BACAS

CAPAS CAWET

Royal Belgian Academy Council
of Applied Science

Nanotechnology: hype or opportunity?

"…But I am not afraid to consider the final question as to whether, ultimately – in the great future – we can arrange the atoms the way we want; the very atoms, all the way down!"

"There's Plenty of Room at the Bottom", December 29, 1959
Richard Feynman
Nobel Prize Physics 1965

May 2008

Koninklijk Vlaamse Academie van België
voor Wetenschappen en Kunsten

Paleis der Academiën
Hertogsstraat 1, 1000 Brussel

Académie royale des Sciences,
des Lettres et des Beaux-Arts de Belgique

Palais des Académies
rue Ducale 1, 1000 Bruxelles

Nanotechnology: hype or opportunity?

Table of Contents

1. Executive Summary

2. Introduction

3. Current Status of Nanotechnology

3.1 Analytical Methods in Nanotechnology
3.1.1 Looking at the nanoscale
3.1.2 Analytical methods
3.1.3 Availability of expertise

3.2 Nanoelectronics and Nanophotonics
3.2.1 Nanotechnology for electronics
3.2.2Nanotechnology for photonics

3.3 Impact of Nanotechnology on Materials and Manufacturing
3.3.1 Materials at the nanoscale
3.3.2 Nanotechnology devices and applications
3.3.3 Enabling technologies

3.4 Nanotechnology in the Food Industry
3.4.1 Introduction
3.4.2 Nanotechnology for food

3.5 Impact of Nanotechnology on Sustainable Generation of Energy

3.6 Nanotechnology and Environment
3.6.1 Introduction
3.6.2 Nanotechnology and water purification
3.6.3 Nanotechnology and remediation of contaminated soil
3.6.4 Nanotechnology and gas cleaning

3.7 Nanotechnology: Health and Environmental Risks
3.7.1 Introduction
3.7.2 Toxicity of nanomaterials
3.7.3 Ecotoxicity of nanoparticles
3.7.4 Regulatory issues and research

4. Nanotechnology in Belgium and Europe

4.1 Introduction

4.2 Nanotechnology and the Belgian Science Policy Office (BELSPO)
4.2.1 The Interuniversity Attraction Poles (IAP)
4.2.2 Research infrastructures

4.3 Nanotechnology in Flanders
4.3.1 The Flemish Science Policy Council (VRWB)
4.3.2 Nanotechnology in Flemish higher education

4.3.3 Nanotechnology research at Flemish universities
4.3.4 Nanotechnology at Flemish R&D institutions

4.4 Nanotechnology in Wallonia and Brussels
4.4.1 Education and training in French-speaking universities
4.4.2 Nanotechnology research in French-speaking universities

4.5 Nanotechnology and the Belgian Industry

4.6 Nanotechnology Initiatives by the EC and in some European Countries
4.6.1 The European Commission
4.6.2 Some European Countries

5. Conclusions and Recommendations

6. References

The Belgian Academy Council of Applied Science (BACAS) consists of CAWET (a Committee of the Koninklijke Vlaamse Academie van Begië voor Wetenschappen en Kunsten) and CAPAS (a Committee of the Academie royale des Sciences, des Lettres & des Beaux-Arts de Belgique). Its members come from academia and from industry

Composition of the CAWET/CAPAS Study Group

Nanotechnology: hype or opportunity

Chairmen
Em. Prof. dr. Yvan Bruynseraede, KULeuven
Dr. ir. Guy Haemers, Inventures Group Europe

Members
Em. Prof. dr. Philippe Bourdeau, ULB
Em. Prof. dr. Frans Deschryver, KUleuven
Ir. Jan Meneve, VITO
Em. Prof. dr. Harry Reynaers, KULeuven
Prof.dr. Marc Van Rossum, IMEC

1. Executive Summary

While handling the questions for the final exam a professor caused a stir among the students. One of them leapt up and asked: but professor, those are the same questions as last year! That's right he answered, but the answers have changed.
This expresses the transformation nanotechnology generates through science, technology and industry. It's the generation of new answers to familiar questions; of new solutions for new challenges. Having access to elementary components of materials, scientists have the possibility to pave the way towards completely new paths in as well innovative as familiar industrial segments and give birth to totally new industrial areas.
This Report summarises the origin and basics of nanotechnology and the impact it has on many industrial activities such as electronics, material, manufacturing, energy, food … and the inherent huge opportunities for science and technology. It also addresses the problem of health and environment, and gives an overview of the nanotechnology efforts in Belgium.
It is foreseen that the market for nano-products will rise exponentially in the next decade and grow to a trillion euro by 2015. Nanotechnology will create jobs, but has also a social and ethical impact which is at the basis of future strategies for technological risk assessments.
(The Report is also available on the website http://www.kvab.be/CAWET.aspx)

Nanotechnology isn't hype or theory: It's becoming one of the world's fastest-growing, highest-impact industries.

Summary of recommendations

Here are some points for consideration on the coming nano-wave:

1. Nanotechnology is foremost a collection of productivity enhancing technologies that will permeate many industries. The development of enabling technologies in the field of machine tools, quality control and cost estimates are an important factor to realise this permeation.

2. Business ventures should be nurtured that seek to reinvest nano-enabled productivity gains from established industries into the growth of new industries.

3. Nanotechnology education is a thorny problem due to its position at the intersection of many disciplines and is likely to work best in (virtual) nano-institutes.

4. Nano centres-of-excellence should provide retraining programs for professionals in order for members of the highly skilled science and engineering workforce to learn enough about other disciplines to collaborate effectively in interdisciplinary teams.

5. The comparative advantage that Belgium enjoys in creating high-tech start-up companies can be enhanced by educating researchers about entrepreneurship while likewise educating MBA's about nanotechnology.

6. Nanotechnologists should adopt a code of conduct for responsible nanosciences and nanotechnologies, e.g. in conformity with the recent European Commission recommendation how to govern research in this field

2. Introduction

When the characteristic length scale of the microstructure is in the 1-100 nm range, it becomes comparable with the critical length scales of physical phenomena resulting in the so-called "size and shape effects". This leads to unique properties and the opportunity to use such nanostructured materials in novel applications and devices**.** Indeed, materials in this size range can exhibit fundamentally new behaviour when their sizes fall below the critical length scale associated with a given physical or chemical property **(Figure 1).**
Nanoscience and nanotechnology is however not merely working with matter at the length scale below 100 nm, but also includes research and development of materials, devices, and systems that have novel properties and functions due to their nanoscale dimensions or components. It also touches upon a wide range of fields, from physics, chemistry and biology to electronics, engineering, computation, and medicine. Like information technology, nanotechnology has the potential to impact virtually every industry, from aerospace and energy to healthcare and agriculture.
Today there is a nanotechnology gold rush. Scores of researchers and institutions are scrambling for a piece of the actions. However, it is becoming increasingly clear that we are only beginning to acquire the detailed knowledge that will be at the heart of future nanoscience and nanotechnology.

Characteristic lenghts in solid-state science model		
Field	Property	Scale length
Electronic	Electronic wavelength	10-100 nm
	Inelastic mean free path	1-100 nm
	Tunneling	1-10 nm
Magnetic	Domain wall	10-100 nm
	Spin-flip scattering length	1-100 nm
Optic	Quantum well	1-100 nm
	Evanescent wave decay length	10-100 nm
	Metallic skin depth	10-100 nm
Superconductivity	Cooper pair coherence length	0.1-100 nm
	Meissner penetration depth	1-100 nm
Mechanics	Dislocation interaction	1-1000 nm
	Grain boundaries	1-10 nm
	Crack tip radii	1-100 nm
	Nucleation/growth defect	01.-10 nm
	Surface corrugation	1-10 nm
Catalysis	Surface topology	1-10 nm
Supramolecules	Kuhn length	1-100 nm
	Secondary structure	1-10 nm
	Tertiary structure	10-1000 nm
Immunology	Molecular recognition	1-10 nm

Fig. 1. Characteristic length scales of various processes (Source: Materials Today)

Past, present and future

The reason for the widespread interest in this field is that materials can exhibit very different or enhanced properties compared with the same material at a larger size. The two main reasons for this change in behaviour are an increased relative surface area, and the dominance of quantum effects. An increase in surface area (per unit mass) will result in a corresponding increase in chemical reactivity, making some nanomaterials useful as catalysts to improve the

efficiency of fuel cells and batteries or making them ideal for use as absorbers and sensors. As the size of matter is reduced to tens of nanometres or less, quantum effects can begin to play a role, and these can significantly change a material's optical, magnetic or electrical properties.
The techniques used in nanotechnology are categorised as either 'top-down' or 'bottom-up.
"Top-down" techniques involve starting with a block of material, and etching or milling it down to the desired shape. In contrast, 'bottom-up' involves the self-assembly processes of smaller sub-units (atoms or molecules) to make ordered arrangements spontaneously, given the right conditions. These two methods have evolved separately and have now reached the point where the best achievable feature size for each technique is approximately the same, leading to novel hybrid ways of manufacture.
It is only in recent years that sophisticated tools have been developed to investigate and manipulate matter at the nanoscale, which have greatly affected our understanding of the nanoscale world. A major step in this direction was the invention by Rohrer and Binnig in 1982 of the scanning tunnelling microscope (STM), and in 1986 by Binnig, Quate and Gerber of the atomic force microscope (AFM). These tools use nanoscale probes to image a surface with atomic resolution, and are capable of picking up, sliding or dragging atoms or molecules around a surface to build rudimentary nanostructures.
The discovery of the fullerene molecule C60 in 1985 (Kroto, Smalley and Curl), the subsequent discovery of carbon nanotubes (CNTs) in 1991 (Iijima) and more recently the development of graphene (Geim and Novoselov in 2004) have launched entirely new fields of material research and development. It is now well established that those different carbon based structure are ideal model systems for studying the physics in two-and one-dimensional solids and have significant potential as building blocks for various practical nanoscale devices.
It is important to view the development in the nano-field as an outgrowth of highly disciplined collaborations that produced a suite of novel synthesis and measurement advances. We can expect that the next several years will hold spectacular advances in the application of these instruments and materials in a wide variety of existing as well as new technologies. With deliberate and concerted efforts to tailor the structure of materials at the nanoscale, it will become possible to engineer novel materials that have entirely new properties never before identified in nature.

A new industrial revolution

The discovery of atom manipulations and new carbon structures are just two of many innovations percolating in the world of nanoscience and nanotechnology. There are nanoparticles being developed that could greatly improve pharmaceuticals because their size, structure and behaviour can be used to combat illnesses beyond the reach of conventional drugs. Nanomaterials that can repel stains or kill bacteria are being built into clothing fabric. Food companies are experimenting with nanoparticles that can be incorporated into packages to detect spoilage or pathogens. Cosmetics companies have developed products with nanoparticles that, because of their microscopic size and novel properties, allow sunscreens and moisturizers to perform better. And these are just some of the current and near-to-market applications. Nanoscience and nanotechnologies are widely seen as having huge potential to bring benefits in areas such diverse as drug development, water decontamination, information and communication technologies, high performance batteries, cheap solar cells, more sensitive sensors, and the production of stronger and lighter materials. They are attracting rapidly increasing investments from governments and from businesses in many parts of the world. It has been estimated that global investment in nanotechnologies is currently around 5 billion EUROS. The number of publications increased sevenfold from 1996 (5.000) to 2006

(35.000); the number of patents increased fourfold from 1996 (400 patents) to 2003 (1500 patents). Overall, experts estimate that innovations sparked by various types of nanotechnology will soon encompass a global market in goods and services worth $1 trillion. Clearly, today, small is big.

Against this background of increased research funding and interest from scientists and industry, several non-governmental organizations and some nanotechnologists have expressed concerns about current and potential future developments of nanotechnology. These include uncertainties about the impact of new nanomaterials on human health, questions about the type of applications that could arise from the expected convergence, in the longer term, of nanotechnologies with technologies such as biotechnology, information technology and artificial intelligence.

Exploration of this new world is likely to generate a new industrial revolution as well as its own ethical problems in 10 tot 20 years from now, which we have to anticipate. This new frontier confirms the infinite character of scientific and technological exploration.

Four generations

Today, the nanotechnology revolution is still at a very early stage. Most applications to date can be described as 'bulk nanotechnology' – i.e. the commercial-scale production of ultra-thin films and nano-sized particles, such as metal oxides and clays. Carbon fullerenes – nanotubes and 'bucky-balls' – are a further particularly exciting class of materials once methods have been developed to manufacture them inexpensively in industrial quantities. M.C. Roco of the U.S. National Nanotechnology Initiative has described four generations of nanotechnology development. The current era, as he depicts it, is that of passive nanostructures, materials designed to perform one task. The second phase introduces active nanostructures for multitasking; for example, actuators, drug delivery devices, and sensors. The third generation is expected to begin emerging around 2020 and will feature nanosystems with thousands of interacting components. A few years after that, the first integrated nanosystems are expected to be developed. **(Figure 2)**

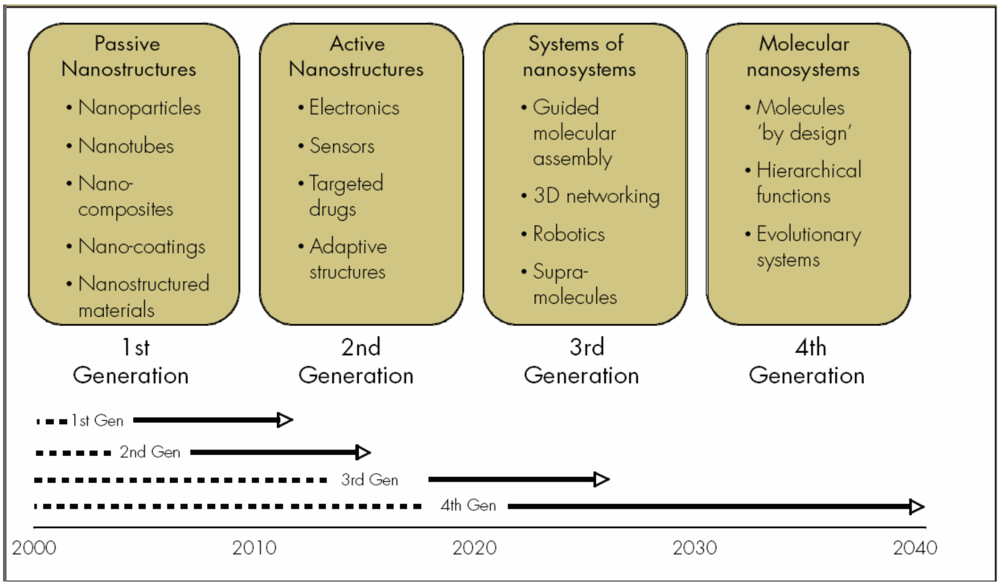

Fig. 2. Development of nanotechnology 2000-2040
(Based on Roco, M.C., AIChE. J. 50(5), 890-897, 2004)

In what follows we provide an overview of some key current developments in nanoscience and nanotechnologies, address the importance of risk-based research and discuss some possibilities for the future Nanotechnology R&D in Belgium. It should be noted that the Report covers some major domains and applications but is not exhaustive.

3. Current Status of Nanotechnology

3.1 Analytical Methods in Nanotechnology

3.1.1 Looking at the nanoscale

Nanostructured materials have grown explosively in the last decade, because of the increasing availability of tools of characterisation and manipulation at the nanoscale.
Scanning probe microscopy (SPM) combined with high-resolution electron microscopy (HRTEM), has enabled direct images of the structures and the study of properties at the nanoscale **(Figure 3)**. For example, scanning tunnelling spectroscopy and surface potential atomic force microscopy provide information on the electronic structure and related properties. Phase imaging with nanoscale contrast combined with sub-nanometer resolution topography measurements can be done using tapping mode atomic force microscopy. Magnetic force microscopy directly images magnetic domains, and magnetic resonance microscopes can detect nuclear or electron spin resonance with submicron spatial resolution.

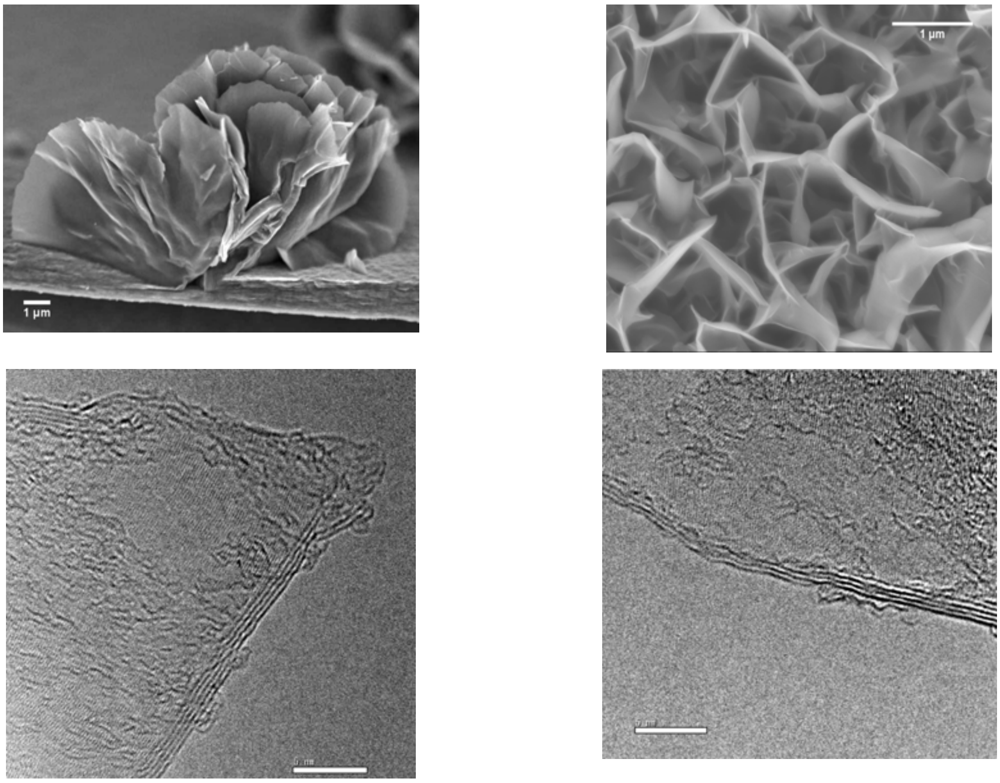

Fig. 3. Top pictures: high resolution SEM micrographs of plasma grown graphene sheets (nano-thick graphite flakes), side- and topview. Bottom pictures: high resolution TEM micrographs demonstrating that the graphene flakes are only 4 to 6 graphite planes thick. (Courtesy VITO)

Newer versions of nanomanipulators are being developed by using technologies such as nanoelectromechanical systems (NEMS).
Scanning Nearfield Optical Microscopy (SNOM) allows optical access to sub-wavelength scales by breaking the diffraction limit. Optical tweezers, using a laser beam to manipulate atoms and particles, provide an elegant means to investigate the mechanical properties and dynamics of particles and molecules. In addition to near field optical methods, the development of a wide array of far field fluorescence microscopy techniques with now lateral resolution far below the diffraction limit has added a substantial number of techniques allowing nm resolution in material and bioscience in addition to in depth analysis. Single-molecule fluorescence spectroscopy (SMFS) has recently developed into a powerful tool for studying biocatalytic activity and biophysical phenomena, combining high spatial with excellent temporal resolution.
Nanoindentation has emerged as a powerful tool for measuring nano- and microscale mechanical properties. Nanomechanics performed using the atomic force microscope enables the study of single molecules, and is valuable in understanding folding and related problems in biological molecules.
Neutron- and synchrotron high energy X-ray radiation represent very useful probes for ultra fast, non-destructive characterisation of nanostructured materials. These techniques allow the spatially resolved determination of gradients in the atomic structure, chemical composition and micro-structural inhomogeneities in nanomaterials, enabling the atomic-level understanding between structure and function. An extensive overview of the field of nanometrology techniques can be found in the Eight Nanoforum Report: Nanometrology, www.nanoforum.org.

3.1.2 Analytical methods

The essence of nanoscience and nanotechnology is the ability to understand and manipulate matter to create structures at the nanoscale with potentially novel properties and/or functions. Typical examples are available or still under development in all branches of hard and soft condensed matter. Characterization of the structure, size and shape of nanosized samples in the range from 5nm up to 1000nm needs highly specific tools, the majority of these being only recently developed or still under development. Two groups of experimental tools are available: those allowing to visualise the nanosized objects in real space and the ones extracting similar information from a reciprocal space approach (scattering and diffraction).

Real space analytical tools

In this group TEM and SEM continue to be very successful when applied under static conditions, although very often specific sample manipulation is needed prior to analysis and this might well affect the results. The latest development in the field of electron microscopy is Cryo-TEM which is extremely promising in soft condensed matter related nano-research on complex samples. On the other hand, x-ray imaging based on absorption contrast in matter profits from the latest developments in synchrotron radiation research. Today a large part of nanotechnology related problems pertain to structural research on the nanostructure of surfaces. SPM probes surface structures even up to atomic detail. Fascinating developments are the use of the latter techniques in a time-resolved way.

Reciprocal space tools

They are based on the scattering of x-rays, neutrons or electrons and offer a number of advantages, but can only safely be applied if suitable and correct physical models are available. The main advantage is the simultaneous accessibility of the proper length and time-scales of the nanosized objects under investigation. Moreover, the present sources are tunable, allowing for proper selection of the wavelengths as needed. In the case of neutrons and x-rays studies are performed with special devices allowing to collect the proper information of the nanosize objects at small angles by small angle x-ray scattering and/or small angle neutron scattering (SAXS and SANS).
Neutron scattering experiments need a neutron source which up to today is still a nuclear reactor by preference with high neutron flux. No such reactors are available in Belgium. At present there are no neutron sources in Europe allowing time-resolved experiments. Synchrotron radiation (SR) sources offer a brightness surpassing an x-ray laboratory source by several orders of magnitude. Perfect tunability in the x-ray wavelength domain creates the opportunity for high and low resolution studies in situ in a time resolved way using nanofocusing devices and / or nanometer sized beams.

3.1.3 Availability of expertise

Although powerful neutron and x-ray sources are not available in Belgium, on the other hand, there is considerable state-of–the-art laboratory scale instrumentation and top expertise for electron- and scanning probe microscopy, x-ray scattering and diffraction, and fluorescence microscopy. Instrumentation and expertise are mostly developed in the context of university or research institute laboratories.
The situation is quite different for access to the European Large Facilities in Grenoble such as ESRF (European Synchrotron Radiation Facility) and ILL (Institut Laue Langevin).The Belgian Federal government supports participation in ESRF and ILL. Moreover, in the framework of a Dutch (NWO) – Flemish (FWO) collaboration a CRG (Collaborating Research Group) exploits at ESRF beamline BM26 with considerable facilities for soft and hard nanomatter research. It is puzzling that only a small number of research groups in Belgium found their way towards these powerful instruments for nanoscience and nanotechnology. Future competition of Flemish research and industry needs our presence in the first row. Hence one has to consider the future position of Flanders in the framework of European collaborations as pointed out in a recent study of the VRWB. One way to proceed could be the foundation of a Flemish virtual expertise centre for nanoscience and nanotechnology bringing together and placing into profile all existing competences in universities and research centres.

3.2 Nanoelectronics and Nanophotonics

3.2.1. Nanotechnology for electronics

Top-down approach

Nanoelectronics are a major driver for the spectacular growth of the integrated circuit (IC) industry, one of the most remarkable trends in today's world economy. Fast expansion of this sector started very early after the invention of the first integrated circuits (1959 - 1960), and has since long been associated with “Moore's law”. To put the latter in Moore’s own words: “With unit cost falling as the number of components per circuit rises, by 1975 economics may

dictate squeezing as many as 65.000 components on a single silicon chip". 40 years later, unit cost is still decreasing with the number of components, and as long as this favourable trend persists, the "law" will remain firmly in place.
The decrease of the average transistor price has been mainly achieved by the reduction of its size. This allows putting more components on the same silicon area, and therefore strongly reducing the manufacturing time and consumables required for the production of integrated circuits. Device physics tells us that the performance of the MOSFET (Metal-Oxide-Semiconductor Field-Effect Transistor) - mainly its speed and overall power dissipation - should improve with decreasing dimensions, providing the scaling rules are properly applied. This statement has been amply legitimated by experiments and provides significant added value to Moore's law, thereby considerably strengthening its impact on CMOS (Complementary Metal Oxide Semiconductor) development.
Over a decade ago, the National Technology Roadmap for Semiconductors (now the International Technology Roadmap for Semiconductors, or ITRS) was established in order to codify the expected progress of Moore's Law into a set of process targets and specifications, structured by the definition of future CMOS technology nodes. Today, the ITRS compiles the results of a worldwide consensus building process, predicting the main trends of CMOS technology out to a 15 years horizon. Therefore, the popular formulation of Moore's law as a "doubling of the number of IC components every 18 months" must be taken as an average over many actors and a fairly long time frame. **(Figure 4)**

	Year of Introduction	Transistors
4004	1971	2,250
8008	1972	2,500
8080	1974	5,000
8086	1978	29,000
286	1982	120,000
Intel386™ processor	1985	275,000
Intel486™ processor	1989	1,180,000
Intel® Pentium® processor	1993	3,100,000
Intel® Pentium® II processor	1979	7,500,000
Intel® Pentium® III processor	1999	24,000,000
Intel® Pentium® 4 processor	2000	42,000,000
Intel® Itanium® processor	2002	220,000,000
Intel® Itanium® 2 processor	2003	410,000,000

Fig. 4. Moore's law in action (Source: Intel)

The forces driving Moore's Law can be divided into technology push and market pull drivers. Push drivers are the technology innovations that enable low cost manufacturing of smaller transistors. Market pull drivers are the new applications that these advanced devices enable. According to the present perspectives, technology push factors can still drive further miniaturization for about a decade, but at that stage a significant slowdown in the scaling process should be expected. As a result, it is easy to predict that, when measured on a historic time scale, Moore's Law will "soon" become invalid.
To complete this picture, it is useful to mention the bifurcation model, which may well represent the endpoint of CMOS evolution some years from now. According to this scheme, the slowdown of the ITRS cycles (be it for technical or for economical reasons) will signal the

onset of maturity for CMOS technology. In this phase, the exponential growth of CMOS will gradually become linear, whereas a diversification of technologies will provide further expansion drive to the IC market. The global timescale provided by Moore's clock will be replaced by a number of smaller synchronized domains. Moreover, the market forces will attribute stronger weight to design activities than is the case today, since the latter will become a crucial interface between the ever changing market needs and a more stable process technology.

Bottom-up approach

Major breakthroughs in bottom-up nanotechnology have given us the ability to structure materials and devices starting from building blocks of nanometer dimensions. The synthesis and control of electronic materials structures at the nanoscale can produce new material properties and device characteristics in unprecedented ways, resulting in increased performance and new functionalities. The reason for this is that the nanopatterned materials can give rise to new and improved electronic properties heretofore unavailable in conventional materials and devices. Thus, essentially any material property can be changed and engineered through the controlled size-selective synthesis and assembly of nanoscale building blocks. Nanostructuring therefore represents the beginning of a new age in technological development. The field is rapidly expanding worldwide, with semiconductor technology in general, and nanoelectronics in particular, as one of the main beneficiaries. An important characteristic of this domain is the rapidly mounting level of interdisciplinary activity. The intersections between the various disciplines define areas where much of the novel activity resides, and this activity is growing in importance. **(Figure 5)**

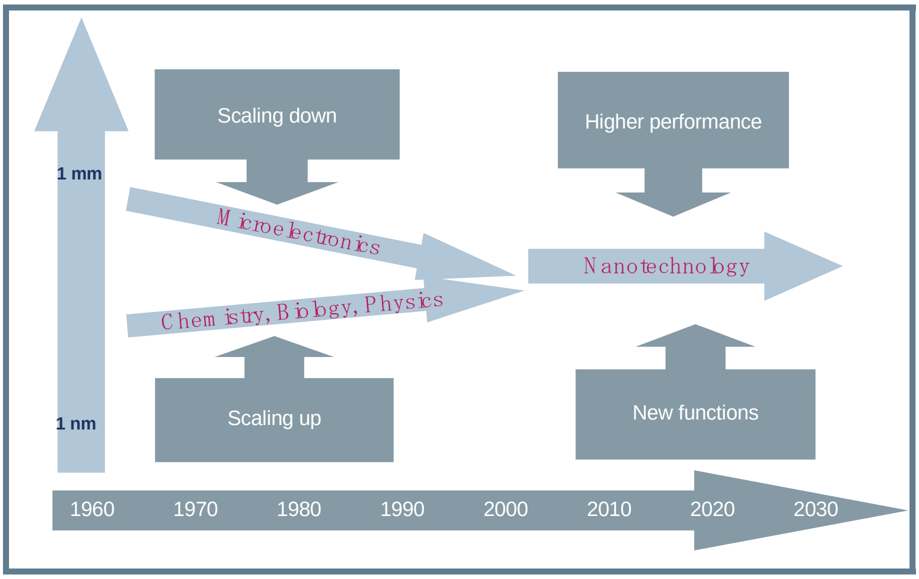

Fig. 5. Defining new domains in nanoelectronics by the convergence of top-down and bottom-up disciplines. (Source: IMEC)

Synthesis and assembly strategies being employed in nanostructuring range from sophisticated deposition and etching techniques down to fundamental biological methods for self-assembling molecules, and a variety of physical and chemical techniques for making

clusters or nanoparticles. Their combination will create unprecedented capabilities in the manufacturing of functional structures for nanoelectronics.
In fact, bottom-up nanotechnology is already used in the development of the latest generations of CMOS devices, for pathfinder devices exploring new avenues and for components at the boundary of biology and electronics (bio-electronics, bionics, biosensors…). However, it is not very useful to make nanoscale devices if they cannot be assembled in a circuit with interconnects that are themselves nanoscale. Thus, a complete rethinking of this area is required, based on the potentialities offered by generic nanoscale structures such as quantum wires.

3.2.2. Nanotechnology for photonics

Nano photonics is the research field that studies the generation, manipulation, storage, scattering and amplification of light at length scales that are typically smaller than the wavelength of light. Nanophotonics can provide ultra-small optoelectronic components for high bandwidth and high speed optical transmission. This technology has the potential to revolutionize telecommunications, computation and optical sensing. Some of the most characteristic application domains for nanotechnology in photonics are:

Waveguide couplers
In this technology, it is important to achieve extremely low coupling losses between an optical fibre and a high-index contrast waveguide. This can be achieved by using high-index contrast materials incorporating special nanosize tip structures.

Photonic crystals
Photonic crystals allow to tailor the path of photons in matter in some well-defined directions by defining an artificial periodic structure in the “forbidden” regions. The artificial crystal produces a photonic bandgap, thereby blocking the propagation of light in some parts of the optical medium.

Optical metamaterials
In their most sophisticated version, photonic crystals turn into metamaterials, an object that gains its material properties from its structure rather than inheriting them directly from the materials it is composed of. Metamaterials are promising for a diversity of optical/microwave applications, such as new types of beam steerers, modulators, band-pass filters, super lenses, microwave couplers, and antenna radomes.

Optical biosensors
Biosensors cover a very different application area, in which one tries to detect biological entities with optoelectronic devices. In optical biosensors, the presence of a bio structure is signalled by the emission of light with well-defined properties. One of the most promising detection mechanisms is based on surface plasmon resonances, which measure the change of refractive index at the surface of a metallic film on which biological material has been deposited.

Organic light-emitting diodes
OLED’s have been emerging for years, but they are gradually getting more and more exciting, starting to give traditional LED’s a run for their money. In a few years we might be able to wallpaper our home in light-emitting sheets, or maybe turn all our windows into heads-up

displays. They may also be the future of energy-efficient lighting. Recently, researchers used nanowires to create the first active matrix display containing OLED's.

3.3 Impact of Nanotechnology on Materials and Manufacturing

3.3.1 Materials at the nanoscale

The physical and chemical properties of nanomaterials can differ significantly from those of the atomic-molecular or the bulk materials of the same composition. Suitable control of the properties and response of nanostructures can lead to new devices and technologies. It should be recognised however that well established industrial processes, such as catalysis and photography, already employ nanostructured materials for several decades.

The growth of nanotechnology in the last decade has been possible because of the success in the synthesis of nanomaterials in conjunction with the advent of tools for characterisation and manipulation. For example, a wide variety of nanosized single- and multiphase particles are currently being synthesized using vapour-phase (inert gas condensation, flame and plasma synthesis, spray pyrolysis), solution precipitation (including sol-gel synthesis), and solid-state processes (thermal treatment followed by mechanical attrition), or a combination of these techniques.

The most striking issue in nanotechnology is the uniting of disciplines: materials science and engineering, physics, molecular biology and medicine, chemistry, etc. - are now able to communicate on the same wavelength. Nanoscience and technology is therefore seen as a unity of knowledge, an integration of technique, and a bottom-up mastery of matter.

This is well reflected in recent advances in the field of biomaterials, leading to diagnostic and therapeutic technologies that will revolutionise the way healthcare is administered.

Biomaterials have evolved from off-the-shelf products to materials that have been designed with molecular precision to exhibit the desired properties for a specific application, often mimicking biological systems. Proteins that mediate cell interactions that lead to tissue and bone regeneration interact with the surface chemistry, charge, energy, and topography at the nanoscale. Nanostructured tissue scaffolds are being applied to improve tissue design, reconstruction, and reparative medicine.

3.3.2 Nanotechnology devices and applications

The technology sectors in which nanomaterials are expected to contribute significantly are diverse: drug delivery, medical therapies, medical testing and diagnostics, imaging and sensing, electronics, computing logic and architecture, telecommunication, transportation, information storage, thermal management, energy conversion and storage, and manufacturing.

One good example of how nanostructured materials are expected to impact our every day life is in the automotive sector, where huge space for innovations is found in each of its key drivers: reduced air pollution; reduction of weight; recyclables; safety; better performance and engine efficiency; aesthetics; longer service life; increased comfort; and cost effectiveness. Moreover, nanotechnology developments in the automotive sector hold major promise in preserving our environment: various sources estimate that in the short term (5 years), nanotech has the potential to reduce carbon emissions chiefly through weight savings and improved combustion in transport applications. Short term applications include light weight nanocomposites and fuel cell additives. On the longer term (10-40 years), advances in battery technology, super capacitors as well as nanotech enabled fuel cells will play determining roles in reducing noxious emissions from road transport.

3.3.3 Enabling technologies

Implementation of “nano” in innovative products requires several technological developments “enabling” to enter the market: (1) The availability of reliable cost estimation tools to calculate the impact of the integration of new technologies into existing products; (2) The development of appropriate standards, metrology and quality control systems allowing to build up a reliable process chain; and (3) The availability of high-throughput, high yield manufacturing equipment to be able to realise the envisaged nano-breakthrough in a cost effective way.
The first element is emphasizing the cost to performance aspect of new technology integration. Cost is related to manufacturing technology and this will require extensive research e.g. into the manufacturing technology and cost of components made of nano-particle based materials. The second element is referring to traceability of measurements, highly accurate quality control systems and reliable high-end (e.g. high precision) manufacturing equipment. The third element refers to the up scaling of tools and methods for nanotechnology in order to come to high-throughput, cost-effective manufacturing, involving major developments in machine design and control. Typical examples of the latter are ultra-precision vacuum stages to be used in SEM/TEM or parallel concepts for bottom-up SPM based manufacturing.

3.4 Nanotechnology in the Food Industry

3.4.1 Introduction

Since the last five years one detects a rather slow but persistent growing interest of food scientists and food industries in the potential benefits of introducing the new nanoscience approaches in their own basic research on single food components, structural aspects of food such as nano-composites, nano-emulsions and nano- particles, food safety by packaging involving nano-sensors and nano-tracers, food processing by heat, flow, pressure, chemical reactions, solubility and phase separation.
Understanding food needs to start at the molecular level, the chemical building blocks, and to cover all hierarchical levels from the nano-scale over the micro-scale up to the macroscopic properties. The principal aspects of the chain of knowledge involve: production, processing, packaging, distribution and consumption.
One should realise that the whole field of food science is at the crossing point of many formerly “independent” scientific disciplines such as chemistry, physical chemistry, biochemistry, materials science, nutritional science, biology and microbiology, bioengineering, toxicology, environmental science, consumer science, medicine, physics, engineering

3.4.2 Nanotechnology for food

Understanding the fundamental components

Proteins in general are clearly among the best studied and understood food components and protein crystallography continuous to be successful in contributing to our detailed knowledge on their structure and function. If crystals of suitable size can be obtained and isomorphous heavy atom derivatives are available, then by actual standards, solving a structure is experimentally no longer a challenge. In practice data collection at advanced SR beam-lines is

now fully automatic. Things become a little bit more difficult if crystals are much too small (micron size). Here beam-lines with nano-focusing devices offer the potential for irradiating only a micron or nano-sized ‘ordered ‘part of a crystal in a complex crystal cluster to obtain the data needed.
Quite similar problems are occurring in the study of lipids and lipid blends where one also often suffers from too small crystals and additionally complexities due to polymorphism. Polysaccharides as well as biopolymeric polyelectrolytes belong to the most difficult group of basic food molecules. Samples often appear as nano-sized fibers which can now be more conveniently handled at expert beam-lines for data collection and structure solving.

Food processing and product engineering

Understanding food properties involves the study of the nano-level in order to engineer the characteristics on the macro-level. Here we offer a few examples to illustrate the challenges. Batch processing of fatty acids for instance involves strict control of lipid crystallization, polymorphism and crystal size. Creating stable physical (thermo) (stable) (reversible) gels in food applications is completely controlled by the nano-sized structures of the physical cross-links, their mutual distance, cross-link density and thermal stability. Long term gel stability of food multi-component systems as a function of time and temperature is another hot item. An example is the control over the cross linking density of protein and/or polysaccharide fibrils in gels. Similar problems appear in the processing of drinks where stability of suspensions is determined by nano-sized particle interactions.
Analogous to trends in pharmaceutical delivery systems is the growing importance for nano-encapsulation systems that are adopted for the delivery of drugs via nutrients to be released in the specific parts of the digestive system where they have optimal effects. The new nano-technologies offer even other opportunities. Because of the high accuracy of micro-sieves it is possible to sieve out bacteria or yeast cells from certain beverages and pasteurizing them without heating.
Finally nano-technologies allow for improvements in food packaging. Carbon nano-tubes can be used to strengthen packaging materials, but real innovation will be in improved barrier characteristics and special coatings that reduce the microbial pressure on the food product inside. Special indicators are needed that utilize nano-technology to signal oxygen leakage in modified atmosphere packaging, which will result in quality deterioration. Other indicators can provide information on the ripeness of packaged fruits. Combined with printable RFID-electronics (also a product of nano-technologies) sensors can provide direct information on the quality of the product and the remaining shelf life.

3.5 Impact of Nanotechnology on Sustainable Generation of Energy

Recent news bulletins are crystal clear: on one hand the hunger for energy in the world was never so large; on the other hand there is a growing awareness that the way we currently deal with energy cannot be maintained much longer. The level of daily energy consumption equals about 15 terawatts. To give the people around the world the level of energy prosperity of the developed countries, i.e. a few kWh, it is needed to generate about 60 terawatts by the end of this century. It will be a great challenge to find technically viable and socially acceptable sources to cope with this. As fossil fuels however become depleted, and cause high CO_2-emissions and correlated climate change, a shift to renewable energy sources by the middle of this century is to be expected. The prediction that so-called earth-based renewable energy sources like hydro-electricity, wind, tides, geothermal and biomass, fall significantly short of the total future energy demand, feeds the awareness that nanotechnology can have a profound impact on the total chain of energy production.

Thermoelectrics : electricity from heat, heat from electricity

Thermoelectrics can be a first example where nanotechnology comes in at efficiently converting energy from one state to another (Peltier and Seebeck effects). The production of such nanostructured materials involves for example the application of a five nanometer thin layer antimony telluride to a layer of just a nanometer of bismuth telluride. It is quite conceivable that in this way anyone with a cheap source of heat, e.g. geothermal heat, could produce electricity in an economic way.

Nanostructured solar cells for conversion of solar energy to electricity

Analogous to photosynthesis or the conversion of sunlight in another energy state by vegetation, solar cells or photovoltaic (PV) cells convert solar energy in electricity. The current PV market is dominated by technology based on inorganic crystalline silicon wafers. Due to the high production cost of crystalline silicon, a clear trend in solar cell development is towards the use of organic cells, so-called Graetzel cells, with nano-sized features. Although organic semiconductors are less stable and have lower electrical conductivities compared to inorganic semiconductors, recent advances have paved the way for organic solar cells. Currently, cheap solar cells concepts with high efficiency are being investigated in different labs around the world, e.g. solar cells that could be painted on roofs of cars, busses and houses and even on flexible substrates. As they could be printed on plastic film, they could become very affordable, reducing the cost price of the electricity generated.

Efficient energy storage with nanostructured battery materials

Smart organising of materials with nano-features can also lead to breakthroughs for the storage of electrical energy with batteries. The key parameter for batteries is energy density, and the trend is to move gradually towards ever higher energy densities. By introducing nano-materials in the design of the electrodes, more and faster storage of energy in batteries becomes possible. As a consequence, batteries will become more competitive for application in the transport sector.

Electricity from controlled electrochemical reactions: fuel cells

A fuel cell can be seen as an ever-lasting battery that can supply electrical current by means of a controlled electrochemical reaction as long as the device is being fed with fuel. Efficient fuel cells have been demonstrated, and the industrial sector is devoting large efforts to reduce the costs for fabrication and improve the performance and durability. Here nanotechnology can contribute significantly by promoting more efficient anodes, more efficient cathodes, and better ion-conducting membranes that allow selective passage of protons from anode to cathode. Nano-structuring the electrodes using nano-sized electrocatalysts, the ratio of surface area to volume will strongly increase.

High density storage of hydrogen using nanotechnology

Considering fuel cells, hydrogen is the fuel that first comes to mind. A challenge is the safe storage of hydrogen since this would mean a serious step forward towards the hydrogen economy. It would mean anyway that charging (better 'refueling') will be less necessary and would take less time. In order to achieve a high energy density, storage of liquid hydrogen in a porous material is one of the options investigated. Since a large specific surface area is required, materials like carbon nanotubes are being considered.

Direct generation of hydrogen with sunlight or photolysis

As there is no natural source for hydrogen on earth it is important to produce hydrogen making use of for instance solar energy. Nanotubes from titanium oxide, obtained from titanium oxide films generated in an electrolytic bath, can effectively separate water in hydrogen and oxygen under the influence of UV-light. This is possible because UV-photons are being trapped in the pores of the nanotubes and because the available surface area for the splitting of water is sufficiently large.

Will nanotechnology bring environment and energy in harmony?

Today's worldwide energy consumption involves high economical and environmental costs. This justifies the development of cheap and environmentally friendly systems for future energy production and conversion. Although it is already possible at this moment to advance vehicles using rechargeable batteries, solar cells or hydrogen, the gap between the current knowledge and state of the technology and the demands from an efficient and cost effective, sustainable economy is still very large. The above examples demonstrate that nanotechnology has a lot to offer and it can be expected that nanotechnology will play a prominent role in our future energy systems.

3.6 Nanotechnology and Environment

3.6.1 Introduction

Nanotechnology has also an enormous potential for tackling environmental problems. As a consequence, the environmental sector is currently overwhelmed by a wave of new ideas building on nanotechnology. Most environmental applications of nanotechnology fall into three categories: resource saving, coupled to waste prevention; development of sensors for environment monitoring, and pollution detection; remediation of existing pollution in water, air and soil

Nanotechnology offers many possibilities for resource saving through improvements in efficiency for renewable energy sources, energy storage, reduced material consumption, and the possibility of using alternative or more abundant materials.

The ability to detect the presence of pathogens or toxic agents in our environment is the first step towards taking remedial action. Presently, there are many monitoring devices available; however, advances in nanotechnology offer the potential for more sensitive and faster detection, with less bulky and even portable equipment. The new sensors have excellent response, operational simplicity and low cost in comparison with conventional analysis techniques. However, nanotechnology will have the most important contribution to an environmental friendly and sustainable society, in the remediation of existing pollution of water, air and soil. In what follows some relevant examples are discussed.

3.6.2 Nanotechnology and water purification

Water purification and drinking water production is seen world wide as one of the highest priorities. Although the earth is abundant in water, only 1 % of the earth's water is drinkable. 97 % of the water is sea water and contains an intolerable level of salts. Traditional techniques used in drinking water production are unfit for removing some micro pollutants (e.g. pesticides, humus acids, pharmaceuticals) and are incapable of desalination. Filtration on the nanoscale can offer the solution. The nanomembrane processes are not new, and have already been implemented at large scale in the drinking water production and for the treatment of waste waters. However, it is very clear that the innovative nanotechnologies of today, can lead to a new generation of nanomembranes with a strongly improved throughput, and consequently, a substantial decrease of the required energy. One example is the development of nanomembranes using carbon nanotubes or alumina nanofibers. Due to a tight parallel stacking of the nanotubes or fibers, these membranes have an extra high surface area, and an extraordinary high permeability (up to 10 000 x higher), combined with a good mechanical and thermal stability. These membranes are expected to reach the market in 5 to 10 years.

3.6.3 Nanotechnology and remediation of contaminated soil

With respect to remediation of contaminated soil and ground water, the range of nanotechnology applications mirrors the spectrum of non-nano strategies: adsorptive (remove contaminants) versus reactive (degradation of contaminants), and in-situ versus ex-situ. Nanotechnology results in adsorbents with extra high surface areas (~1000 m^2/g) and tunable adsorptive properties. For ex-situ reaction by photo catalysis, the potential benefits of nanosized (< 10 nm) photo catalysts have long been recognized, and are due to the band gap increase with particle size decrease. One of the most promising ways for in-situ degradation of contaminants in groundwater is the use of reactive iron barriers. The system consists of a trench filled with small zero-valent iron grains, positioned vertically and downstream of the pollution plume. When the polluted groundwater is permeating the wall, the zero-valent iron is oxidized and the contaminants are reduced to harmless or less-mobile products. In this way, many organic pollutants as chlorine containing solvents and heavy metals and compounds can be removed. The system is economical, and avoids the pumping up of groundwater or the digging off of large amounts of soil. Nowadays, iron grains of millimeter or micrometer size are mostly used. Nanosized particles have special relevance since they can easily be injected, even up to high depths, and they have a higher specific surface making them much more reactive. The degradation of pollutants occurs faster, and a broader range of pollutants can be attacked. This has lead to a very rapid transfer of this technology from laboratory testing to full-scale commercial applications in the field.

3.6.4 Nanotechnology and gas cleaning

Nanotechnology is also a driving force in the development of novel filter materials to remove contaminants from air. With nanotechnology filters can be designed at the molecular level, to remove even the most minuscule of impurities. This finer filtration will result in cleaner burning, with less soot and smog-creating impurities. Presently, one of the most urgent worldwide gas-separation problems is the CO_2 removal from the exhaust gases of power stations. Currently CO_2 is captured by absorption. Dense polymer membranes would be a more energy-efficient alternative, if only their selectivity would be sufficiently high. Again nanotechnology opens up new possibilities.

3.7 Nanotechnologies: Health and Environmental Risks

3.7.1 Introduction

Nanotechnologies may contribute to the protection of human health and of the environment. For example, they may produce implants and miniature sensors for medical diagnostic and treatment as well as for monitoring environmental pollution. They may also be used in wastewater treatment and contaminated soil clean-up (see preceding section). On the other hand, nanotechnologies may have adverse effects on the health of industrial workers, consumers and the general public as well as on other living organisms. A rigorous hazard evaluation and risk assessment must accompany the development of these technologies in order to avoid unpleasant surprises. This concern has been recognised and has led to action at national and European Union levels, as shown by the references at the end of this report.

3.7.2 Toxicity of nanomaterials

Nanotechnologies are concerned with materials that have various dimensions in the nanometer range. Those with dimensions two and three have a potential for toxicity as they can become easily airborne and be inhaled, ingested or come in contact with the skin.
There are ultrafine particles in the environment, most of them originating from combustion processes and gas-solid reactions (involving i.e. sulphur compounds and terpenes), and these are known to penetrate deeply in the lungs and have various negative impacts, such as the exacerbation of asthma symptoms, cardio-vascular effects and possibly carcinogenicity.
Nanoparticles have the additional potential to cross epithelial barriers and to escape normal biological clearance mechanisms. They could thus reach organs and tissues which are not normally exposed to particulate material and thus produce systemic effects. Little is known, at present, on the ensued risk but it seems likely that each individual nanomaterial must be considered on a case-to-case basis. Most of the information available today is concerned either with fine particulate matter in air pollution or manufactured materials already in use, such as TiO2 particles.
In vitro studies on isolated cultured cells as well as on laboratory animals have shown that biological responses such as oxidative stress, inflammation, cytotoxicity, cellular transformation, increase with the specific surface of chemically identical particles as well as with the lengthening of the particle. The biological response depends obviously on the chemical composition of the particle, as some toxic components may be dissolved or the number and kind of reactive sites may differ.
The molecular mechanisms involved are still not well understood, but the triggering of the response seems to be linked to the stimulation of proteinic receptors in the cellular membrane, the lipoperoxidation of membrane phospholipids by free radicals and the direct alteration of intra-cytoplasmic, mitochondrial and nuclear components.
At the organism level, penetration may occur through the skin, the central nervous system (through the olfactive nerve, but this is still disputed), the alveolar-capillary lung barrier, the placenta, the intestinal mucosa and the hemato-encephalic barrier. Effects are tissular (inflammation, fibrosis) and systemic (cardio-vascular and central nervous system responses). Tumour-related effects have been observed in rats but these may be related to overload conditions
Data from human subjects have dealt with deposition in lung tissue and clinical studies after inhalation. They have confirmed the evidence from animal studies, at least in the short term. A substantial amount of information is available from epidemiological studies on the effect of exposure to fine particles in air pollution. They have revealed cardiovascular and

thrombogenic effects as well as effects on the respiratory function of asthmatics and on the permeability of the bronchial epithelium. The seriousness of the observations has led to a strengthening of the limit values of fine particulate matter (PM10 and PM2.5) in air.

3.7.3 Ecotoxicity of nanoparticles

Much less is known about the potential impact of nanomaterials on the environment. Their inputs into the environment will obviously be linked to their life cycle: production, uses, ultimate disposal. Their fate in the environment is largely unknown so far, although it is clear that some current applications, e.g. in cosmetics and inks, lead to a dispersion in ecosystems. One modelling study indicates that single-wall carbon nanotubes may eventually be present at a concentration of thousands of units per cubic centimetre in estuarine waters.
Toxicity studies on bacteria, zooplankton, plants and fish are very few. They show negative effects at fairly low concentrations. The fish data confirm the data on mammals. One important finding is that, contrary to conventional wisdom, bioaccumulation of nanoparticles may occur in living organisms, with the consequence that the environmental risk assessment methodology for chemicals cannot be applied as such.

3.7.4. Regulatory issues and research

The lack of adequate assessment of worker exposure to nanoparticles (not to speak of consumers and the general public) and the very limited understanding of the hazards they constitute make risk assessment very uncertain. As recognized in the September 2006 EU Finnish Presidency Conference on “Nanotechnologies-Safety for Success” this calls for accelerated development in the characterization of nanomaterials, of adequate, operational materials and processes and of international safety guidelines and standards.
As part of its nanotechnology action plan, the European Commission has initiated a review of its regulatory frameworks applicable to nanomaterials to see if any adaptations are necessary and is funding a number of research projects on the safety aspects. Details are available on the EC Cordis site. It is indeed urgent to act in this area in a broadly concerted way in order to avoid the adverse reactions that other modern technologies, e.g. biotechnologies and in particular those related to the GMO’s (genetically modified organisms), have met in their development, especially in Europe.

Belgian research on the safety of nanomaterials is so far very limited.
The KULeuven participates in two EU-FP6 projects: NANOSAFE 2 will establish processes to detect track and characterise nanoparticles and IMPART whose primary aim is to understand the potential impact of nanoparticles on human health and the environment. The spin-off NANOCYL S.A. is involved in NANOTOX, contributing to the improvement of safety of nanoparticles by documenting potential methods of dispersal and contamination by nanoparticles and agglomerated nanocrystals.
VITO is a partner in the EU-FP6 DIPNA in which the major goal is to develop an integrated platform for nanoparticles analysis to verify their possible toxicity and the eco-toxicity. VITO is initiating also several projects on exposure assessment in workplace settings.

4. Nanotechnology in Belgium and Europe

4.1 Introduction

The main objective of this paragraph is to give a brief overview of the nanotechnology activities in Belgium as well as some information about research initiatives by the European Commission and in some Europe countries. The federal structure of Belgium means that primary competence for science and technology policy has been devolved on the regions of Flanders, Wallonia and Brussels.
In terms of research productivity, it may be noted that in the period 1999-2004 Belgium ranked 5th for high impact scientific publications in nanoscience, after Switzerland, the Netherlands, USA and Canada, before the UK, Denmark, France, Japan and Germany. (Source: Nature Nanotechnology 1, 81-83 (2006))

4.2 Nanotechnology and the Belgian Science Policy Office (BELSPO)

4.2.1 The Interuniversity Attraction Poles (IAP)

The "Interuniversity Attraction Poles" Program aims to provide support for Belgian teams of excellence in basic research. The program is funded by the Belgian Federal Science Policy Office. The research teams work as part of a network in order to increase their joint contribution to general scientific advances and, where applicable, to international scientific networks. Since 1987 the IAP program has been implemented in five year phases. During phase V (2001-2006), three major networks on nanotechnology were funded, under the heading of respectively "Quantum Size Effects in Nanostructured Materials", "Supramolecular Chemistry and Catalysis" and "Photons and Photonics : from basic physics to system concepts ". In Phase VI of IAP (2007 – 2011), and out of 15 Networks in the Exact and Applied Sciences, 4 are related to nanoscience and nanotechnology: "Photonics@be : Micro-, nano- and quantum-photonics" ; "Advanced complex inorganic materials by a novel bottom-up (nano)chemistry approach: processing and shaping"; "Functional supramolecular systems"; "Quantum effects in clusters and nanowires". Participant institutions in both phases are all the Belgian universities as well as international laboratories.

4.2.2 Research infrastructures

It is now possible to operate at the nanometer scale, observing and manipulating, as well as designing, atom by atom, increasingly complex materials. Most techniques are available in relatively small laboratory environments (like the atomic force microscope, or the atomic layer deposition chambers), but, when it comes to operating with increasing definition on larger pieces of materials, the need is to be able to "illuminate and reach" all atoms of the materials under investigation. This requires "large facilities" capable to provide the adequate "brilliances", much like the need for a strong light to explore a dark environment.
Large research infrastructures provide unique opportunities to train skilled people while stimulating knowledge and technology transfer. For decades Belgium has been actively participating in international, mostly European, scientific organisations. Funds allocated to international research infrastructures constitute a significant part of the budget of BELSPO for scientific and technological activities. Many Belgian researchers and their students from universities and research institutes use those infrastructures each year.

Photon Sources

Light photons are only one, but the most flexible, of the many complementary “probes” which can be used in nanotechnology. Large related instruments are Synchrotrons, Integrated Laser Laboratories or High Power Lasers. A recent technological breakthrough has added the Free Electron Lasers capable not only of much higher brilliances but also of short time “flashes” opening the dynamic “filming” of atom-related properties.
The participation of Belgium, through the BENESYNC-consortium sponsored by BELSPO, in the International Hard X-Ray source ESRF (Grenoble) opens interesting possibilities for researchers active in nanotechnology. Moreover, researchers of the Flemish Community have access to the light line “DUBBLE” which has been funded and built within the framework of collaboration between FWO Flanders and the Dutch NOW.

Neutron Sources

The use of neutrons as a probe of matter is strongly complementary to photons as they are unique to detect and measure very important aspects of materials and biological matter. Infrastructures for neutron spectroscopy use low energy neutrons. Their magnetic moment allows the detection of magnetic structures, while their small momentum allows the measurement of thermal and mechanical properties, and the differential measurement of Hydrogen and Deuterium in important sites of biological matter. The neutron source at the Institut Laue-Langevin (ILL) has recently become available to Belgian scientists in the framework of an agreement between BELSPO and ILL.

4.3 Nanotechnology in Flanders

4.3.1 The Flemish Science Policy Council (VRWB)

In the frame of the action “Technology and Innovation in Flanders”, co-ordinate by the VRWB, a dedicated Expert Group working in the cluster “New materials, Nanotechnology and Manufacturing” has analyzed the relevance of nanotechnology / nanomaterials and its impact on the Flemish socio-economic tissue.
The following Priority Trends have been identified by the Expert Group:

Trend 1: New materials
The development of new and better materials is crucial for future markets and production technologies. In the future, advanced materials will be used in ever smaller and multifunctional components and products. Many industry domains will be involved such as ICT, energy, textile, biomedical and others. Nanotechnology will lead to higher efficiency and reliability of new materials, along with longer life cycles and lower production costs.
Trend 2: Nanoelectronics
Nanomaterials will also be used to implement new electronic functions for data processing and data storage, leading to substantial capacity increases. Moreover, they will have a strong influence on the development of nanosensors and nanoactuators, as well as other devices combining electronics with mechanics, fluidics and optics.
Trend 3: Biomimetics
The way nature fabricates and uses nanostructures can also be a source of inspiration for new synthetic nanomaterials. Copying nature requires multidisciplinary research, combining biology, chemistry, physics and materials science.

Trend 4: Nanomedicine
Improved understanding of the functioning of the human body at the molecular and nanometer scale is of utmost importance to meet future challenges of health and ageing. Diseases like cancer, diabetes, Alzheimer's and Parkinson's disease, cardiovascular problems, inflammatory and infectious diseases and depression will require novel approaches. Early diagnosis, 'smart' treatments and the triggering of self-healing mechanisms are new objectives that can be targeted with a nanomedical approach.
Trend 5: Modeling and simulation
Modeling and simulation are key technologies for 21the century industries. Computer aided design (CAD) is now common in many industrial fields, contributing to more efficient product and process development. Special approaches will be required to extend these techniques into the nanotechnology domain. New environments must be created in which these simulation techniques can be widely used not only by quantum researchers but also by specialists in other fields.
Trend 6: Integrated process design
Complex, integrated process flows are becoming increasingly important. They are strongly affected by fast developments in ICT, nanotechnology and materials science. Moreover, smart production tools now exhibit a high degree of autonomy which is supported by mechatronics-based designs and wireless networks. These developments must be taken into account by process designers to deliver integrated production flows that are flexible, accurate and efficient.
Trend 7: Automation and robotics
Robotics and automation of production processes are already well-established. However they will be strongly influenced by the introduction of smart autonomous nanosensors and nanoactuators. The latter will probe the environment and communicate with each other via wireless channels. Automation will also make use of novel robot architectures: reactive robots, cognitive robots, evolutionary robots, etc.

Based on the expert's recommendation, several working groups have been installed in order to define concrete R&D objectives involving Flemish academia, industry and research institutes. It is expected that the first projects will start in 2009.

4.3.2 Nanotechnology in Flemish higher education

There is a strong need to develop a coercive curriculum to equip the future engineers, scientists, and researchers charged with developing and commercializing nanotechnology applications. Therefore a need is felt to implement some core courses and laboratory modules, which can easily adapt to either a major or minor in nanotechnology, nano-biotechnology, or nanoscience programs. Several Flemish Universities have launched higher education programs on nanoscience and nanotechnology.

At the Catholic University Leuven (KULeuven), the local nanoscience and nanotechnology Master's has been expanded into an international curriculum in the framework of the Erasmus Mundus program from the European Union. The Erasmus Mundus Master Course "Nanoscience and Nanotechnology" is a truly integrated program, with a strong research backbone and an international outreach. The objective of the program is to provide top-quality multidisciplinary education in nanoscience as well as in the use of nanotechnologies for devices and systems at the macroscale. Ethical and societal aspects with respect to the use of nanoscience and nanomaterials are also part of this curriculum. The participating institutions are: KULeuven; Chalmers Tekniska Högskola; Technische Universiteit Delft; Universiteit Leiden; Technische Universität Dresden.

The Free University of Brussels and the Ghent University have launched in 2007 a joint Master's degree in Photonics. It is designed to give the student a thorough knowledge and competence in areas such as lasers, photonic materials and components, as well as systems such as optical sensors and detectors. The courses will cover the fundamental physics as well as the design and application of photonic components. Moreover, the European Union has recently given the green light for the development of a joint Erasmus Mundus Master of Science in Photonics. The participating institutions are: Ghent University; Free University of Brussels; St-Andrews University; Heriot-Watt University, Royal Institute of Technology, Stockholm.

The University of Antwerp's Advanced Master in Nanophysics program is aimed at Belgian as well as foreign students who want to prepare themselves for a PhD research project in nanophysics or who intend to start a career in research and development in a university or industrial research centre. The program focuses on: present-day theoretical and computational techniques; experimental techniques for the characterization of nanostructures; practical computational and experimental experience. The studied topics include quantum dots, nanoparticles, nanotubes and fullerenes, nanotechnology and electronics, nanobiology, metallic nanostructures, nanomagnetism, electron microscopy, scanning probe microscopy and others.

The University of Hasselt organizes a Master in Bioelectronics and Nanotechnology program who focuses on the novel and interdisciplinary scientific domain at the boundaries between physics, chemistry, electronics and biomedical sciences. In addition to the fundamental aspects, the program offers an in depth introduction into several important application areas. Topics range from integrated detection techniques for cells and molecules (biosensors) to the nano engineering of implant materials and the working principles of biomedical devices. The curriculum of this Master's program is the result of intensive collaboration between physicist, (bio) chemists, clinical and biomedical researchers and engineers specialized in medical instrumentation.

IMEC organizes a series of lectures under the heading "Capita Selecta of Nanoscience and Nanotechnology". The lectures are given by Belgian and international experts on various topics related to new and important developments in nanotechnology, the opportunities for nanotechnology applications, and the ethics and risks of nanotechnology developments.

4.3.3 Nanotechnology research at Flemish universities

In Flanders curiosity-driven research and nearly all strategic basic research is done at the universities. A bottom-up approach, a strong emphasis on the scientific excellence, and transparent funding mechanisms are the characteristics of the Flemish science policy. Each university receives within the BOF-system (see bellow) a lump sum to develop its own basic research.
Within the framework of this Report it is impossible to give a detailed analysis of the many research activities (fellowships, projects, etc.) related to nanotechnology at the 6 Flemish Universities. We refer to the website of the Universities for more information about their research activities in the framework of nano. Recently, new initiatives by the universities or

the Flemish government have funded new nanotechnology driven projects in the framework of:

The Centres of Excellence which provides a 5 year funding for research initiatives within specific areas, often by means of internal networking between research groups with complementary competencies.

The Impulse Projects intend create a suitable and challenging research environment for the researchers, especially the availability of advanced research infrastructures necessary to participate in modern top-research. This initiative will be continued in the future by the so-called **Hercules Program** of the Flemish Government.

The Methusalem Program provides long term (7 years) structural funding for top researchers in Flanders. The program is meant for experienced researchers with an international recognition.

The Odysseus Program intends to attract top researchers to Flanders with a financial incentive. The target group is Flemish and other researchers with a position at foreign universities. When hired in Flemish universities, these top researchers are expected to develop research groups and create centres of excellence.

In what follows, a short overview of the main actors financing nanotechnology research at the Academic Institutions is given.

The Special Research Fund (BOF)

In order to strengthen the research potential of the universities the Flemish government allocates each year a substantial budget for fundamental research activities. The Flemish minister for Economy, Management, Science, Innovation and International Trade as well as the Department of Economy, Science, and Innovation (EWI) are the central units for coordination and financing of scientific research.

Each university has an internal research council that evaluates and gives financial support to researchers within the BOF- system. The main budget is related to the Concerted Research Action (GOA) program. Several of the currently running GOA projects are nanoscience and nanotechnology oriented.

The Institute for the Promotion of Innovation by Science and Technology in Flanders (IWT)

The IWT supports nanotechnology-related research mainly through its SBO program (Strategisch BasisOnderzoek). Strategic basic research is situated between fundamental general knowledge expanding research (mostly at universities and research centers) and the more specifically focused applied research (mainly in companies, government institutions and other economic or social actors). The SBO financing channel is aimed at the expansion of strategically important knowledge platforms with a wide range of economic and/or social applications. All scientific disciplines (and multidisciplinary combinations thereof) and all economic sectors or social domains are given a chance. Several of the currently running SBO projects are related with nanoscience and nanotechnology, at the technical level as well as at the socio-economic level.

The Research Foundation-Flanders (FWO-Vlaanderen)

FWO finances basic research which is aimed at moving forward the frontiers of knowledge in all disciplines. Basic research is carried out in the universities of the Flemish Community and in affiliated research institutes. Therefore the FWO is Flanders' instrument to support and stimulate fundamental research in the scope of scientific inter-university competition. The activities of FWO are centred on the support of individual researchers and research teams as well as the promotion of national and international mobility including the participation in European research organisations. Research proposals from the academic community are evaluated and supervised by dedicated scientific commissions. Several FWO-commissions deal with nanotechnology-oriented fellowships and research projects.

4.3.4 Nanotechnology at Flemish R&D Institutions

The Interuniversity Micro-Electronics Center (IMEC)

IMEC is Europe's largest independent research and training center with more than 1400 staff in the field of microelectronics, nanotechnology, enabling design methods and technologies for ICT systems. Nanotechnology R&D at IMEC include nano-CMOS and novel devices for nanoelectronics, micro- and nano- electromechanical systems (MEMS and NEMS), development of nanomaterials and nanopatterning, use and improvement of nanoprobes, surface functionalization and self-assembly, molecular interconnects and molecular electronics. There is also a strong link with the nano-bio domain, including the study of the chemical and electronic nature of the interface between biospecimen and solid-state devices and the transfer of signals across that interface mediated by appropriate self-assembled molecular layers.

The Flanders Institute for Biotechnology (VIB)

VIB is an entrepreneurial research institute where more than 750 scientists and technicians conduct gene technological research in a number of life-science domains, such as human health care and plant genetics. Through a close joint venture with four Flemish universities (the UA in Antwerp, the VUB in Brussels, the UG in Ghent, and the K.U.Leuven in Leuven), VIB unites the forces of nine university research teams in one single institute.
Recently VIB and IMEC have jointly set up a Neuro-Electronics Convergence Laboratory, which is unique in Europe. The convergence lab is located on the IMEC premises and contains multidisciplinary tools for semiconductor processing, nanotechnologies, biosensor fabrication, cell culture, molecular biology and electro-physiology. Experts in molecular biology, cell biology, medicine, microelectronic engineering and physical sciences from various research institutions will use this infrastructure with the common goal of developing research in neuro-electronics and in different branches of nanomedicine.

The Flemish Institute for Technological Research (VITO)

VITO, with a staff of approximately 500, is an independent and customer-oriented research organisation, which provides innovative technological solutions as well as scientifically based advice and support in order to stimulate sustainable development and reinforce the economic and social fabric of Flanders. The Institute is active in the development of nanostructured materials and surfaces, carbon nanotubes and graphene in various nanotech areas including multifunctional surfaces, bio functional devices, ultra porous media for tissue engineering, etc. Analysis and characterisation tools at the micro-and nano scale are used. The Environmental Toxicology Centre at VITO studies the effects of pollution and chemicals on men and the environment in order to provide a solid scientific basis for hazard and risk assessment. The VITO Air Quality Measurement Group is monitoring engineered nano-particles in occupational setting, including the measurement of multiple nanoparticles characteristics.

4.4 Nanotechnology in Wallonia and Brussels

4.4.1 Education and training in French-speaking universities

In the last 25 years the terms "nanoscience" and " nanotechnology" have been used more or less indifferently by scientists and engineers; yet, the first refers to fundamental theory and is treated by scientists whereas the second is concerned with applications and is in the realm of engineers. The situation in Belgian universities is somewhat paradoxical in that some science faculties have transferred directly from science to technology and initiated start-ups while some engineering faculties have operated in the nanoscience area and produced no start-ups. It is from this point of departure that one can examine the situation in the French-speaking universities.
Since the Bologna reform, the subject is covered in the programs in chemistry, physics, electricity and mainly material science, where it is taught at an advanced level (second year of Master in science or Master in civil engineering). Some in the engineering faculties consider now that the current arrangements are too much of a patchwork and that an entirely new curriculum should be developed for nanotechnologies, distinct from the classical engineering programs, and based on quantum physics.

FUNDP (Facultés Universitaires Notre Dame de la Paix) in Namur is highly concerned with nanoscience. There are two elective courses in nanostructures in the second year of the Master in physics and one elective course in nanotechnologies in the second year of the Master of chemistry programs ("spécialisation approfondie").

UCL (Université Catholique de Louvain) has, in its engineering program , a complete option in nanotechnologies with three courses leading to the degree of Master in civil engineering in chemistry and science of materials. There is also an elective course for the electrical and physical engineers.

ULB (Université Libre de Bruxelles) has a course in nanophysics in the Master in physics ("spécialisation approfondie") program and one elective course (nanostructured materials) in the Master in civil engineering (chemistry and material science) program.

ULg (Université de Liège) offers several possibilities. In the faculty of sciences, for the Master's degree in physics ("spécialisation approfondie"), there are two elective courses in nanotechnology and nanomaterials and for the Master in chemistry (" spécialisation approfondie"), two elective courses in micro magnetism and nanoparticles. In the faculty of applied sciences for the program of the second year of Master in physics and in electricity (" spécialisation approfondie"), there is also one elective course in nanoelectronics

UMH (Université de Mons-Hainaut). In the second year of the Master's program in physical and chemical sciences, there is one course in nanotechnologies ("spécialisation approfondie").

FPMs (Faculté polytechnique de Mons). This faculty of engineering has an elective course on advanced materials and processes in the second year of its Master in civil engineering (chemistry –materials science) program.

Under the aegis of FNRS, all above-mentioned universities are partners in the MAIN doctoral school ("Matériaux, Interfaces et Nanostructures").

4.4.2 Nanotechnology research in French-speaking universities

Several laboratories from the major universities of Wallonia and Brussels have joined forces to create a network for nanotechnologies and nanosciences : Nanowall which is part of the Marshall plan for Wallonia. It was allocated a budget of about 20 million euros for the 2002-2007 period by the Direction Générale de la Technologie, de la Recherche et de l'Energie (DGTRE) of the Walloon Government. Its general objective is to connect academic and industrial actors active in the nanotech field in Wallonia. The initiative is motivated by the need to set up a structure that would favour stronger interactions between the actors in the nano field. The structure will also allow the sharing of equipment facilities and improve the overall knowledge as well as technology transfer. There are three main lines of activity: building machines via Technoerd, nanopowder production via Tesprint and developing new applications of nanopowders . New equipment available at SIRRIS (formerly CRIF/WTCM) will be used to produce a wide range of nanomaterials. The specialised following programs refer to nanotechnologies: MIRAGE and NANOCOMP. DGTRE is also a member of the ERA-Net MATERA a European coordination network among 16 partners from 14 countries

Following are some current research topics in the French-speaking universities:

FUNDP
There is a research center for nanomaterial chemistry with three lines of work: simulation of porous materials, study of recognition effects in porous systems, design and understanding, at molecular and atomic level, of porous structures and nanostructures. Since 2001, it has dealt with many problems from the synthesis of nanostructured materials to self-cleaning glass and hybrid nanoreactors. Professor Nagy initiated the Nanocyl start- up company

UCL
The CERMIN Centre's objective is to promote the most efficient use of micro and nanotechnologies at the UCL. It can rely upon the following services: metallurgy, microelectronics, microwaves, nuclear physics, physical chemistry, techniques of physics and chemistry, polymers. Work is currently carried out on 18 topics.

ULB
The focus is on the synthesis and functionalisation of nanoparticles, nanotubes, multilayered nanostructures, hybrid nanoparticles, and physics of nanostructures. The faculty of sciences has set up a research center called PSIN (Physique des Solides et Nanostructures), which deals with nanoalloys, nanostructures and nanomechanics. .

ULg
The focus is on the nanostructure of polymers, the preparation of nanohybrids and mechanochemistry.

UMH Mons
Has a strong interest in nanocomposites and new materials development MATERIA NOVA is a private Centre created by UMH and FPMs in 1995 which works also in nanotechnology.

4.5 Nanotechnology and the Belgian Industry

The number of new companies in Belgium involved in nanotechnology is limited and difficult to trace back. In what follows a non-exhaustive list of large and small companies is given.

Umicore is a materials technology group. Its activities are centred on four business areas: Advanced Materials, Precious Metals Products and Catalysts, Precious Metals Services and Zinc Specialties. Umicore is active in nanomaterials such as products for cosmetics, paint, laminated glass, textile, the automotive industry, etc…

Agfa Graphics has a large number of products based on nanotechnology such as digital printing plates, colour inks for inkjet printers, etc…

Solvay has initiated activities in nanotechnology to explore opportunities in the field of advanced functional materials (nanoparticles) such as pharmaceuticals, chemicals and plastics.

Bekaert nv/sa develops and manufactures advanced materials in such areas as fibre technologies, combustion technologies, composites, industrial coatings, nanotechnology-enabled performance window films, etc..

Nanocyl originating in 2002 as a start-up company from the RMN laboratory of FUNDP (Prof.Nagy) it is now a SME in its third expansion phase and quoted on the Brussels Bourse. It offers several kinds of carbon nanotubes under different products and forms in quantities ranging from several kg to several tons: powder and intermediates (predispersed in liquid and solid carriers)

Ablynx nv/sa is a biopharmaceutical company (started operation in 2002) and has generated Nanobody™ leads against a number of human disease targets across a wide range of therapeutic areas. –

NanoMEGAS was created in 2004 by a team of scientists and experts in the field of electron crystallography and catalysis.

TopChim nv/sa patented nano-hybrid technology, NanoTope is being used in paper production surface treatment.

Europlasma nv/sa offers a wide range of gas plasma surface treatment equipment tailored to the needs of markets such as automotive, textile and filtration, medical, aeronautics and aerospace, electronics.

Xenics nv/sa, a commercial spin-off from IMEC, is active in the field of advanced IR imaging products and applications.

4.6 Nanotechnology Initiatives by the EC and in some European Countries

4.6.1 The European Commission

(Based on "Nanosciences and Nanotechnologies: An action plan for Europe 2005-2009. First Implementation Report 2005-2007", Brussels, 6.9.2007 COM (2007) 505 final)

The European Commission (EC) plays two important roles in the development of nanosciences and nanotechnologies (N&N); as policy maker and as funding body for research and innovation. The Action Plan provided impetus for developments, and progress in almost every area has been identified. Over the last years, European research in N&N has benefited from considerable financial support, complemented by increased coordination and coherence in relevant policy areas. EU Institutions, Member States, industry, researchers and other interested parties have worked together, sharing information and regularly consulting one another. Efforts have also been made to work more closely with international partners, bi- and multilaterally.

International competition increased markedly during 2005-2007, challenging European progress. Some weaknesses are becoming apparent in Europe, in particular a shortage of private investment in research and industrial innovation, a lack of leading interdisciplinary infrastructures, and an increasing risk of duplication and fragmentation in research efforts due to rising investment by the Member States.

Support for research and technological development (R&D) came from both the EC and EU Member States, with particular emphasis on coordination of policies, programmes and projects. Under the 6th Research Framework Programme (FP6, 2002-2006) funding of almost EUR 1.4 billion was provided to more than 550 projects in N&N. By contrast, the EC contribution was about EUR 120 million in FP4 (1994-1998) and EUR 220 million in FP5 (1998-2002). Over its lifetime, FP6 accounted for almost a third of total public expenditure in Europe for N&N.

Global expenditure in N&N, both public and private, in the period 2004-06 was around EUR 24 billion. Europe accounts for more than a quarter of this worldwide total, with the EC funding directly accounting for 5-6%.

In terms of public funding, Europe has become the largest investor worldwide. In terms of private funding, however, Europe is at a significant disadvantage to the US and Japan. The EU has set a target of investing 3% of its GDP in R&D, with two-thirds coming from industry. However, private spending on R&D currently accounts for about 55% and this trend is also visible in the nanotechnology sector. On the other hand, the private sector is making progress in this area, as part of its activities in the different European Technology Platforms (ETPs) and its various contributions highlighted elsewhere in this document.

Under FP7, EC funding for N&N increased significantly. The average yearly funding is more than double that in FP6. This is thanks to increases in the "Cooperation" specific programme and the significant reinforcement of "bottom-up" actions in the "Ideas" and "People" specific programmes. Funding in the latter is almost four times that in the corresponding activities of FP6 (NEST and Marie Curie). In addition to this overall growth, the growing interest in N&N may increase the *share* of the funding from "bottom-up" actions. Additional funding may come from the cross-thematic approaches developed in FP7, as nano-, bio- and information technologies have an interdisciplinary character and can contribute to different industrial sectors and policy objectives (e.g. in health, food, energy, environment and transport).

Several European Technology Platforms (ETPs) are dedicated to nanotechnology applications, such as Nanoelectronics (ENIAC), Nanomedicine and Sustainable Chemistry, and have produced vision papers and strategic research agendas. Other ETPs particularly relevant to N&N include Advanced Engineering Materials and Technologies, Hydrogen and Fuel Cell Technology, Industrial Safety (Nanosafety hub) and Photonics21, which includes nanophotonics and nanobiophotonics. ETP priorities are being taken on board in FP7 calls for proposals.

N&N often benefit greatly from interdisciplinary approaches, which may challenge more traditional education and training schemes. Within Erasmus Mundus, Masters Degrees in some areas of N&N have been developed. There has also been significant support for training in N&N through the Marie Curie actions of FP6, with grants of EUR 161 million, some 8% of their total budget.

"The nanotechnology research portal of the European Commission" offers website access to funding opportunities and EU funded projects, information on international co-operation, financing and innovation, education and mobility, health, environment and safety aspects, and communication and debate. The site also includes publications and events in nanotechnology, the latest nano-related news, and press material on nanotechnology in general and on specific funded projects. It also presents information on the European Strategy and the Action Plan on nanotechnology.

4.6.2 Some European Countries

Although many ad-hoc collaborations in the nanotechnology field exist, the overall Belgian nanotech scene is disperse, fragmented, and is lacking a global strategy. Belgium would certainly profit from a more systematic networking of all competent, academic as well as industrial players in the field.
Almost all European countries and several European regions have taken initiatives related to nanoscience and nanotechnology. The following selection highlights some recent actions in countries or regions comparable in size to Belgium.

The Netherlands

NanoNed, the Nanotechnology Network in the Netherlands, combines the Dutch strengths in nanoscience and technology in a national network with scientifically, economically and socially relevant research and infrastructure projects. It is aimed at enabling a knowledge leap through strong research projects, an infrastructure investment programme and economically relevant dissemination of the knowledge and expertise, targeting high added value economic growth. The total budget amounts to 235 M€ and the 5 year programme runs until 2009. Of the total budget, 85M€ is reserved for NanoLab NL, an investment programme of high-level, state-of-the-art nanotechnology infrastructure that is accessible to NanoNed and the Dutch research community as a whole. NanoNed is executed by a consortium of 9 partners, eight knowledge institutes and Philips, developing co-operations on the subject of nanotechnology in its different application areas. The programme is organised in 11 large interdependent so-called Flagship programmes: Advanced Nanoprobing ; Bottom-up Nano Electronics ; Chemistry and Physics of Individual Molecules ; BioNanoSystems ; NanoElectronic Materials ; NanoFabrication ; NanoFluidics ; NanoInstrumentation ; NanoPhotonics ; NanoSpintronics ; Quantum Computation.
Additionally, a Technology Assessment (TA) programme is an integrated part of NanoNed. The assessment will result in a mapping of the societal impact of nanotechnology in close collaboration with the scientists involved.

In autumn 2007, the Dutch nanotechnology community is preparing a ten-year research strategy after the end of the current NanoNed research programme in 2009. The Dutch government will incorporate this in its new action plan for nanotechnology which will be sent to the parliament by end of 2007.

Denmark

In 2005, a nanotechnology action plan was initiated, based on foresight studies sponsored by the Danish Ministry of Sciences, Technology and Innovation. The Action Plan envisages a total Danish public investment in nanoscience and nanotechnology of the order of 60M€ a year. To that should be added the contributions from the individual institutions and enterprises. This is estimated to correspond to a four- or five-fold increase in relation to the present level of grants. Research and innovation policy instruments will be aimed at activities both inside and outside nanotechnology centers for strategic research and innovation.

Switzerland

The Swiss National Science Foundation has set up a National Center of Competence in Research (NCCR) on "Nanoscale Science". The role of "leading house" for this NCCR is played by Basel University. It combines basic science with application-oriented research. In various projects researchers focus on nanoscale structures and aim at providing new impact and ideas to the life sciences, to the sustainable use of resources, and to information and communication technologies.

Ireland

The current focus of activity is around the NanoIreland project. This brings together government, industry, academia and the interests of societal actors and consumers, in order to develop the best public policy for investing in nanotechnology and managing its impact on the Irish society and economy. Research groups working on nanotechnology include: the Tyndall National Institute in Cork; Dublin City University's National Centre for Sensor Research; and Trinity College Dublin's Centre for Research on Adaptive Nanostructures and Nanodevices.

Catalonia

Nanoscience and Nanotechnology were regarded as areas of special interest in the 3rd Research Plan of Catalonia, initiated by the Government of Catalonia’s Minister of Universities, Research and Information Society. The expert commission recommendations led to a Special Nanotechnology Action Plan in February 2003. This plan established that three main initiatives would be carried out in Catalonia: a program of grants to facilitate the training of young researchers abroad; the creation of a Bioengineering Reference Centre; and the creation of a Catalan Institute of Nanotechnology.

5. Conclusions and Recommendations

Nanosciences and nanotechnologies are highly promising areas for research and industrial innovation, with a potential both to boost the competitiveness of industry and to create new products that will make positive changes in the lives of everyone . Nanotechnology, even if at its beginning, is no longer in its infancy and impressive progress is being made in many technological fields, from chemistry to electronics, from new sensors to functionalised surfaces and novel fabrics.

Productivity and jobs

Nanotechnology is recognized as a very strong innovation driver and is therefore seen as a strategic technology for the world's future economy. This perception is globally present and many countries invest heavily in nanotechnology through national or transnational nanotechnology programs with high expectations.
Introduction of a new technology requires not only investment in R&D and capital goods, but in new labour skills. This is a boom time for jobs for the science and engineering workforce. In addition, there is need for supporting labour services, which will create job opportunities for other skilled workers.

The conversion of disciplines

A universally recognized characteristic of nanotechnology efforts is the interdisciplinary research. Many benefits will come from interplay between nanotechnology, biotechnology, information technology and cognitive sciences. More specific we can distinguish four main domains of research activities: i) electronics, physics and informatics; ii) material sciences, mechanics and robotics; iii) chemistry, biotechnology and genetics; iv) societal, ethical and juridical. Nano is an umbrella that embodies a collection of technologies.

Potential applications

At the nanoscale, the physical, chemical and biological properties of materials may differ in fundamental and valuable ways from the properties of individual atoms and molecules or bulk matter. Nanotechnology presents new opportunities in:
***Tools and Methods (**Scanning probe microscopy; software & simulation; directed self assembly & lithography)
***Consumer electronics and computing (**Miniaturized supercomputers; terabit non-volatile memory; pervasive computing; low voltage and high brightness displays)
***Chemicals and basic materials (**Ultra-lightweight, high-strength, precision-formed materials; nano-composite polymers for structural and electronic applications; high efficiency and novel catalysts; wrinkle/stain/water-resistant textiles)
***Energy (**Thin film photovoltaic for cost effective solar energy; cost competitive fuel cells for automotive applications; high capacity, rapid charge batteries)
***Pharmaceuticals and medical products (**New and more effective drug compounds and drug delivery; new diagnostics and sensors; DNA sizing and sequencing; bioelectronics)
*** Environment** (Sensors, wastewater treatment and soil clean-up)

Education and training

Every new science or technology initiates its own supply of scientific workers, who must come from colleges and universities, foreign countries, or shift from other science-engineering activities. Successful R&D efforts rely on teamwork and communication. A complicating factor for the nanotechnology effort is the interdisciplinary nature of the work, which requires communication across technical and scientific fields. Presently there are a number of nanotechnology master degree programmes in Belgium; research institutes are directing some of their activities towards nano; universities are starting to set up nano-centres. In the near term, industry will draw from graduate students and postdoctoral fellows affiliated with the principal investigators of the nano-centres.

An important educational mission for nanotechnology centres-of-excellence has been largely unrecognized: retraining professionals. The postdoctoral position in traditional science fields is becoming an “academic purgatory” rather than a stepping stone to professorship because the number of tenure positions in academe is not growing to match the production of PhDs. The result is that many students have become disillusioned with science as a career option. This supply of disenchanted students could be reenergised by the promise of nanotechnology.

Regional innovation and intellectual property

Local policy makers can influence many elements of technological infrastructure. For example, many states sponsor regional conferences to facilitate idea exchange, provide links between small business and potential partners, and promote start-up incubators in targeted technologies. Attracting new high tech-firms has strong implications for regional policies toward nanotechnology. Academic and research institutions are the primary key to innovation. They are at the forefront of generating novel knowledge and are able to attract exceptionally productive scientists. The so-called ‘star’ scientists should transfer their knowledge to the commercialization process through collaboration with engineers or scientists in industry, or by founding their own start-ups.

Intellectual property rights are an important incentive for individuals and firms to innovate. Yet they can also be an impediment to communication and knowledge sharing. Nanotechnology will increase substantially the number of patents, a key indicator for the R&D effort. Currently the number of patents in Belgium (2005) is much lower (2477) as compared to for instance Sweden (7100), the Netherlands or Switzerland (8500).

The market for nanotech products

Analysts estimate that the market for products based on nanotechnology could rise exponentially to several hundred billion dollars by 2010 and exceed one trillion **(Figure 6).** Nanotechnology is expected to impact upon virtually all technological sectors as an “enabling” or “key” technology, especially upon medicine and health, information technology, energy production and storage, transportation, vehicles and infrastructure, materials science, food, water and the environment. Next to the ongoing progress in nanoelectronics, expectations are especially high for nano-bio applications, nano-based integrated sensors, and nanomaterials in the longer term.

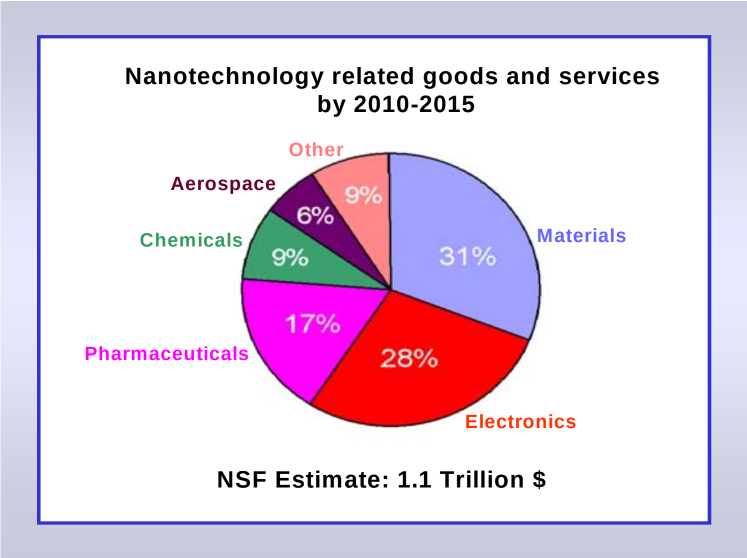

Fig.6. Nanotechnology impact on various domains (Source: NSF/IN Realis)

The social and ethical impacts of nanotechnology

There are several general strategies for technological risk governance which should also be respected in the case of nanotechnology. These include the development of i) an inclusive, globally focused, risk governance framework that addresses both short and long-term applications and ii) the adoption of strategies that ensure the interests of all potentially affected parties are addressed. Academic researchers, developers, potential users and other important actors should be actively involved in this scenario building exercise.
The private sector is a major player in the development and diffusion of nanotechnology. It is in the best interest of private investors to assure that minimum standards for safety and health protection are established and enforced internationally and that potential risks are investigated and assessed before actual damage occurs.
It is recommended that health and safety standards are rapidly agreed upon worldwide or at least at the EU level.

Nanotechnology in Belgium

Belgium has initiated significant nanotechnology efforts, based on its educational culture of integration and networking. Networking is encouraged across multiple centres of excellence, including the universities and the research institutes. Commercial applications of nanotechnology are being developed mainly through the university and research institute spin-offs and SMEs, with little large industry involvement at present.
A more coordinated action is needed on all levels of research activities and funding, in particular between the federal and regional authorities, the finance institutions, the research centres, the universities, and the industry. Initiatives have been started or planned to set up a focused effort in nano- and its converging technologies.
In Wallonia-Brussels a Strategic Network for Nanotechnology "NanoWal" has been set up for the period 2002-2007. In concurrence with the innovation plans for "Flanders in Action", a Strategic Cluster for nano-electronics, micro- and nanosystems technology, and quantum computing has recently been proposed by the Flemish Research Council (VRWB) as a priority.

Summary of recommendations

Here are some points for consideration on the coming nano-wave:

1. Nanotechnology is foremost a collection of productivity enhancing technologies that will permeate many industries. The development of enabling technologies in the field of machine tools, quality control and cost estimates are an important factor to realise this permeation.

2. Business ventures should be nurtured that seek to reinvest nano-enabled productivity gains from established industries into the growth of new industries.

3. Nanotechnology education is a thorny problem due to its position at the intersection of many disciplines and is likely to work best in (virtual) nano-institutes.

4. Nano centres-of-excellence should provide retraining programs for professionals in order for members of the highly skilled science and engineering workforce to learn enough about other disciplines to collaborate effectively in interdisciplinary teams.

5. The comparative advantage that Belgium enjoys in creating high-tech start-up companies can be enhanced by educating researchers about entrepreneurship while likewise educating MBAs about nanotechnology.

6. Nanotechnologists should adopt a code of conduct for responsible nanosciences and nanotechnologies, e.g. in conformity with the recent European Commission recommendation how to govern research in this field

----

6. REFERENCES

§ 2. Introduction

Nanotechnology. Analysis of an Emerging Domain of Scientific and Technological Endeavour. Report by W . Glänzel et al., Steunpunt O&O Statistieken, 2003.
http://www.steunpuntoos.be/nanotech_domain_study.pdf

Nanotechnology Homepage of the European Commission
http://cordis.europa.eu/nanotechnology

The National Nanotechnology Initiative at Five Years: Assessment and Recommendations of the National Nanotechnology Advisory Panel, May 2005
http://www.ostp.gov/pcast/PCASTreportFINALlores.pdf

The Social and Economic Challenges of Nanotechnology. S. Wood, R. Jones and A. Geldart. UK's Economical and Social Research Council (ESRC)
http://www.esrcsocietytoday.ac.uk/ESRCInfoCentre/Images/Nanotechnology_tcm6-1803.pdf

Nanoforum Report. European Nanotechnology Gateway**.**
www.nanoforum.org

§ 3.1.1 Looking at the nanoscale

Nanomaterials Handbook, Yuri Gogotsi (ed.), CRC Press ISBN 0-8493-2308-8, 2006
Greenbook GENNESYS (**G**rand **E**uropean Initiative on **N**anoscience and **N**anotechnology using Neutron and **Sy**nchrotron **S**ources); ed. H. Dosch & M.Van de Voorde, MPI-Metallforschung Stuttgart, to be published

Eighth Nanoforum Report: Nanometrology, July 2006
www.nanoforum.org

§ 3.1.3 Availability of expertise

The European Synchrotron Radiation Facility
http://www.esrf.fr

The Institute Laue-Langevin for neuton scattering and diffraction mediated research
http://www.ill.fr

De Vlaams-Nederlandse CRG DUBBLE te ESRF Grenoble
http://www.fwo.be/ links

De Vlaamse deelname aan grote internationale onderzoeksinfrastructuur, VRWB Studiereeks 19, 2007
www.vrwb.be

ISO Focus: Nanotechnologies, Vol. 4, No. 4, April 2007, ISSN 1729-8709,
http://www.iso.org/iso/iso-focus_2007-04

§ 3.2 Nanoelectronics and Nanophotonics

G.E. Moore, Electronics 38 (8) 1965

ITRS 2007 Documents
http://www.itrs.net/reports.html

Vision 2020-Nanoelectronics at the Centre of Change. Report of the High level Group-June 2004
http://cordis.europa.eu/nanotechnology

Nanoelectronics research for European systems
www.medeaplus.org

ENIAC Strategic Research Agenda
www.eniac.eu/web/divers/SRA_2006.pdf

Strategic Research Agenda of the European Technology Platform on Smart System Integration
www.imt.ro/technological_platforms/sra_EPoSS.pdf

IEEE Journal of Selected Topics in Quantum Electronics, 12 (6) November-December 2006

§ 3.3. Impact of Nanotechnology on Materials and Manufacturing

Nanomaterial Roadmap 2015 "Promising Nanomaterials for Industrial Applications", September 2005
www.nanoroad.net

Chemical Industry R&D Roadmap for Nanomaterials by Design: From Fundamentals to Function. December 2003
www.ChemicalVision2020.org

Nano matters, Carol Lynn Alpert, MaterialsToday 9 (5), 52, May 2006

NanoRoad sme Nanomaterial Roadmap 2015 – Roadmap Report Concerning the Use of Nanomaterials in the Automotive Sector, March 2006
http://www.nanoroad.net/download/roadmap_ai.pdf

Environmentally Beneficial Nanotechnologies: Barriers and Opportunities, Oakdene Hollins Report, May 2007
http://www.defra.gov.uk/environment/nanotech/policy/pdf/envbeneficial-report.pdf

Point-One Strategic Research Agenda, April 2007,
www.point-one.nl

European Technology Platform on Smart Systems Integration, EPoSS,
www.smart-systems-integration.org

European Technology Platform for Micro-and Nanomanufacturing, MINAM, www.minamwebportal.eu

§ 3.4.2 Nanotechnology for food

Nanotechnology in Agriculture and Food. T. Joseph and M. Morrison, Nanoforum Report 2006
www.nanoforum.org

§ 3.5 Impact of Nanotechnology on Sustainable Generation of Energy

R.E.Smalley, "Future Global Energy Prosperity: The Terawatt Challenge", MRS Bulletin, Vol.30, P.412-417, June 2005

N.S.Lewis, "Powering the Planet", MRS Bulletin, Vol.32, October 2007

European Commission, EUR 21151 "Nanotechnology – Innovation for Tomorrow's World", ISBN 92-894-7498-X, 2004

M.Dresselhaus, G.Crabtree and M.Buchanan, "Addressing Grand Challenges through Advanced Materials", MRS Bulletin, Vol.30, p.518-524, 2005

S.Gledhill, B.Scott and B.Gregg, "Organic and Nano-structured Composite photovoltaics: an Overview", J.Mater.Res.Vol.20, N° 12, p.3167-3179, December 2005

J.J.Hickmann, "Nanoscience and its Applications to Energy", Nanotechnology Center (NSTC), University of Central Florida
http://www.asmeconference.org/EnergyNano06/3

L.E.Foster, "Nanotechnology: Science, Innovation and Opportunities", Chapter 2, Nanotechnology and Our Energy Challenge, Published by Prentice Hall, ISBN 0131927566, December 2005

O'Regan and M.Grätsel, Nature 353, 735-740 (1991)
http://nanopedia.case.edu/NWPage.php?page=hydrogen.economy.externalities2

Y.Bruynseraede, "Energie en Nanotechnologie: Strategie voor de Toekomst", Leuven 2007

§ 3.6 Nanotechnology and Environment

Nano & the Environment, report of the workshop organized by Nanoforum and the Institute for Environment and Sustainability, JRC Ispra, 30 and 31 March 2006, Brussels

Nanotechnologies for environ mental cleanup. K. Tratnyek and J. Johnson, Nanotoday, 1, 44-48, 2006

Environmetal, Health, and Safety Research Needs for Engineered Nanoscale Materials. Report of the National Nanotechnology Initiative of the US, 2006

Characterizing the Environmental, Health, and Safety Implications of Nanotechnoloy : Where Should the Federal Government Go From Here? Report prepared by ICF International, US, December 2006

Overview and Comparison of Conventional and Nano-based water treatment technologies. Background Paper for the International Workshop on Nanotechnology, Water and Development, October 2006, India

Nanotechnology, Water & Development. M. Musassinghe, Y. Deraniyagala, T. Hillie, M. Hlope, Report of the Meridian Institute, 2006

Hydrogen as an Energy Carrier. Publication by the Royal Belgian Academy Council of Applied Sciences (BACAS – CAPAS/CAWET), April 2006
http://www.kvab.be/downloads/CAWET/Hydrogen_energycarrier.pdf

§ 3.7 Nanotechnology: Health and Environmental Risks

White paper on "Nanotechnology Risk Governance", O. Renn and M. Rocco, June 2006 (www.irgc.org)

Nanotechnology: A Research Strategy for Addressing Risk, A. D. Maynard, Woodrow Wilson International Center for Scholars, Washington DC, 2006
(www.wilconcenter.org/nano)

EC CORDIS. Nanotechnology Action Plan. Safety Aspects
(http://cordis.europa.eu)

EC DG Environment, 2006. Nanotechnologies: Panacea or Pandora box. The Environment for Europeans, 24 May 2006.

ECETOC, 2007. The potential risks of nanomaterials: a review carried out for ECETOC Submitted by Veronique Thierry-Mieg. Copyright 2007 NANOSAFE2-EU Project NMP2-CT-2005-515843.

EU Finnish Presidency, 2006. Conference on "Nanotechnologies-Safety for Success". 14-15 September 2006, Espoo, Innopoli, Finland

Health and Safety Executive (UK) Watch Committee 2006. Occupational health aspects of nanotechnologies. Paper 2006/10.

Nanomaterials: Toxicity, Health and Environmental Issues, Wiley, Kumar, Challa S.S.R. (editor), 2006

Ministère de l'Ecologie et du Développement durable, Comité de la Prévention et de la Précaution, Nanotechnologies, nanoparticules, quels dangers, quels risques ? Paris 2006.

Environmental, health and safety research needs for engineered nanoscale materials, US National Science and Technology Council, September 2006.

European Commission code of conduct for responsible nanoscience and nanotechnology.
http://europa.eu/rapid/pressReleasesAction.do?reference=IP/08/193&format=HTML&aged=0&language=EN

European Commission review of safety aspects
(http://cordis.europa.eu/nanotechnology/src/safety.htm

§ 4.3 Nanotechnology in Flanders

Technologie en Innovatie in Vlaanderen: Prioriteiten. Proces van Prioriteitsstelling en Resultaten. Studiereeks VRWB, 2006
(www.vrwb.be)

Erasmus Mundus - Master Nanoscience and Nanotechnology
http://www.emm-nano.org/indexnano.htm

Nano-education from a European Perspective, I. Malsch
www.nanoforum.org

Education in the Field of Nanoscience. T. Kulik and J.D.Fidelius, Nanoforum Publication, February 2007
www.nanoforum.org

Erasmus Mundus Master Course "Nanoscience and Nanotechnology"
http://www.emm-nano.org/indexnano.htm

Erasmus Mundus Master of "Science in Photonics"
www.master-photonics.org

§ 4.6.1 The European Commission

Communication from the European Commission to the Council, the European Parliament and the European Economic and Social Committee. Nanosciences and Nanotechnologies: An action plan for Europe 2005-2009. First Implementation Report 2005-2007. Brussels, 6.9.2007 COM(2007) 505 final.
http://ec.europa.eu/nanotechnology/pdf/comm_2007_0505_en.pdf

European Nanoelectronics Initiative Advisory Council.
http://www.eniac.eu/

European Technology Platform medicine.
http://cordis.europa.eu/nanotechnology/nanomedicine.htm

Erasmus Mundus Master. Nanoscience and Nanotechnology.
http://www.emm-nano.org/

The Nanotechnology Homepage of the European Commission.
http://cordis.europa.eu/nanotechnology/

Commission recommendation of 07/02/2008 on a code of conduct for responsible nanosciences and nanotechnologies research. Brussels, 07/02/2008 C(2008) 424 final.
http://ec.europa.eu/nanotechnology/pdf/nanocode-rec_pe0894c_en.pdf

§ 4.6.2 Some European Countries

NanoForum Report “Nanotechnology in Europe - Ensuring the EU Competes Effectively on the World Stage”
(www.nanoforum.prg)

Dutch Nanoscientists prepare Netherlands Nano Initiative Strategy. Nanoforum, October 2007
(www.nanoforum.org)

Technology Foresight on Danish Nanoscience and Nanotechnology. Action Plan. Published by the Ministry of Science, Technology and Innovation, 2003.
(www.vtu.dk)

Brussels, May 2008