiver.	Applied R & D	Mass Production	2009
Transceivers (with WDM)	Key technical challenges: • low cost wafers are needed. • low-loss coupling structure to interface between chip and fibre. • The previous issues become more complex if WDM is envisaged	Applied R & D	Mass Production	2010
Transceiver with integrated source		Basic R & D	First Applications	2013
Passive photonic integrated circuits - PIC (waveguides, splitters, filters, (de)multiplexers, delay lines etc.).	For acceptable loss levels for PIC: • in the range of 0.1 to 1dB/cm Current SOI waveguides show 2-3dB/cm losses, and amorphous Si waveguides show 4-5dB/cm.	First Applications	Mass Production	2009
Micro/nano-cavity laser sources -silicon or III-V based	Designs with extreme modulation speeds (>100GHz) and ultra low thresholds (<10µA) have been reported.	Basic R & D	First Applications	2013
Slow switching/tuning functions.		Applied R & D	Mass Production	2010
Electro-optic devices (modulators, detectors).	Bandwidths above 10GHz have been obtained, e.g. in doped silicon ring modulators and germanium detectors.	Applied R & D	Mass Production	2010
All-optical devices (switches, frequency converters).	Designs with very low switching powers have been demonstrated. We mention e.g. that 100fJ switching energies with switching in less than 100ps was achieved in a photonic bandgap structure (NTT, 2005).	Basic R & D	First Applications	2015
Passive ultra-compact photonic components (e.g. optical filters, splitters, cavities, antenna) based on plasmonics effects	• Low loss • Ultra-small size.	Basic R & D	First Applications	2015
All-optical active nanodevices. (e.g. modulator, transistor, nanolaser) - based on plasmonics effects	• Low loss. • Ultra-small size.	Basic R & D	Applied R & D	2015

Device	Performance	Current Status	2012 Status	Mass Production
Nanoparticles doped active fibres for optical amplification – **1st generation**	Higher rare-earth concentration in direct nanoparticle deposition active fibre than in conventionally manufactured active fibre higher gain power shorter piece of amplification fibre required (5m vs. 15m for conventional fibre used for amplification at 1550nm)	First applications	Mass Production	2008
Nanoparticles doped active fibres for optical amplification – **2nd generation**	The control of the rare-earth environment will permit to optimize the gain shape in the C and L band (toward wider and flatter gain) and will permit to increase the efficiency in a silica matrix of other rare earth ions while keeping the high reliability of silica based fibres and their connectivity ability with conventional transmission fibre. It will permit to provide efficient and reliable amplification devices in other bands (e.g.: Tm for S-band).	Applied R & D	Mass Production	2010
Nanoparticles doped active fibres for optical amplification – **3rd generation**	Semi-conductor nanoparticles will be associated with rare-earths. Indeed some of this nanoparticles are able to transfer their energy to the rare earth ions (e.g.: silicon to Er). As semi-conductors nanoparticles have a very wide absorption effective arera, this will allow to pump the fibre with very lost light sources	Basic R & D	Mass Production	2012

Table 5 - Datacoms & Telecoms related devices

Lighting

Device	Performance	Current Status	2012 Status	Mass Production
LED emitting at 385 nm based on II-VI materials - **ZnO**	The targeted efficiency of white LEDs is about 200 lm/W at nominal power	Basic R & D	First Applications	2015
LED emitting at 385 nm based on II-VI materials - **GaN based with QD nanophosphors**	These nanophosphors are expected to replace conventional phosphors based on rare earth doped materials. • Targeted Quantum yield is above 70% (70% already demonstrated with QD) • Target overall efficiency > 100 lm/W, life time > 10 000 h	Basic R & D	Mass Production	2010
White LED - GaN-based LED with Photonic Crystal structure	For this application, the purpose of the Photonic pattern in the surface layer is to couple out a maximum of the light generated within the active layer of the device (50% improvement in output coupling). • Target performance: increase of efficacy beyond 100 lm/W	Basic R & D	Mass Production	2008
Other LEDs - AlGaInP	For this application, the purpose of the Photonic pattern in the surface layer is to couple out a maximum of the light generated within the active layer of the device (50% improvement in output coupling). • Target performance: increase of efficacy beyond 100 lm/W	Basic R & D	Mass Production	2009
OLED -Quantum Dot based	• Sizes of quantum dots can be easily adjusted to different wavelengths. • Light emitting properties of inorganic quantum dots may provide a solution to the poor efficiency of OLEDs for lighting applications.	Applied R & D	First Applications	>2015
GaN based LEDs with SP enhancement based on plasmonics effects	Efficiency beyond 100 lm/W	Basic R & D	Mass Production	2011
Organic LEDs with surface plasmon enhancement	Efficiency	Basic R & D	First Applications	2015
III-V based LEDs based on nano concepts	• Target performance: increase of efficacy beyond 100 lm/W. • UV: target dislocation density below 10e7 cm-2	Basic R & D	Mass Production	2012

Table 6 - Lighting related devices

Data Storage

Device	Performance	Current Status	2012 Status	Mass Production
200GB optical storage near-field SIL based on plasmonics effects	Targeted disk capacity: • 200 GB in 2008 • 1TB in 2015.	Applied R & D	Mass Production	2012
200GB optical storage Superrens based on plasmonics effects	Targeted disk capacity: • 200 GB in 2008 1TB in 2015.	Applied R & D	Mass Production	2012
1TB optical storage	>100 Gbit/in²	Basic R & D	Applied R & D	>2015
High density storage media based on II-VI quantum dots and wires	High storage density (>50 GB/layer ?) targeted	Basic R & D	Applied R & D	>2015
III-V quantum dot laser	NA	Basic R & D	Mass Production	2012
Quantum dot memory based on II-VI quantum dots and wires	Ultra dense storage capacities Fast read/write times Non-volatility	Basic R & D	First Applications	2013

Table 7 - Data storage related devices

Imaging

Device	Performance	Current Status	2012 Status	Mass Production
Quantum dot infrared photodetector (QDIP) based on III-V quantum dots	Detection at 8-12µm with the following current performance: • responsivity (exp) : 800mA/W • detectivity (exp): 3e11cmHz^½/W	Applied R & D	Mass Production	2010
Pixel sized colour filter – based on integration of Nanophotonic structures with electronic ICs/Silicon Photonics	Colour filters using pigments or dyes are commonly used for the RGB filtering. Filter using nanoparticles could replace these filters with higher performance	Basic R & D	Mass Production	2011
Pixel sized nanostructured colour filters – based on integration of Nanophotonic structures with electronic ICs/Silicon Photonics	In that case, sub-wavelength patterned layers (e.g. in metal) are used as colour filters. Such pixel design is called Integrated Colour Pixel (ICP) that can be an alternative to current pixel design that employs colour filter arrays. Demonstrations with nanopatterned metal layers or photonic crystal structures have been made	Basic R & D	First Applications	2013
Integrated microlens	With the reduction of the pixel size, refractive lenses have limited performance. One of the solution to decrease the focal spot size is to use optical field confinement devices as plasmonics devices	NA	NA	NA

Table 8 - Imaging related devices

Sensors

Device	Performance	Current Status	Status 2012	Mass Production
Functionalized fluorescent nanoparticles based on II-VI quantum dot	Fluorescent labels/markers for biological molecules to be detected by means of optical spectroscopy and microscopy Nanoparticles are competing with organic dye. The target performance are those of the dyes: • High fluorescence efficiency (30-95 % for dyes, 15-80% already achieved with nanoparticles) • Lifetime: organic dyes suffer from photobleaching that limits lifetime to several tens of seconds to tens of minutes. II-VI nanoparticles are much more stable and exhibit lifetimes of tens of hours (limited by oxidation so far)	Basic R & D	Mass Production	2009
Functionalized fluorescent nanoparticle for single molecule observation based on II-VI quantum dots	See above	NA	Applied R & D	>2015
Quantum wire polarization sensor based on III – V quantum dots	Quantum wires have a large aspect ratio and thus are excellently suitable for anisotropy sensing of radiation	Basic R & D	First Applications	2015
Si-nanocrystal optical sensor - based on Semiconductor quantum dots&wires in silicon including colloidal nanostructures	Large optical response upon UV-excitation in the fs-range	Basic R & D	First Applications	2012
Sensor for biomolecules.	One has designed label-free schemes, using the sensitivity of microscale optics to the local dielectric environment. We mention e.g. interferometric approaches, or the shift of a high quality resonance, such as a ring mode. Very useful devices incorporate microfluidic channels next to the optical waveguides. Highly parallel, fast and multifunctional sensing can be achieved in this way.	Basic R & D	First Applications	2014
Sensor for strain or pressure	Compared to the fibre Bragg grating sensors, these integrated devices are very compact. Compared to electronic sensors there is no EM interference problem, or safety problem in combination with explosive substances.	Basic R & D	First Applications	2014
Sensor for gas/liquid concentration	It is safer to use optical methods instead of electrical methods in dangerous environments (e.g. measuring hydrogen levels).	Applied R&D	First Applications	2013

Device	Performance	Current Status	Status 2012	Mass Production
Integrated spectrum analyzer	Small, reliable and inexpensive solutions are envisaged; in contrast with bulk optical components or MEMS. The wavelength dependence can be implemented by using (de)multiplexers such as arrayed-waveguide gratings or planar concave gratings.	Basic R & D	First Applications	2014
Microstructured fibre sensors based on Photonic Crystals in other materials	NA	Basic R & D	First Applications	2013
Sensing of specific (bio)molecules based on plasmonics effects	• Single molecule sensitivity • Nanoscale devices • Single particle spectroscopy	First Applications	Mass Prodution	2010
Detector of DNA hybridisation based on plasmoinc effects		NA	NA	NA
Refractive-index sensor based on plasmonic effects		First Applications	Mass Production	2010

Table 9 - Sensors related devices

Displays

Device	Performance	Current Status	Status 2012	Mass Production
Nanophosphors based on II-VI Quantum Dots	These Nanophosphors are expected to replace conventional phosphors based on rare earth doped materials	Applied R & D	Mass Production	2009
Active Flat Panel Displays based on II - VI	Power consumption may be 3-4% compared to conventional FPDs.	Basic R & D	First Applications	>2015
Field Emission Display small area, low complexity -i.e. flat panel display using tiny electron emitters made of CNT. Motorola call its FED device a NED (nano emissive display) based on Carbon Nanotubes	Advantages of FED versus other technologies : • Less power consumption than Plasma technology. Same brightness and image quality than CRT (standard TV) but with the same thickness than LCD • 20~30% of cost competitiveness compared to PDP or TFT LCD • Targeted brightness is about 800 cd/m² (600 cd/m² already obtained) • Field of view is about 180°.	Basic R & D	Mass Production	2011
Field Emission Display – large area - i.e. flat panel display using tiny electron emitters made of CNT. Motorola call its FED device a NED (nano emissive display) based on Carbon Nanotubes	Advantages of FED versus other technologies : • Less power consumption than Plasma technology. Same brightness and image quality than CRT (standard TV) but with the same thickness than LCD • 20~30% of cost competitiveness compared to PDP or TFT LCD • Targeted brightness is about 800 cd/m² (600 cd/m² already obtained) • Field of view is about 180°.	Basic R & D	First Applications	2015
Field Emission backlighting for LCD based on Carbon Nanotubes	Addressable backlighting using FED is a competitor of LED backlighting, so the same level of performance is requested. 30 lm/W have been obtained with FED	Basic R & D	First Applications	2014
Surface-conduction Electron-Emitter Displays (SEDs)	• Efficiency: power consumption is close to CRT that is four times less important than plasma technology (160 kW/h instead of 640 kW/h). • Contrast: sharpness even for high speed movements.	First Applications	First Applications	2013
Organic Light Emitting Diodes (OLED) and pLED : solid-state semi conductor device that contains a 100 to 500 nanometre thick organic light emitting layer. There are two techniques : - Small molecules OLED from Kodak	• Brightness : 400 cd/m² (for pLED of CDT) • Lifetime : 100 000 hours (for pLED of CDT) • Voltage : < 5 V activation (for pLED of CDT)	First Applications	Mass Production	2010

Device	Performance	Current Status	Status 2012	Mass Production
- Polymers from CDT (pLED)				
AR coating (anti reflective organic coating)	• A main criterion is the transmission % or reflectance %. • Traditional organic technology is lower cost AG (anti glare) that diffuse the light instead of transmitting it. Typical transmission value is 96 % • Scratch resistance is also an important requirement	Basic R & D	Applied R & D	>2015
Liquid crystal on Si projection displays.	• -Resolution. • -Large size: >50".	NA	NA	NA

Table 10 - Display related devices

Photovoltaics

Device	Performance	Current Status	Status 2012	Mass Production
Si QD multi-junction cell	NA	Basic R & D	First Applications	2013
Hot carrier QD cell	NA	Basic R & D	Applied R & D	>2015
Quantum dot solar cell	Multiple-band solar cells may offer high-efficiency performance 40-70%	Applied R & D	Mass Production	2011
Quantum dot intermediate band solar cell (QD-IBSC)	Quantum dot intermediate band solar cells may enable conversion efficiency theoretically as high as 60%	Applied R & D	Mass Production	2011
Organic solar cell with QD materials	NA	Basic R & D	Mass Production	2012
Hybrid solar cell based on II-VI materials	The following manufacturing issues are identified: • raw material used for synthesis are quite expansive. Recent progress have been made for using cheaper materials • fabrication in high volume has to be developed. Current processes allow small volume production (several grams per batch) Regulation issues: • Organic molecules used for synthesis are highly toxic (e.g. phosphin). Toxicity of nanoparticles is still an issue, even if no sharp toxicity have been demonstrated Contrary to fluorescent nanoparticles, fluorescence must be avoided in order to collect carriers efficiently. No passivation with shell is used. The bandgap structure of the nanoparticle and the polymer must be optimized to collect electrons and holes without relaxation	Basic R & D	Applied R & D	2015
Wavelength conversion devices based on II – VI materials	Same as above	Basic R & D	Applied R & D	2015
Active junction in multijunction solar cells based on II-VI materials	So far, this technology exists only on a research scale. There is no proof yet that there is a significant improvement of efficiency compared to standard organic solar cells. Furthermore, it is unclear how such materials/structures might be fabricated at low production cost on a large scale.	Basic R & D	Applied R & D	2015

Device	Performance	Current Status	Status 2012	Mass Production
Polymer - fullerene (C60) bulk heterojunction solar cells	Potentially Low cost techniques, such as printing techniques, can be used for example in a future roll to roll process. Manufacturing of the devices should be possible on flexible substrates. This will significantly reduce the weight of the assembly. The approach may open the way for new applications, such as semi transparent and colour tuned solar cells. For the considered application (i.e. flexible solar cells for portable applications), the target performance is 5% of conversion efficiency and a lifetime of 3000 hours (5% efficiency and 3000 hours lifetime have already been obtained in laboratories so far) The target cost is less than 1$/W	Applied R & D	Mass Production	2012
Polymer - Polymer bulk heterojunction solar cells	Same as above	Basic R & D	First Applications	>2015
Polymer Metal Oxide bulk heterojunction solar cells	Same as above	Basic R & D	First Applications	>2015
Small molecule based **controlled bulk** heterojunction solar cells	The overall target of solar cell concepts based on small molecules is to produce light weight and low cost cells. Current organic solar cells the efficiencies are typically in a range of a few %. Standard BHJ cells show only around 1% efficiency. Target, however is to reach at least 5% at a low manufacturing cost. This requires cost efficient manufacturing methods that produce structures in a very controlled and reproducible way	Applied R & D	Mass Production	2011
Small molecule based planar heterojunction solar cells	The overall target of solar cell concepts based on small molecules is to produce light weight and low cost cells. Current organic solar cells the efficiencies are typically in a range of a few %. Target, however is to reach at least 5% at a low manufacturing cost. This requires cost efficient manufacturing methods that produce structures in a very controlled and reproducible way	Applied R & D	Mass Production	2011
Small molecule/ C60 based solar cell	Demonstration devices manufactured so far exhibit promising efficiency values.	Applied R & D	Mass Production	2011
Multi layer (multi junction) cells based on small molecules	This concept should allow manufacturing of higher efficiency cells within one process flow.	Basic R & D	First Applications	2013
QD based organic solar cells using small molecules	The performance of organic solar cells is progressing rapidly. Novel nanophotonic concepts will have to prove that they improve the preformance on top of the current development.	Basic R & D	First Applications	2013

Device	Performance	Current Status	Status 2012	Mass Production
Polymer based PV cell doped with SWNTs	For the considered application (i.e. flexible solar cells for portable applications), the target performance is 5% of conversion efficiency and a lifetime of 3000 hours (5% efficiency and 3000 hours lifetime have already been obtained in laboratories so far) The target cost is less than 1$/W	Basic R & D	First Applications	2013

Table 11 - Photovoltaics related devices

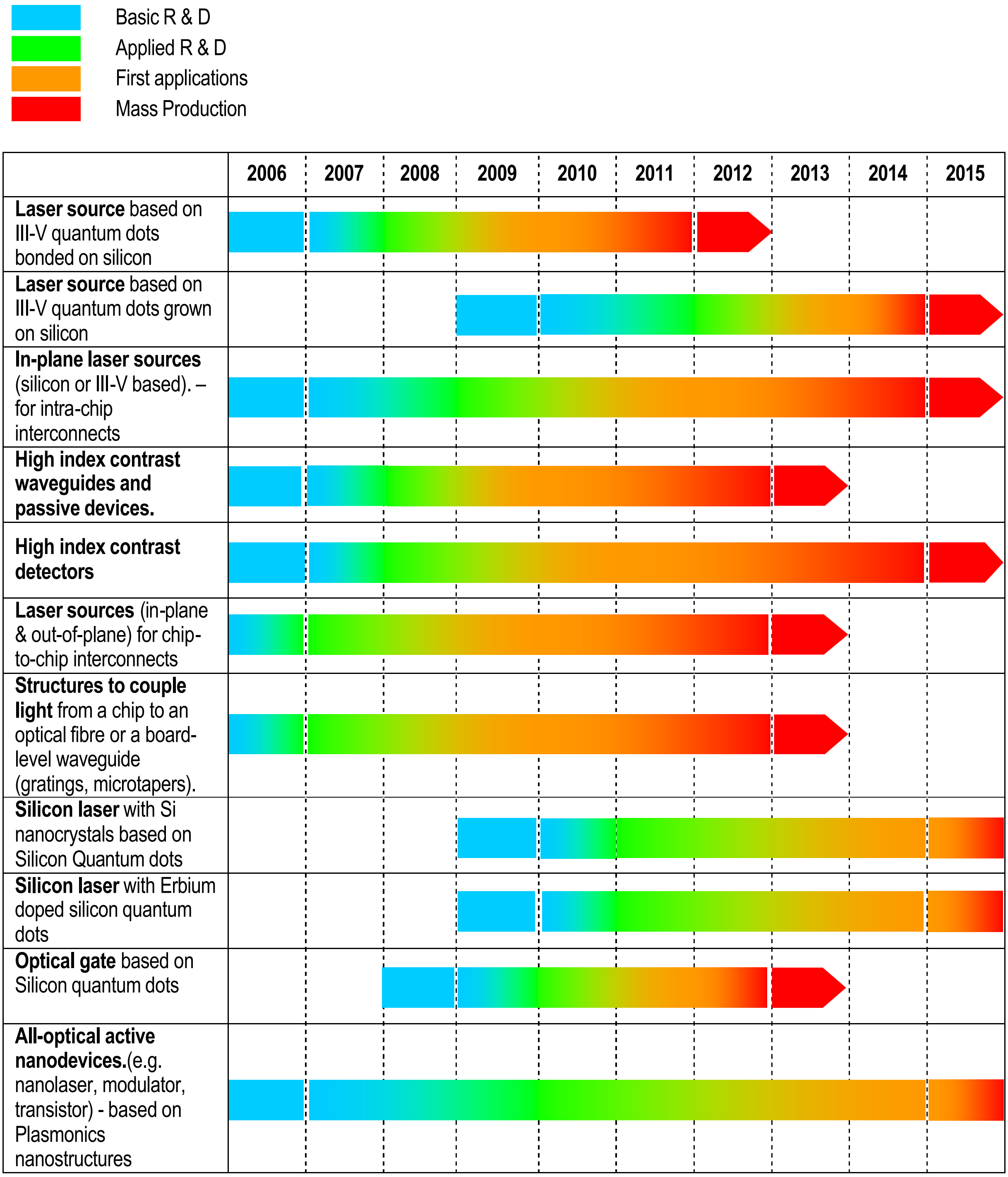
Instrumentation and equipment

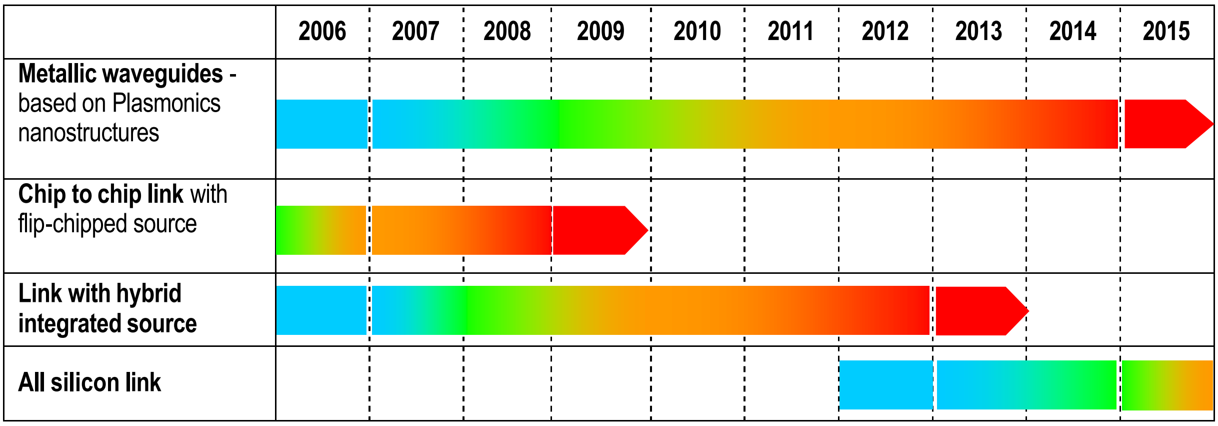
Device	Performance	Current Status	Status 2012	Mass Production
Nanostructures probes based on Si quantum dots and wires	10-100 nm apertures. Arrays can be fabricated for faster scanning. Batch fabrication compatible with volume production.	Applied R & D	First Applications	>2015
SP lithography	-Distance control between mask and photo resist: between few nm and 10 nm. The extraordinary transmission effect could be a solution to increase this distance. -Modelling: light enhancement and confinement.	Basic R & D	First Applications	>2015
Near-field microscopy	Make it more robust, so less training needed for operation.	Mass Production	Mass Production	NA
SiC "superlens" for Near-Field Microscopy	The surface of the thin film must be extremely smooth. Surface imperfections scatter light and overlay finer details of the evanescent field. The film thickness has to be carefully controlled. If the film is too thick, material losses dominate the evanescent field refocusing.	Basic R & D	First Applications	>2012
Metamaterial for optical frequencies	Structure sizes below 1μm arranged in a lattice. Fabrication of highly reproducible ~50nm structures necessary.	Basic R & D	First Applications	>2012
Active/tunable meta-materials for IR/optical frequencies	NA	Basic R & D	First Applications	>2013

Table 12 - Instrumentation related devices

C.5. Timelines for the application

Optical Interconnects




2006
2007
2008
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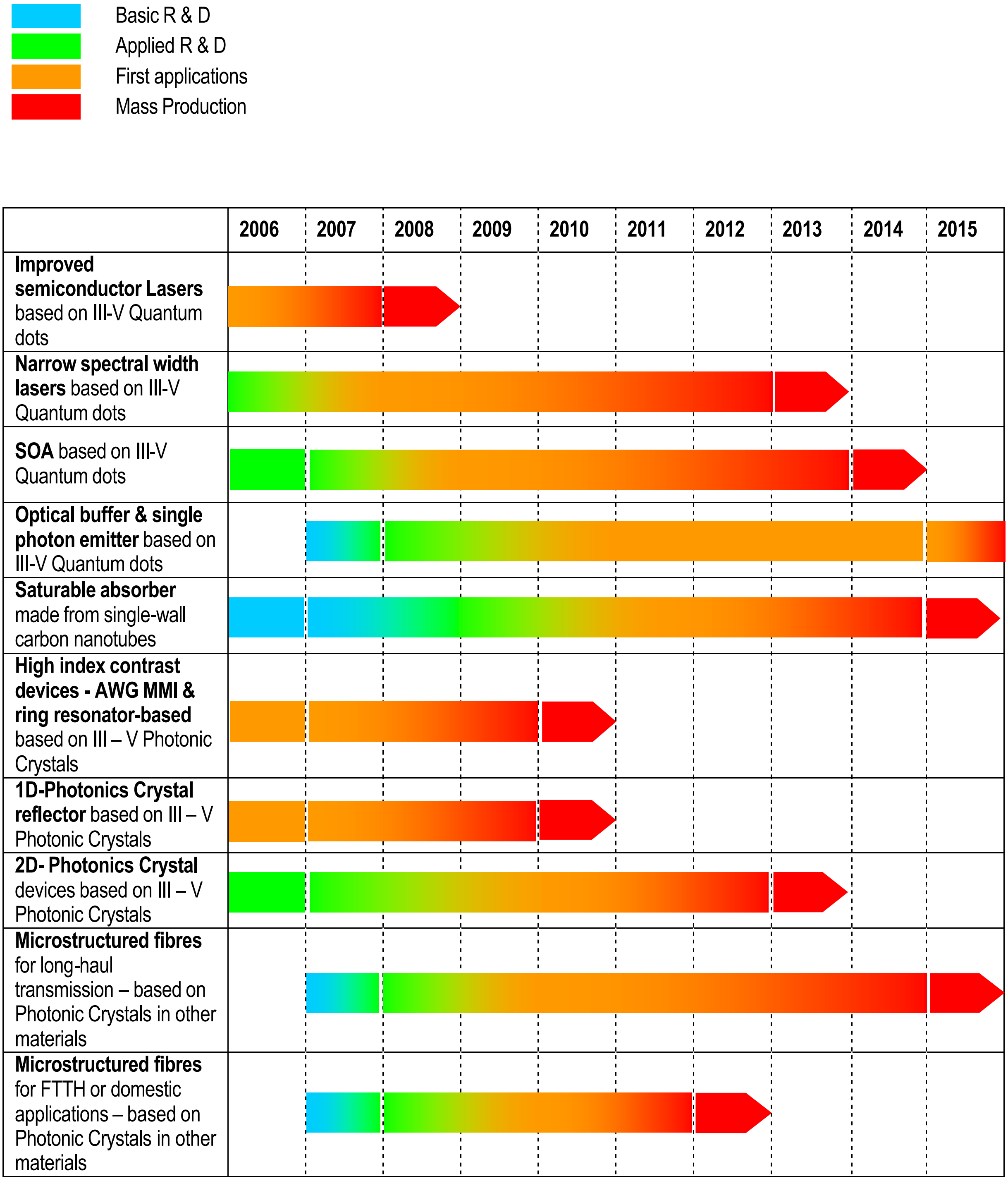
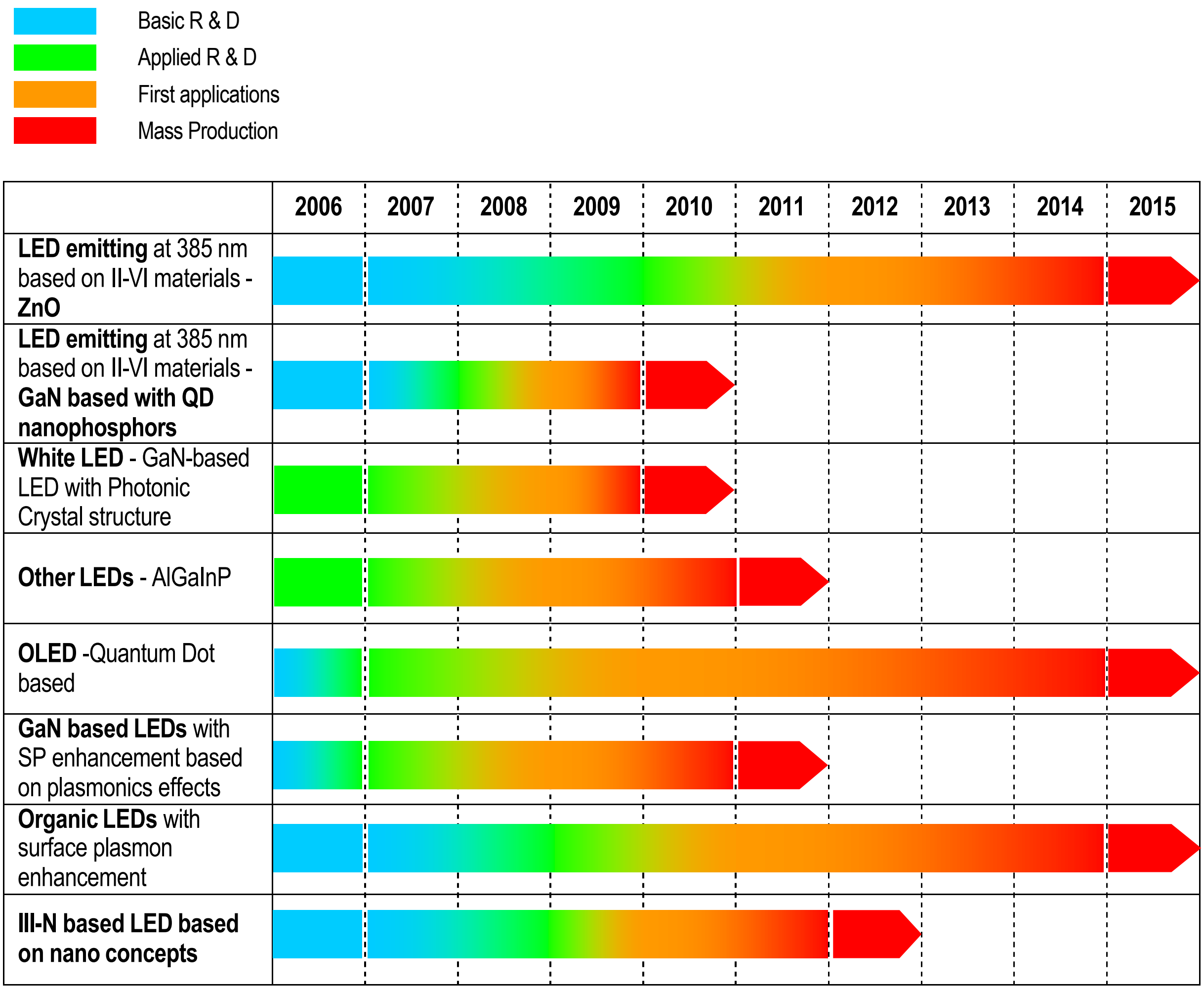
Metallic waveguides - based on Plasmonics nanostructures
Chip to chip link with flip-chipped source
Link with hybrid integrated source
All silicon link

Datacoms & Telecoms

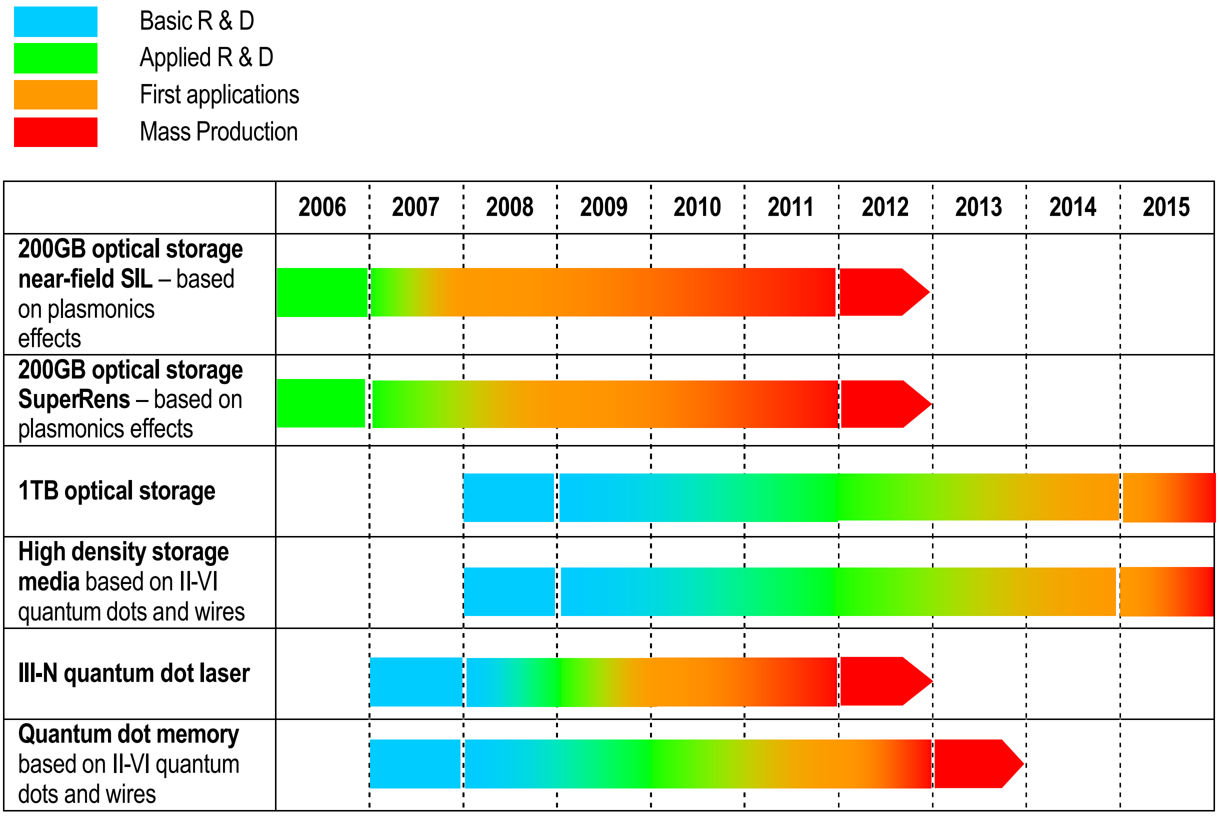


	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Microstructured fibre for other applications (lasers, amplifiers…) – based on Photonic Crystals in other materials										
Transceivers (no WDM)										
Transceivers (with WDM)										
Transceiver with integrated source										
Passive photonic integrated circuits - PIC (waveguides, splitters, filters, (de)multiplexers, delay lines etc.).										
Micro/nano-cavity laser sources -silicon or III-V based										
Slow switching/tuning functions.										
Electro-optic devices (modulators, detectors).										
All-optical devices (switches, frequency converters).										
Passive ultra-compact photonic components (e.g. optical filters, splitters, cavities, antenna) based on plasmonics effects										
Active all-optical nanodevices (e.g. modulator, transistor, nanolaser) - based on plasmonics effects										
Nanoparticles doped active fibres for optical amplification – **1st generation**										
Nanoparticles doped active fibres for optical amplification – **2nd generation**										
Nanoparticles doped active fibres for optical amplification – **3rd generation**										

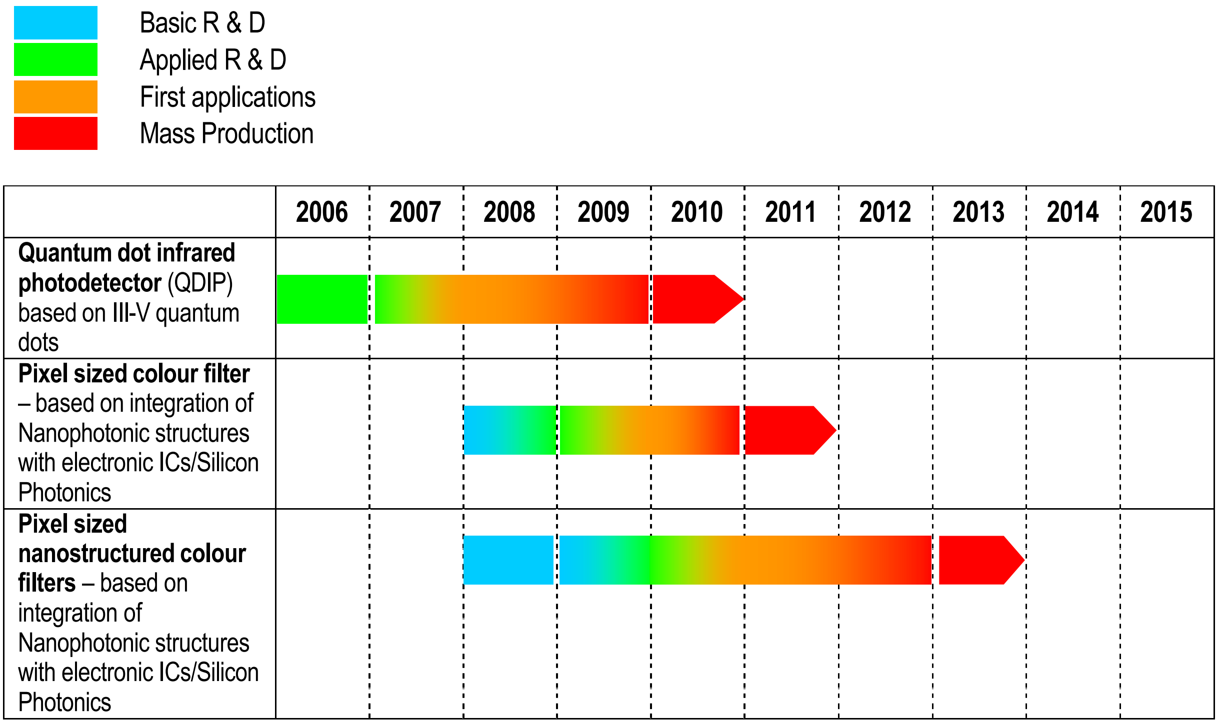
Lighting


Basic R & D
Applied R & D
First applications
Mass Production
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
LED emitting at 385 nm based on II-VI materials - ZnO
LED emitting at 385 nm based on II-VI materials - GaN based with QD nanophosphors
White LED - GaN-based LED with Photonic Crystal structure
Other LEDs - AlGaInP
OLED -Quantum Dot based
GaN based LEDs with SP enhancement based on plasmonics effects
Organic LEDs with surface plasmon enhancement
III-N based LED based on nano concepts

Data Storage

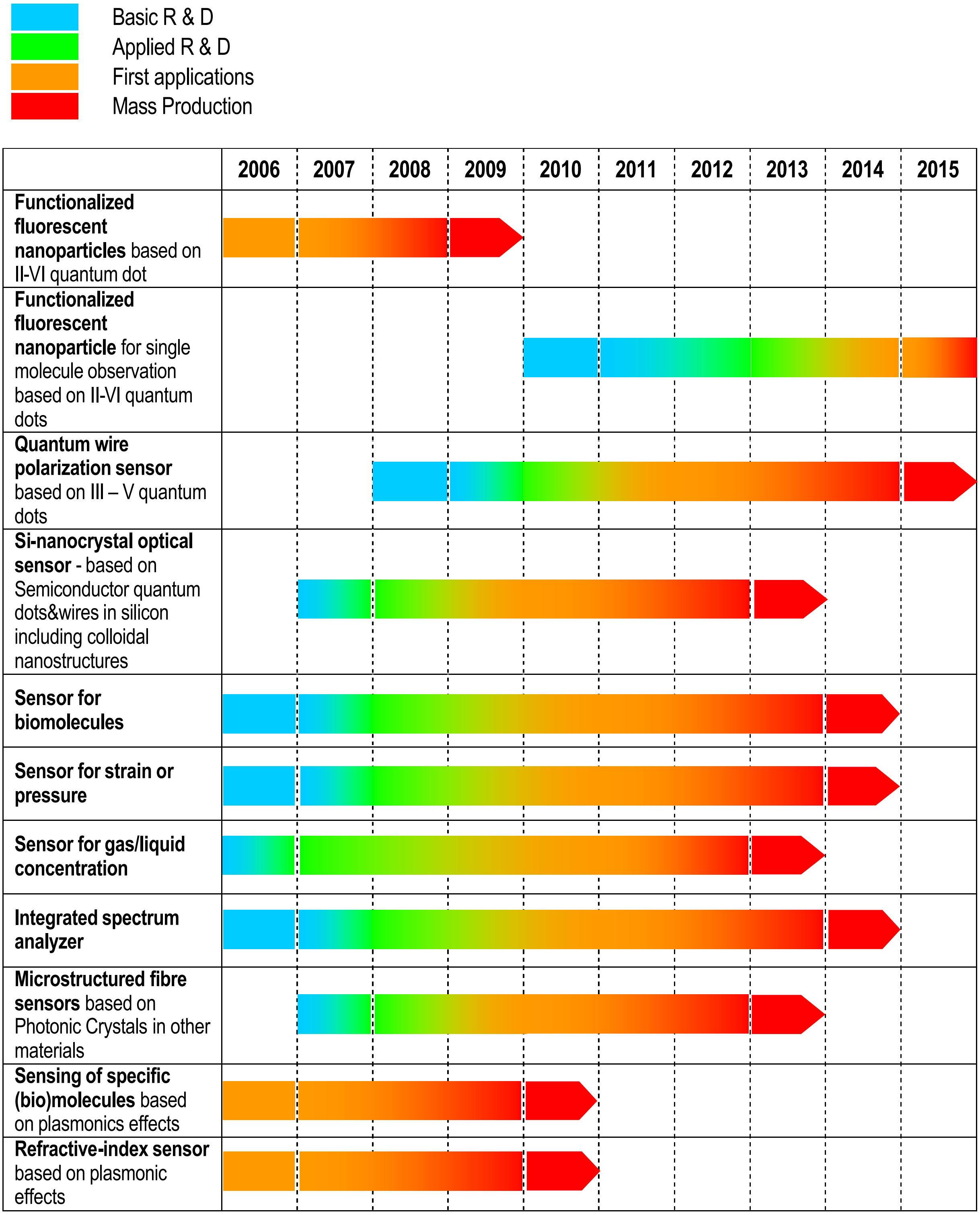


Imaging



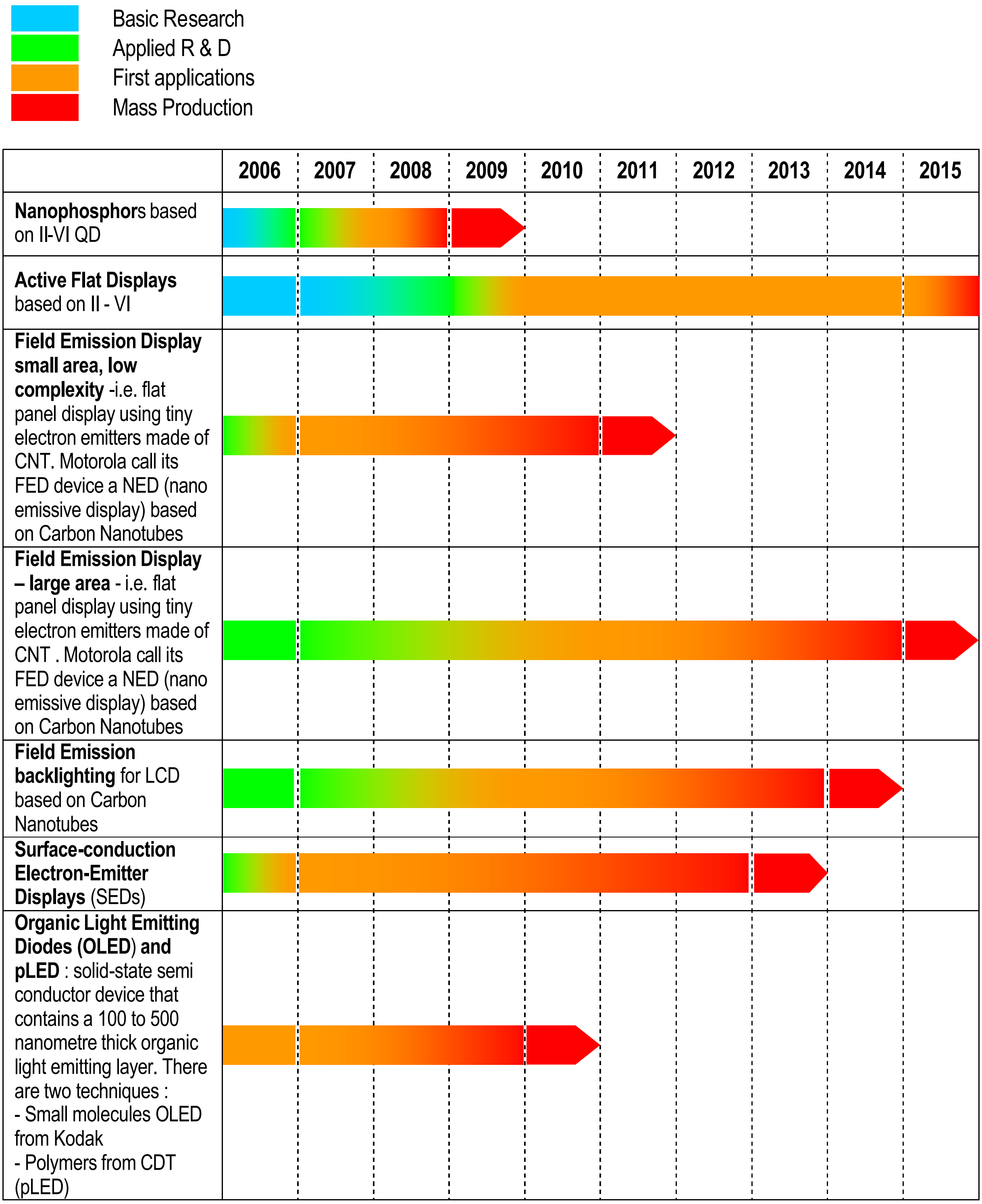
Basic R & D
Applied R & D
First applications
Mass Production
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
Quantum dot infrared photodetector (QDIP) based on III-V quantum dots
Pixel sized colour filter – based on integration of Nanophotonic structures with electronic ICs/Silicon Photonics
Pixel sized nanostructured colour filters – based on integration of Nanophotonic structures with electronic ICs/Silicon Photonics

Sensors



Basic R & D
Applied R & D
First applications
Mass Production
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
Functionalized fluorescent nanoparticles based on II-VI quantum dot
Functionalized fluorescent nanoparticle for single molecule observation based on II-VI quantum dots
Quantum wire polarization sensor based on III – V quantum dots
Si-nanocrystal optical sensor - based on Semiconductor quantum dots&wires in silicon including colloidal nanostructures
Sensor for biomolecules
Sensor for strain or pressure
Sensor for gas/liquid concentration
Integrated spectrum analyzer
Microstructured fibre sensors based on Photonic Crystals in other materials
Sensing of specific (bio)molecules based on plasmonics effects
Refractive-index sensor based on plasmonic effects

Displays


Basic Research
Applied R & D
First applications
Mass Production
2006
2007
2008
2009
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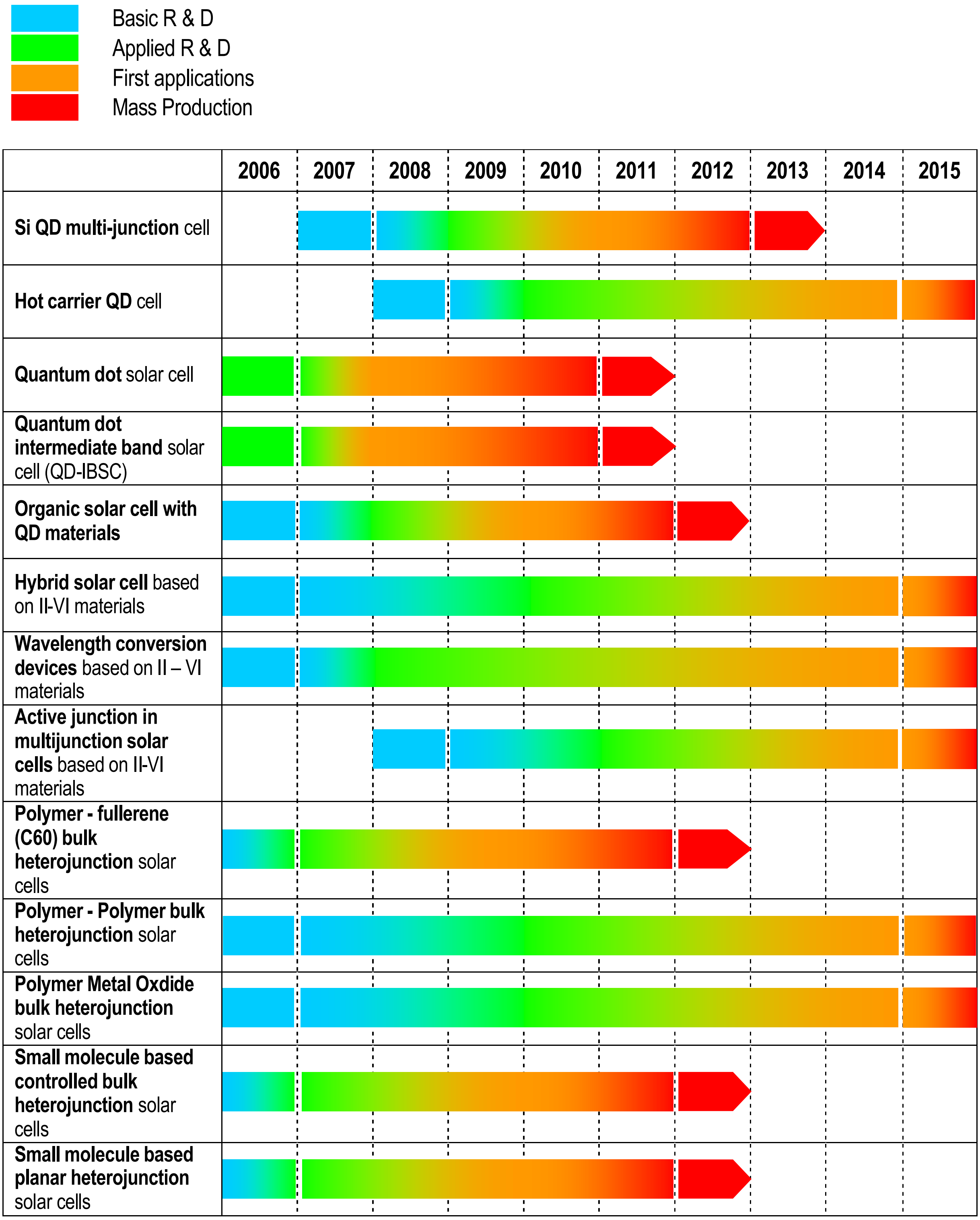
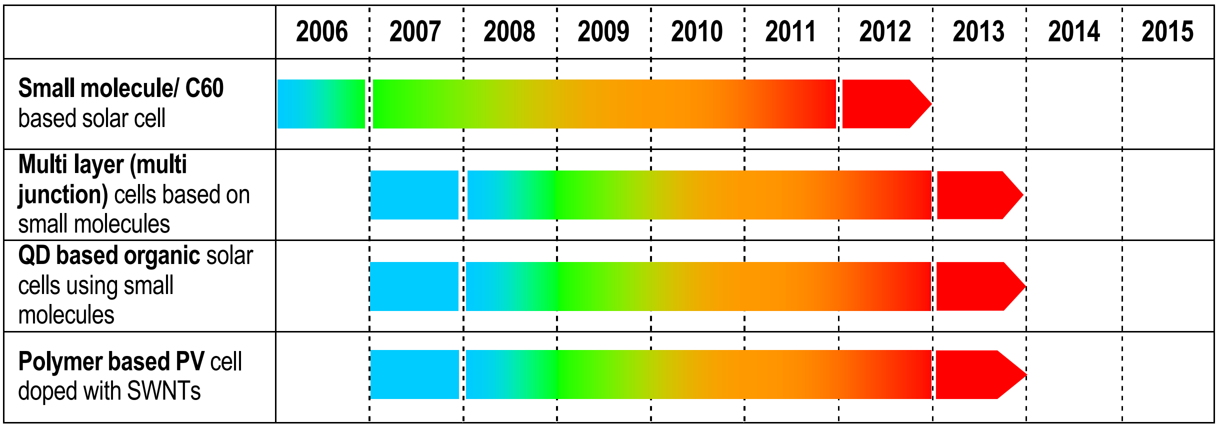
2014
2015
Nanophosphors based on II-VI QD
Active Flat Displays based on II - VI
Field Emission Display small area, low complexity -i.e. flat panel display using tiny electron emitters made of CNT. Motorola call its FED device a NED (nano emissive display) based on Carbon Nanotubes
Field Emission Display – large area - i.e. flat panel display using tiny electron emitters made of CNT . Motorola call its FED device a NED (nano emissive display) based on Carbon Nanotubes
Field Emission backlighting for LCD based on Carbon Nanotubes
Surface-conduction Electron-Emitter Displays (SEDs)
Organic Light Emitting Diodes (OLED) and pLED : solid-state semi conductor device that contains a 100 to 500 nanometre thick organic light emitting layer. There are two techniques :
- Small molecules OLED from Kodak
- Polymers from CDT (pLED)

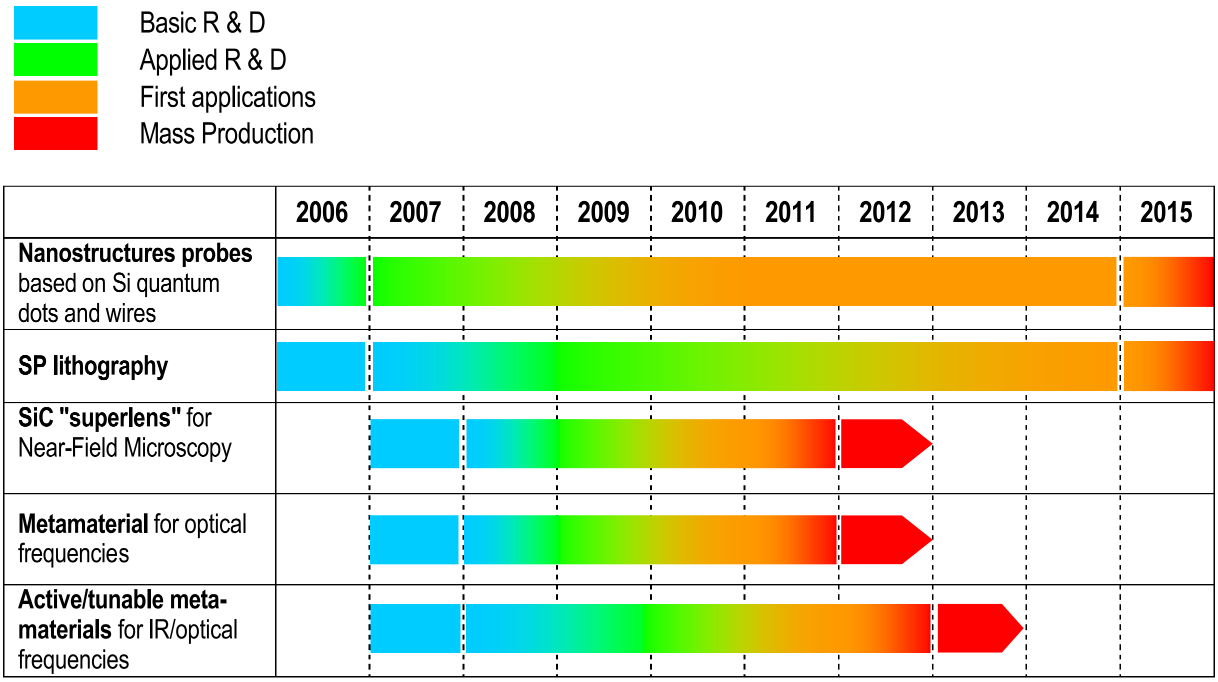
	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
AR display (anti reflective organic coating)										

Photovoltaics




2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
Small molecule/ C60 based solar cell
Multi layer (multi junction) cells based on small molecules
QD based organic solar cells using small molecules
Polymer based PV cell doped with SWNTs

<u>Instrumentation and equipment</u>



Annex D: List of MONA members, contacted experts and workshop participants

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Annex E: List of acronyms

AFM: Atomic Force Microscopy
ALD: Atomic layer Deposition
AR: Anti Reflective
AWG: Array Waveguides
CNT: Carbon Nanotubes
CRT: Cathode Ray Tube
CVD: Chemical Vapour Deposition
DND: Direct Nanoparticle Deposition
DSSC: Dye Sensitized Solar Cells
DWELL: quantum Dot-in Well detector
EFA: Erbium Doped Fibre Amplifier
EP: Electrophoresis
EU: European Union
EUV: Extreme UV
FE: Field Emission
FED: Field Emission Display
FIB: Focused Ion Beam
FOM: Fluctuation Optical Microscope
FPD: Flat Panel Display
FTTH: Fibre To The Home
HVPE: Hybrid Vapour Phase Epitaxy
IR: Infrared
LCD: Liquid Crystal Display
LED: Light Emitting Diodes
MBE: Molecular Beam Epitaxy
MCT: Mercury-Cadmium-Telluride
MOCVD: Metalorganic Chemical Vapour Deposition
MONA: Merging Optics & Nanotechnologies
nc: nanocrystals
NIL: Nanoimprint Lithography
OLED: Organic Light Emitting Display
OVPD: Organic Vapour Phase Deposition
PECVD: Plasma Enhanced Chemical Vapour Deposition
PhC: Photonic Crystal
PIC: Photonic Integrated Circuit
PLED: Polymer Light-Emitting Diodes
PV: Photovoltaic
QD: Quantum Dot
QDIP: Quantum Dot Infrared Photo detector
QLED: Quantum LED
QW: Quantum Wire
QWIP: Quantum Well Infrared Photo detector
RGB: Red Green Blue
RHEED: Reflection High Energy Electron Diffraction
SED: Surface Conduction Electron Emitter

SIL: Solid Immersion Lens
SME: Small and Medium Enterprise
SNOM: Scanning Near-field Optical Microscope
SOA: Semiconductor Optical Amplifier
SOI: Silicon On Insulator
SP: Surface Plasmon
SPR: Surface Plasmon Resonance
SuperRens: Super Resolution Near-field
UV: Ultra Violet
UV: Ultra Violet
VCSEL: Vertical Cavity Surface Emitting Laser
VIS: Visible
WDM: Wavelength-Division Multiplexing