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## **THE ROLE AND FUTURE OF NANOTECHNOLOGY IN RESEARCH, INDUSTRY AND EDUCATION**

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**Abstract:** Major developments in Nanotechnology have taken place across the world over the last few years. From a humble beginning, Ireland inc. became a leader in the Microelectronics industry and now has to face the challenge of developing a strategic plan to maintain its lead position in the nano field which in most cases will supersede the micro phase. Most countries are taking a similar path of development all be it alone or in collaboration with other countries. This process is expensive and requires market drivers and experts to lead and deliver demands from the industries of the future. The approach may be driven from a top down or bottom up, i.e. from macro to micro to nano or from sub nano to nano components and machines. What are the development areas and implications for nano Biotechnology, nanoelectronics and nanomaterials, how are the industries developing and how are we educating our undergraduates and postgraduates in this technology. This paper will discuss some of the key areas of development and the associated industries and research centres and how the knowledge may be transferred to our educational programmes.

The paper provides a summary of the work developed in a number of key reports on Nanotechnology [1-3], combined with the authors views and opinions on developments in the nanotechnology field.

**Keywords:** Nanotechnology, Biomaterials, Nanomaterials,

## 1 Introduction

Nanotechnology is a term to define a wide range of technologies concerned with structures and processes on the scale of a nanometer (one billionth of a meter,  $10^{-9}$  m). It is a collective term for a set of tools and techniques that permit the atoms and molecules that comprise all matter to be manipulated. Nanoscience and nanotechnology are new approaches to research and development that aim to control the fundamental structure and behaviour of matter at the level of atoms and molecules. Applications of nanotechnology are emerging and will impact on the life of every citizen. Nanoengineering represents the extension of the engineering fields into the nano- scale realm (nanofabrication, nanodevices, etc.) and concerns itself with the fabrication of objects which are anywhere from hundreds to tens of nanometers in size.

Nanoscience is the science for nanotechnology. Materials produced on a nanometer scale behave differently from the same materials produced on a larger scale. Nanotechnology is therefore regarded as a key technology which will not only influence technological development in the near future, but may also have decisive economic, ecological and social implications.

Using nanotechnology tools and techniques, it is possible to exploit the size-dependent properties of materials structured on the sub-100 nanometer scale, which may be assembled and organised to yield nanodevices and nanosystems that possess new or improved properties. These tools and techniques, materials, devices and systems present companies in all sectors of the Irish economy with opportunities to enhance their competitiveness by developing new and improved products and processes[4]. Nanotechnology is also an enabling technology which can impact on other fields leading to new developments and challenges (examples range from enabling efficient thermal to electrical energy conversion systems to enabling molecular manufacture on an industrial scale). Table 1. gives a brief summary of the history and innovations in nanotechnology.

|  |
|--|
| 1931 Knoll and Ruska develop the electron microscope – subnanometer imaging  |
| 1959 Richard Feynman “There’s plenty of room at the bottom” – concept of atomic engineering                                    |
| 1968 Cho and Arthur, Bell Labs – technique to deposit single atomic layers on a Surface  |
| 1974 Taniguchi coins the word “nanotechnology” – machining less than a micron Tolerance  |
| 1981 Binnig and Rohrer invent the Scanning Tunnelling Microscope – ability to image and drag individual atoms                  |
| 1985 Curl, Kroto and Smalley discover “buckyballs” – nanometer in diameter   |
| 1986 Drexler publishes “Engines of Creation” –   |
| 1989 Eigler writes the letters IBM - using individual xenon atoms  |
| 1991 Iijima, NEC – discovers carbon nanotubes  |
| 1993 Robinett and Williams connect a VR system to an STM – see and touch Atoms   |
| 1998 Dekker, Delft University - creates a transistor from a carbon nanotube  |
| 1999 Tour and Reed - demonstrate how single molecules can act as switches  |
| 2000 Clinton administration announces the National Nanotech Initiative (NTI) – large funding (\$497m) and increased visibility |
| 2000 Eigler creates a quantum mirage – possible means of transmitting information without wires                                |
| 2001 Scientific America issues special Nanotech report   |
| 2002 Bush administration and congress give \$604.4m budget to NTI  |
| 2003 NTI budget increased to \$679m, \$180m going to Dept. of Defence  |

**Table 1. The History of Ten to the Power of Minus Nine**

## 2. Terminology

NanoBiotechnology is an interdisciplinary field of research based on the cooperative work of chemists, physicists, biologists, medical doctors and engineers. At the interface between biotechnology and nanotechnology, nanobiotechnologists carry out research on the phenomena of self-assembly or self-organisation of biomolecules such as cell membranes or virus particles, in order to adapt these principles to the technical production of nanostructures.

Nano-to-Bio designates the use of nanotechnological tools to study the molecular mechanisms behind various biological processes at the single molecule level. From this perspective, nanoanalysis, nanomanipulation techniques for biological structures and objects, nanotechnologically produced active ingredients for living organisms, nanocarriers for transporting active ingredients, nanomachines, nanobots for research, diagnostics and therapy, nanotechnologically coated implants and nanoelectronic (particularly neurological) implants are possible applications.

Bio-to-Nano refers to bio(techno)logical materials and designs for producing technical nanosystems. These could be exploited in information and communication, energy, environment and many other areas for technical applications. These include e.g. nanotechnology applications based on biological paradigms (biomimetics), the use of biological components on the nanometer scale for technical systems, or nanoelectronics and nanoinformatics using biological components, functional or organisational principles. Nanotechnology and nanoscience are seen as;

- (i) dealing with structures smaller than 100 nm in at least one dimension and
- (ii) as describing the deliberate manufacture and/or manipulation of individual nanostructures.

Research into nanoS&T and its materials typically adopts one of two fundamental strategies:

- (i) the “top-down” approach in which, starting from microtechnology, structures and components are more and more miniaturised. For example, components can be physically reduced in size through etching.
- (ii) the “bottom-up” approach.

### 2.1 Top-down Fabrication

Top-down methods start with large area blocks of a material and carve out structures by selectively patterning and processing well-defined areas on the block surface. Continued miniaturisation of transistor devices over the last 40 years has resulted in exponential increases in both processor speed and also the number of transistors per chip (Moore’s Law), thus enabling greater functionality. Processor chips for modern PCs are fabricated using short wavelength (193 nm) light sources and optical lithography processes which produce transistors with feature sizes as small as 70 nm across wafer slices of silicon crystals up to 300 mm in diameter. These methods are amenable to mass manufacturing, which has resulted in reduced costs (per transistor) for high-end electronics products. However, exponentially increasing fabrication costs and fundamental physical limitations remain significant challenges for continued top-down miniaturisation over the next decade.

### 2.2 Bottom-Up Nanofabrication

Bottom-up processes use chemically- or biologically-inspired routes for synthesis and assembly of nanoscale building blocks into complex nano architectures with novel electronic or optical properties. Self- and directed-assembly mechanisms are often found in nature, from the growth of crystals to the formation of complex functional biotechnological systems – including the cells of the human body. The advantages of bottom-up processes include drastically reduced fabrication costs; however development of controlled assembly strategies for integration of bottom-up nanostructures and nanoarchitectures into electronic devices and circuits remains a

significant long-term challenge. In the medium term, development of hybrid top-down/ bottom-up fabrication strategies for electronics represents a key opportunity.

### 3. Research Developments in Nanotechnology

Nanotechnology and Nanoscience can pervade virtually all technological sectors. The expected level of impact of nanotechnology on the various technology areas, are given in Figure 1. While nanoelectronics will be pervasive in all of the areas identified the level of impact will vary with the sector.

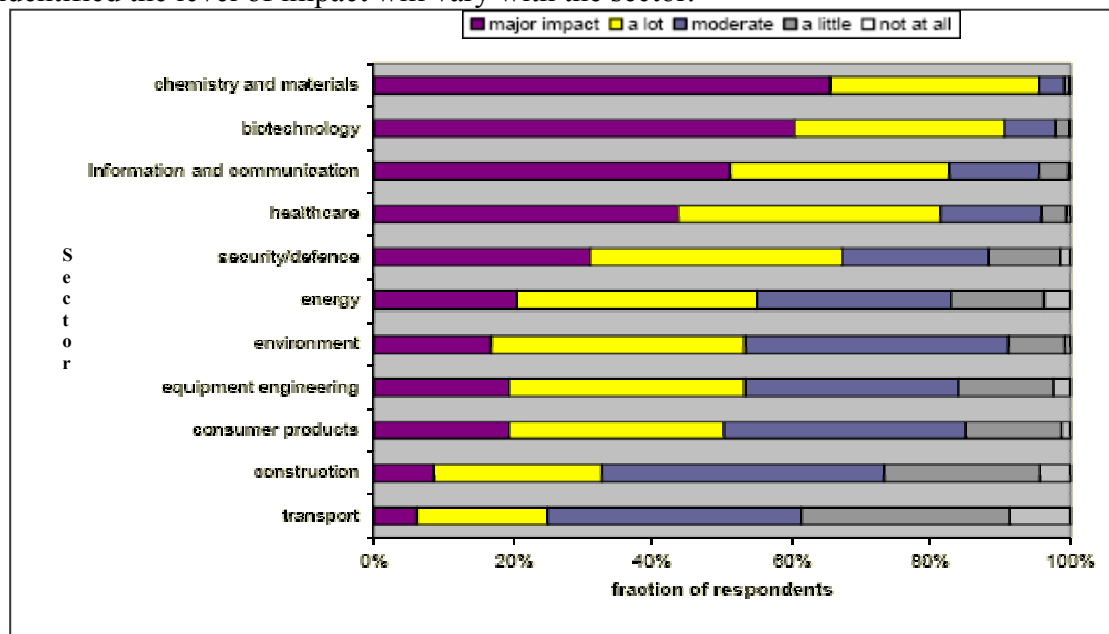


Figure 1. Expected impact of nanotechnology on economic sectors.

Figure 2. shows Japan's governmental nanotechnology budget by research field (fiscal 2001). The red and green areas indicate amounts for non-competitive national funds and competitive individual ones, respectively. Allocation of nanotechnology budgets by research field shows that basic technologies for metrology and manufacturing coupled with nanomaterials occupy some 50% of the total, indicating the government's resolve to strengthen Japan's position in the nanomaterials sector.

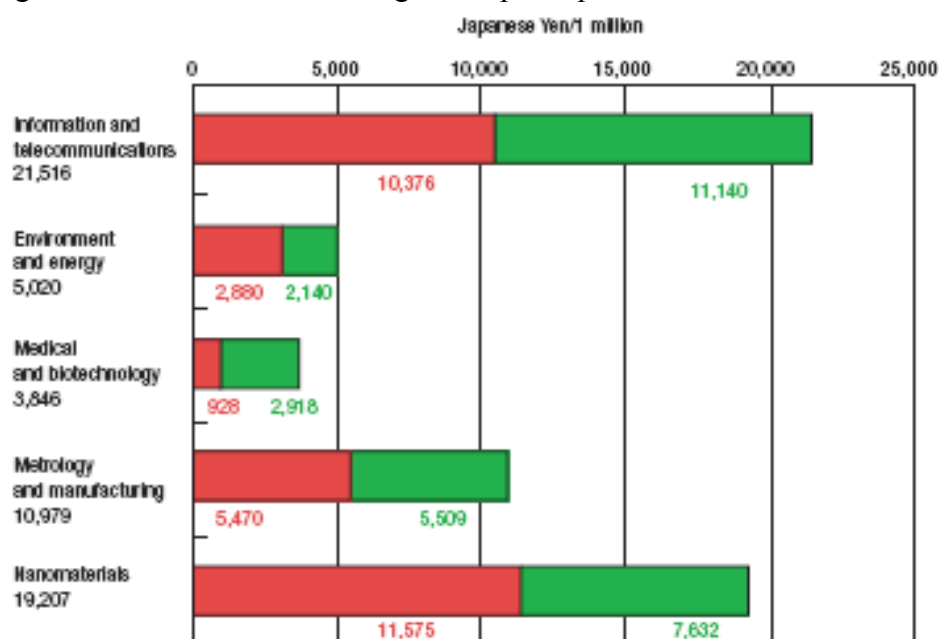
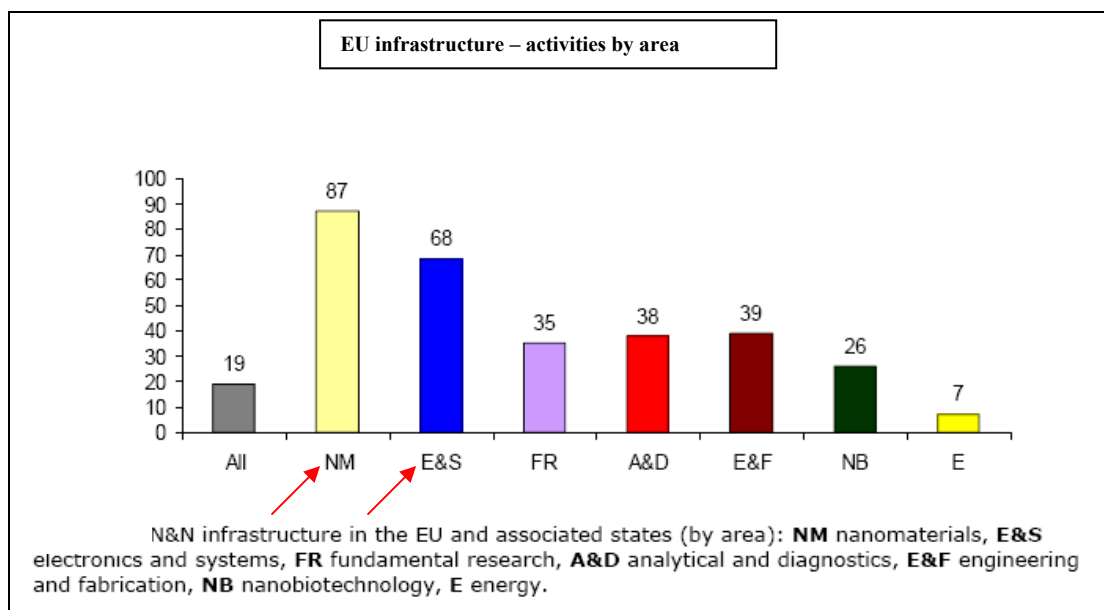


Figure 2. Japan's governmental nanotechnology budget by research field (2001).

Each **new technological generation** requires a steep increase in the level of investment needed to conduct research and build production plants – the European electronics industry currently spends 20% of turnover on research and a typical fabrication facility today costs around €2.5 billion.

NanoMarkets, a leading advanced technology analyst firm based in the US, forecasts that the market for nano-enabled electronics will reach US\$10.8 billion (€8.6 billion) in 2007 and grow to US\$82.5 billion (€66 billion) in 2011. Figure 3. shows the range of applications for nanotechnology in Europe.



**Figure 3. - Nanoscience and Nanotechnology infrastructure in the EU and associated states [7].**

#### 4.1 Industrial Applications

Atomic force microscope (AFM) technology (which can move single atoms about) is being used to create smaller and more sensitive microarrays for use in diagnostics and drug discovery. AFMs can also be used to nanostructure surfaces, and for example make them more biocompatible. Nanoparticles such as fullerenes, dendrimers, and quantum dots (complexes of semi-conductor material that have unique fluorescent properties) are being exploited in many areas including imaging such as enhancement of magnetic resonance imaging [MRI] and ultrasound and drug delivery.

Formulating drugs with nanoparticles can also improve their solubility. Many drugs are not marketed because they are not very water-soluble. Other problems concern ways to increase their resistance to stomach acid and enzymes (allowing better uptake from the small intestine), and allow controlled release (e.g. over days rather than minutes and hours). Nanotubes represent another mechanism for drug delivery, both as a “container” and potentially a system for “nano-injection” into cells.

In hyperthermic therapy, magnetic particles are covered with biological species and injected into cancerous areas. The molecular structure of the coating forces the cancer cells to absorb the particles, while the healthy cells do not. Using an external magnetic field, the particles are then activated, causing the cancer cells to heat up and die. This is one of the more promising treatments for cancer diseases over the next few decades. Nanocomposites of titanium alloys, for example, can be used to improve the

biocompatibility and longevity of surgical devices and implants. Nanostructuring surfaces can improve cellular attachment (e.g. etching surfaces with nanoscale grooves or using instruments such as an AFM to imprint surfaces with cell attachment molecules), and direct cells to grow into defined structures. By incorporating biodegradable polymers to act as a scaffolding, these structures can be assembled into 3-dimensional “tissues”. Nanostructuring can also be used to provide an anti-microbial coating on implants. Antimicrobial agents based on nanomaterials (e.g. silver incorporated into polymer tubes or titanium dioxide coated surfaces) can be used to sterilise medical equipment or other items.

New medical treatments are expected over the medium time scale, e.g. self-organizing hollow spheres that will transport drugs in the bloodstream to a specific area of the body. External control may even be possible via an additional coupling of magnetic particles or antibodies. Drugs that are presently injected may be taken orally with the aid of nanomaterials. The potential of such nanoscale drug delivery systems is estimated at \$50 million by 2007.

#### **4.2 Food and Agriculture**

Nanotechnology also has applications in the agri-food sector. Many vitamins and their precursors, such as carotinoids, are insoluble in water. However, when formulated as nanoparticles, these substances can easily be mixed with cold water, and their bioavailability in the human body also increases. Many lemonades and fruit juices contain these specially formulated additives, which often also provide an attractive colour. The world market potential of such micronized compounds is estimated at \$1 billion. Bio and gas sensors could gain importance in food production. These sensors could be integrated into packaging materials to monitor the freshness of the food. Spoiling of the food could be indicated by a colour change of the sensor. Several concepts have already been developed for such applications based on silicon or polymer thin film sensors.

#### **4.3 Energy and Environment**

Energy research is increasingly important, particularly as regards the role it plays in support of a wide range of key EU policies. Nanotechnology shows promising potential in all segments of the energy sector: production, storage, distribution and use with the potential to change the way we convert, store and utilize the world’s energy supply. Trends in nanotechnology will contribute to cleaner industrial production processes or products, mainly through reducing the use of raw materials and energy. Nanotechnology in conjunction with biotechnology and new materials research can help develop products that require less energy to recycle and produce.

Better energy generation, conservation and storage was identified as the most promising area of nanotechnology research in a survey of 63 specialists worldwide (April 2005). Energy research priorities are identified in the report of the interagency workshop on *Nanoscience Research for Energy Needs* (2004). Key areas include:

1. Highly selective catalysts for clean and energy efficient manufacturing;
2. Energy efficient, resource-saving building materials / lighting / glazing;
3. Nanocomposites for energy efficient vehicles and engines;
4. Low cost fuel cells and batteries;
5. Lightweight, efficient solar cells (power collectors and storage); and
6. More efficient (1 gigawatt) power transmission lines.

Renewable energy areas apart from solar cells include hydroturbines, wind turbines and biomass burners. Other opportunities occur in energy end-use – innovative building design, low consumption heating and lighting and smart energy controls.

While Ireland is not a global producer of energy, it has the potential to contribute in energy storage and transmission technologies through engineering and energy technologies.

#### **4.4 Construction**

Construction is important for the economy of Ireland. Construction output as a percentage of GNP had increased from 13 per cent in 1994 to over 20 per cent in 2001 and that level was sustained and even increased slightly to 21 per cent in 2003. In GDP terms, construction output was 18 per cent of GDP in 2003 (compared with an average of 10.4 per cent of GDP in 2003 for construction across Western Europe). The value of output in the construction industry in 2004 is estimated at € 28.2bn in 2004 , compared with €21.3bn in 2002.

Many applications of nanomaterials in construction derive from the distribution of nanoparticles in a ceramic, metallic or polymer matrix. Introducing nanoscale particles in metals improves the mechanical properties, which can contribute substantially to lightweight construction. Material properties such as hardness, compressive strength, ductility and wear resistance can be enhanced. Examples include:

1. Silicon dioxide nanoparticles in synthetic silicic acid (nanosilica) used as an additive for sprayed and high-performance concrete to help improve bond tensile strength and bond shear strength between concrete and reinforcing steel.
2. Nanometer multilayer coating from conducting polymers for corrosion protection of carbon steel or stainless steel construction materials.
3. Thermal insulation for buildings (e.g. windows with an invisible silver nanocoating forming a transparent thermal insulation)
4. Façade design (e.g. self-cleaning, anti-graffiti protection or high scratch and wear resistance in plastics through appropriate coatings) and
5. interior (e.g. titanium dioxide nanoparticle additives to coatings to protect from discoloration under artificial and natural light).

#### **4.5 Electronics and ICT**

Over 300 overseas ICT companies develop, market and manufacture a wide range of leading edge products in Ireland. 45,000 people are employed here by overseas companies alone (including IBM, Intel, Hewlett Packard, Dell and Microsoft). In 2003, Irish exports in this sector exceeded €21 billion, representing 26 per cent of all exports.

To date, much of the global nanotechnology activity in the electronics and ICT areas has been focused on miniaturisation of components but nanoelectronics and nanoengineering may also lead to new production processes including self assembly of circuits and systems. Areas of development in the industry include design and simulation of materials; synthesis, growth, deposition and processing of materials; high throughput characterization and analysis and device prototyping, integration and analysis. Materials feature in all of these, even potentially in the analysis and testing stages of prototyping.

Much of the miniaturisation of computer chips to date has involved nanoscience and nanotechnologies, and this is expected to continue in the short and medium term. The storage of data, using optical or magnetic properties to create memory, will also depend on advances in nanoscience and nanotechnologies.



Alternatives to silicon-based electronics are already being explored through nanoscience and nanotechnologies, for example plastic electronics for flexible display screens. Other nanoscale electronic devices currently being developed are sensors to detect chemicals in the environment, to check the edibility of foodstuffs, or to monitor the state of mechanical stresses within buildings. Much interest is also focused on quantum dots, semiconductor nanoparticles that can be ‘tuned’ to emit or absorb particular light colours for use in solar energy cells or fluorescent biological labels.

#### **4.6 Materials for medical applications**

Biomaterials and medical devices represent a fast emerging market that was estimated at about 260 billion € world-wide for the year 2000 alone, with Europe's share being about 30%. Biomaterials research in Europe is of very high quality and in strong competition with the USA who are still the world leader. On the other hand, Europe holds its position of excellence in specific areas like tissue engineering.

The new and active life-style of citizens and the ageing European population need multidisciplinary materials research, which are strongly oriented towards promising developments. An example is hybrid tissue engineering that can satisfy the ever-growing demand of tissue and organ replacements or repair avoiding dependence on human donors or xenotransplantation, and all related risks of rejection, infection or transmission of diseases.

Technologies aiming at the improvement of the biocompatibility of all types of implants through, for example, bio-active coatings and nano-structures or newly designed or bio-mimicking materials should be strengthened. NB approaches are also required within the development of materials for new targeted drug delivery systems to fight against diseases that have been so far incurable. Related technologies like minimally invasive surgery, non-invasive diagnostic systems, including reliable biosensors, also need further continuing support.

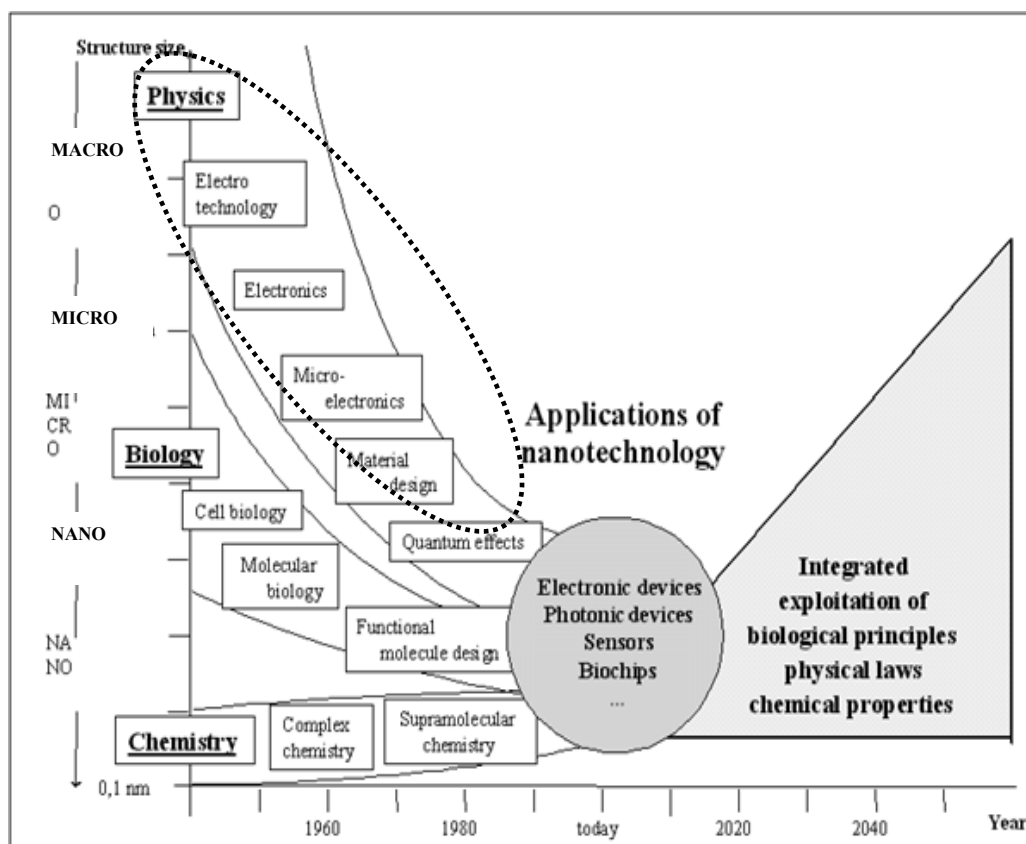
#### **4.7 Nanoelectronics**

The term nanoelectronics refers to electronics at the sub-micron scale. Many chip components in manufacture already feature sizes at the nanoscale. However nanoelectronics also encompasses molecular electronics. This make use of individual molecules in electronics as shown in Figure 4. Up until recently, the size of the smallest electronic circuit element was expressed in microns. Continuous evolution in technology over the years has shrunk circuits so that these dimensions are now less than 65 nanometers. At this scale, some of the classical laws of physics no longer apply and give way to properties defined by quantum physics. Such effects may present challenges for conventional semiconductor technology but also offer opportunities for new technologies. Advances in nanotechnology with applications in electronics include carbon nanotubes that can be used in both chips and displays. Other nanomaterials that can be used in very thin films make smaller, more flexible displays and improved computer hard disks.

Since the 1970's, the microelectronics industry has followed Moore's law, doubling processing power every 18 months. This performance increase has been obtained mainly by decreasing the size of circuit features obtained by optimisation and improvement of existing technology. The minimum feature size is approaching 10 nm for the next decade.

CMOS technology currently dominates manufacture of integrated circuits. Its energy efficiency makes it possible to integrate many more CMOS gates on a chip than those made with alternative technologies, so offering much higher functionality. As a result, CMOS is currently the mainstream technology for microprocessors, memory and

logic circuits on silicon wafers. Due to its advantageous characteristics and future development potential, experts predict that CMOS will remain the mainstream technology for many years and improvements will continue until at least 2016.



**Figure 4. - Position of Nanoelectronics in the Nano Landscape [5].**

While CMOS continues to dominate the semiconductor industry, it appears that several **nanoelectronic devices** originally conceived as successors to CMOS, are now finding their way into niche markets. It is also clear that the Moore's Law exponential increases in density and that the performance that CMOS has enjoyed for over thirty years cannot be maintained for ever. Eventually the increase in density, power consumption and volume of silicon chips will require all the energy in the universe to allow operation [6].

As the result of industry's adoption of new materials / technology platforms - such as spintronics, plastic electronics, molectronics and nanotubes / nanowire electronics, low- and high-k materials, a new demand for novel manufacturing modes is now emerging. **Current investment in electronics accounts for** some 30% of overall industrial investment in the developed world. The **market size** of the nanoelectronics business chain (manufacturers, related industries such as the equipment and material suppliers, the designers, system builders and integrators, etc.) represents currently nearly 1% of the world wide GDP with a strong annual average growth rate of approximately 15%. When considering the leverage effect of this enabling technology (telecom operators, consumer products, internet services, automotive, defence, space, etc.), its **global value** can be increased to an estimated €5,000 billion. Furthermore, the nanoelectronics sector is also a significant generator of highly qualified jobs, given its manufacturing dimension.

In Europe some 40% of the **annual sales** of the semiconductor manufacturers are reinvested in R&D and improved production processes. The worldwide annual market

for electronics at just under €800 billion is now bigger even than the global automotive market. Alternatives or complements to CMOS, such as spinelectronics, molecular electronics and quantum computing, also exist and are in the early stages of research and development. Molecular electronics are the most futuristic devices among all discussed so far. They have a large potential, but there are huge obstacles that must be overcome. For the moment it seems of the utmost importance that chemists, biologists, physicists and engineers develop an interdisciplinary platform for communicating the needs of the electronics industry in one direction and the possibilities of chemical synthesis and self-assembly concepts in the other.

European Nano-electronics Initiative Advisory Council (ENIAC) has stated that for Europe to become the world's most competitive powerhouse, Europe must lead the transition of the micro-electronics sector to the next generation of nano-electronics, with co-ordinated public and private investments of at least €6 billion per year. This is the message from CEOs of leading companies and research organisations also emphasised that smarter and smaller electronics at the nanometer scale, managing vast amounts of data, are becoming key components for many applications, from household appliances and consumer goods to automotive transport, health care and security, and ultimately ambient intelligence.

#### 4.8 Design Technology

Demands on systems design will increase with the adoption of new nanoelectronics technologies and the resultant increase in complexity of the devices and heavily integrated applications. There will be a need for new design approaches that make it possible to reuse designs easily when new generations or families of products appear. These approaches should be coupled with automatic translation of the resulting high-level designs into device manufacture.

Advanced research into **manufacturing process technology** is a driving force behind Europe's significant scientific and manufacturing economies. Going to smaller circuit feature sizes in the nanometer range down to 22nm or even lower, the process technology for nano-lithography, as well as for the deposition and etching of device layers, also needs to be improved. Certain of the device layers will have a thickness of only one or a few atomic layers and their deposition process needs to be very well controlled and take place in an ultra-clean environment. Obtaining the fundamental insights that will lead to acceptable manufacturing yields for the resulting billion transistor devices will be extremely demanding..

#### 4.9 Other Applications

**Ambient intelligence:** Moving from micro- to nanometer dimensions allows chips to become so small and cheap that they can be integrated almost anywhere and interact with each other, making everyday activities systematically smarter and more reactive. Typical applications could centre on personal health, entertainment and leisure delivered through networked multifunctional appliances.

**Nano-scale medical diagnostics and treatment:** Nanoelectronics-based biosensors will speed and simplify measurements at molecular level. This will allow us to design and fabricate ultra-sensitive sensors creating new insights into our health as well as offering better diagnostics and treatments.

**Cleaner, safer and more comfortable transport:** Highly reliable, smart and interactive low-cost devices will be created, able to withstand harsh environments, cut pollution, increase safety, navigation systems and in-car environment and entertainment systems.

**Anti-terrorism and security applications:** Nanoelectronics applications range from surveillance to personal identification and access control.

NanoMarkets [8], a leading advanced technology analyst firm in the US, forecasts developments in three key areas:

The emergence of a large market for **nanomemory** products. The market for such products is expected to grow to US\$8.6 billion (€6.9 billion) by 2007 and US\$65.7 billion (€52.6 billion) by 2011, with the main driver being demand for high-performance, non-volatile memories for mobile communications and computing.

**nano-engineered display technology.** Roll-up displays using plastic electronics and other platforms are expected areas with strong opportunities and have attracted leading electronic firms such as Xerox and Philips.

**carbon nanotubes** as a platform for High Density TV monitors at 42 inches and above. The total nano-enabled display market is expected to grow to US\$1.6 billion (€1.3 billion) in 2007 and reach US\$7.5 billion (€6.0 billion) by 2011.

**Plastic electronics** [9] holds out the prospect of new products with reasonable times-to-market and large revenue potential. One of the key advantages of plastic electronics is in its ability to create products of a kind that really have never existed before such as electronic paper, roll-up displays, photovoltaic cell or sensor laden laminates and coating, and low-cost optical interconnects. They can be printed using techniques similar to those of ink jet printing or rubber stamping which would reduce the need for building giant fabs. There is also considerable industry push behind this technology. Several of the largest materials and electronics firms - DuPont, Lucent, Philips, Siemens, Sony and Xerox, for example - are either already selling, or are developing, plastic electronics products. Even big pharma is getting in on the act - Merck just bought a small U.K. plastic electronics company. A recent report "Emerging Nanoelectronics Markets" by NanoMarkets, forecasts the market for nano-enabled electronics will reach US\$10.8 billion (€8.6 billion) in 2007 and grow to US\$82.5 billion (€66.0 billion) in 2011.

## 5. Nanomaterials

Bulk materials for manufacturing are generally uncontrolled and disordered at small scales. By controlling the nanostructure of materials, novel mechanical, thermal, electrical, magnetic and other properties can be engineered. For instance, metal alloys are made of crystals whose size and shape is only crudely controlled. In comparison, a carbon nanotube (a tiny, hollow tube of carbon atoms) can be perfectly formed, is remarkably strong, and has useful electrical and thermal properties.

Using nanoparticles in composite materials can enhance their strength, reduce weight, increase chemical and heat resistance and change their interaction with radiation. Coatings made from nanoparticles can be unusually tough or slippery, or exhibit unusual properties, such as changing colour when a current is applied or cleaning themselves when it rains. Examples of the uses of nanoparticles are given in Table 2.

|   |  |  |
|---|--|--|
| Electronic, optoelectronic magnetic applications  | Biomedical, pharmaceutical cosmetic applications   | Energy, catalytic structural applications  |
| Chemical–mechanical polishing<br>Electro-conductive coatings<br>Magnetic fluid seals<br>Magnetic-recording media<br>Multilayer ceramic capacitors<br>Optical fibres<br>Phosphors<br>Quantum optical devices | Antimicrobials<br>Bio-detection and labelling<br>Bio-magnetic separations<br>Drug delivery<br>MRI contrast agents<br>Orthopaedics and implants<br>Sunscreens<br>Thermal spray coatings | Automotive catalyst<br>Ceramic membranes<br>Fuel cells<br>Photo-catalysts<br>Propellants<br>Scratch-resistant coatings<br>Structural ceramics<br>Solar cells |

**Table 2. Current and emerging applications of nano-particles [10]**

Although hard to quantify, it has been estimated that nanostructured materials and processes can be expected to have a market impact of over \$ 1 trillion ( $\$ 10^{12}$ ) by 2015 [11].

Some existing applications include:

1. clay nanoparticles in packaging materials, where reduced porosity leads to less gas entering (e.g. less gas such as oxygen that spoils foods);
2. rolled graphite nanotubes used in coatings on car bumpers that better hold their shape in a crash;
3. carbon nanotubes which are sources of field-emitted electrons and create enhanced phosphorescence e.g. in “jumbotron” lamps used at many athletic stadiums
4. nanoparticles of zinc oxide in sunscreens, more efficient at absorbing UV than more traditional white titanium dioxide lotions and leaving the lotion smooth and transparent;
5. textiles which are dirt and crease resistant due to nanocoatings;
6. nanoparticles used as antiseptics, for abrasives and in paints;
7. nanocoatings for spectacle glasses (making them scratchproof and crack resistant)
8. nanocoatings for tiles to reduce slipping;
9. electrochromic or self-cleaning nanofilm coatings on windows, which in sunshine breaks down dirt and helps the water falling on it to carry the dirt away;
10. nanofilms with non-stick properties used as anti-graffiti coatings for walls;
11. ceramic coatings for solar cells to improve scratch and erosion resistance;
12. glues containing nanoparticles with variable optical properties are used in optoelectronics (e.g. for coupling fibres to other optical components); and
13. conductive nanofilms used in casings for electronic devices, such as computers, to provide shielding against electromagnetic interference.
14. Applications under development, some of which are close to market, include:
15. “smart” fabrics that can change their physical properties according to surrounding conditions, or even monitor vital signs;
16. drug delivery mechanisms including antibacterial and antiviral nanoparticles;
17. nanoceramics for more durable and better medical prosthetics;
18. improved catalysts for fuel production; and
19. nanoengineered membranes for energy efficient water purification.

Commentators highlight the importance of nanomaterials to industry by looking at the technical barriers to commercialism, principally mass production and the cost of nanomaterials. Improvements in production will dramatically decrease the cost of materials. For example, 1 gram of low-grade carbon nanotubes cost \$1000 five years ago. Today, they cost just \$30 due to increased manufacturing efficiencies and greater processing know-how.

## **6. General Healthcare**

In addition to the topics covered under medical devices, there is a wealth of opportunity to use nanotechnology in the healthcare field, another important industry for Ireland.

The following healthcare uses of nanomaterials have been identified [12]:

1. Remote health monitoring / non-invasive diagnosis;
2. Nano-based imaging and drug targeting and delivery for early identification and minimally toxic treatment of disease.
3. Drug / hormone delivery on a needs-basis using electronics-derived technology.
4. Patient-friendly, 'smart' cochlear and retinal implants.
5. Medical textiles, with health monitoring, transmission of information and therapeutic capabilities;
6. Nanostructured bandages, surfaces and textiles that encourage cell growth, reduce infection; and
7. Nano-enabled technologies for quality of life for the elderly or infirm (lightweight, flexible interactive displays / robot 'helpers') activated verbally, by minimal movement or even thought.

## **7. Educational implications and opportunities**

The main points that can be summarised for the developments of nanotechnology within the educational system include:

1. Need relevant courses and multidisciplinary teams developing these courses.
2. Educational Institutes must emphasize for this revolution in nano and biotechnology fundamental science and engineering - short term educational strategies are dangerous
3. Commercialisation issues must be understood by students
4. European Research funding could be centralised in major counties
5. Drift in high tech industry is inexorably to low income counties in Far East
6. Need to train highly qualified manpower. Such manpower was a decisive advantage in past but if manpower is running low Industries will have a problem – strategic training is even more important
7. Funding in the Irish context through Enterprise Ireland 'pathways' in 1990s and precursors were laid down
8. High tech start-up companies supported
9. Science Foundation Ireland(SFI) established to link with other state agencies HEA- Enterprise Ireland-IDA etc. and develop specialist centres which can compete for EU funding (Clearly this is a vital national policy)
10. IDA are seeking nano based industries and helping upgrade existing industries
11. FP6 + etc.
12. Need to develop greater collaborations between Researchers- academics- industry – and funding agencies.

## Conclusions

Nanotechnology is forecast to be a \$Trillion industry by 2015 (Electronics and communications \$300bn; Materials and processing \$340bn; Life sciences \$180bn; Sensors and instrumentation \$22bn). The Main beneficiary will be medical diagnostics, implants and drug delivery, materials and sustainable/ renewable energy

As outlined by Stewart Brand:

“The science is good, the engineering is feasible, the paths of approach are many, the consequences are revolutionary-times-revolutionary, and the schedule is in our life time.”

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