Nanotechnology:
The Technology for the 21st Century

Vol. II The Full Report

Asia-Pacific Economic Cooperation
APEC Industrial Science and Technology
Working Group

The APEC Center for Technology Foresight
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Foreword

The APEC Center for Technology Foresight (APEC CTF) was established in Bangkok in February 1998 by the Royal Thai Government with the objective of serving and involving all APEC member economies in diffusing foresight expertise across the APEC region. However, the aim is not just to assist member economies with their own foresight efforts, but also to conduct research at a multi-economy level. Foresight should be able to contribute to strategy and policy development on issues which cross national boundaries. Examples of studies carried out that fit this criterion include "Water Supply and Management", "Technology for Learning and Culture", "Healthy Megacities" and, now, "Nanotechnolgy". APEC CTF has been a pioneer in the field of multilateral foresight. Other organizations that are also supporting multilateral foresight studies include the Institute for Prospective Technological Studies in Seville, Spain, and the United Nations Development Organisation based in Vienna, Austria.

The APEC Center for Technology Foresight has adopted a broad definition of foresight, as follows:

"Foresight involves systematic attempts to look into the future of science, technology, society and the economy, and their interactions, in order to promote social, economic and environmental benefits."

Foresight is concerned with the development of a range of possible futures which emerge from alternative sets of assumptions about emerging trends and opportunities.The knowledge developed through foresight allows organizations to make strategic choices and enables them to adapt quickly to changing trends based on social, technical or economic drivers.

In this study, foresight is applied to the development of a new and exciting research field - nanoscience and nanotechnology.

We are now at a threshold of a revolution in the ways in which materials and products are created. This has resulted from the convergence of the traditional fields of chemistry, mathematics, physics, biology and engineering, to form the new field of nanotechnology. We can define nanotechnology as "*materials and systems whose structures and components exhibit novel and significantly improved physical, chemical and biological properties, phenomenoa and processes due to their nanoscale size*". The goal of nanotechnology is to exploit these properties by gaining control of structures and devices at atomic, molecular and supramolecular levels and to learn to efficiently manufacture and use these devices.

The field of nanotechnology covers a wide range of activities including fabrication of functional nanostructures with engineered properties, synthesis and processing of nanoparticles and materials, supramolecular chemistry, self-assembly and replication techniques, sintering of nanostructured metallic alloys, use of quantum effects, creation of chemical and biological templates and sensors, surface modification and thin films. Given such a wide range of technology options, which will potentially have broad impacts on the world economy and on society, APEC CTF decided to carry out a foresight study of nanotechnology in the APEC region.

The APEC CTF is grateful for the substantial contribution of Position Papers by four economies on nanobiosystems (Australia), nanoelectronics (Japan), nanophotonics (Canada) and nanostructured materials (Chinese Taipei), and to the Philippines for a paper on issues for developing economies. We are particularly grateful to the authors and the institutions that allowed them to devote time to this project.

The APEC CTF would also like to thank the National Research Council of Canada for hosting an Experts' Meeting of 26 nanotechnology researchers from 9 APEC member economies in Ottawa on 5th – 7th November 2001 and for providing opportunities for informal interaction that contributed substantially to the success of the project. We are particularly grateful to the Experts for giving their time and experience to create a successful meeting and to their economies which supported their attendance. An earlier report (Volume 1) was aimed at policymakers and their advisors and set out the essential steps of the process, the key issues for the development of nanotechnology and the views of the Experts on future directions.

This report (Volume 2) contains the Position Papers, the Issues Paper prepared as background material for the study, the short papers presented by the Experts at the Ottawa Meeting on the state of nanotechnology in their respective economies and the background to the creation of scenarios for the future of nanotechnology.

APEC CTF is pleased to acknowledge the continued financial support of the Royal Thai Government through the National Science and Technology Development Agency. This project was run as a self-funded project by APEC CTF under the APEC Industrial Science and Technology Working Group.

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Introduction

2.1 The Rationale for Selection of Nanotechnology

Recent years have seen an explosive growth of interest in nanotechnology. There is potential for enormous industrial developments flowing from nanotechnology research, as well as very significant social consequences if nanotechnology is widely adopted. This has been recognised by many scientists, and by some (but by no means all) national governments. Such growing interest in the topic is confirmed by the strong and unanimous support given to this project by APEC members[1] at the APEC Industrial Science and Technology Working Group at its meeting in Hanoi on 24-26 April 2001.

The APEC CTF recognised the importance of nanotechnology to the future of APEC member economies and agreed that it fitted the Center's chosen criteria for a foresight study. Nanotechnology may have a profound impact on most if not all member economies and many of the concerns about its development and impacts transcend national boundaries, so that an international foresight study can go beyond what might be achieved by a national or bi-lateral study. It has been argued that

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[1] APEC's 21 members are referred to as 'economies' rather than countries or nations, and include: Australia; Brunei; Canada; Chile; China; Hong Kong, China; Indonesia; Japan; South Korea; Malaysia; Mexico; New Zealand; Papua New Guinea; Peru; the Philippines; Russia; Singapore; Chiness Taipei; Thailand; the USA and Vietnam.

APEC economies stand on the brink of a "Nanotechnology Revolution" whose effects on societies and economies will be as pervasive and dramatic as the "ICT (information and communications technology) Revolution" of the late twentieth century. Thus it is imperative to start the debate immediately about how to develop nanotechnology effectively and for the public good, and to engage a very wide range of stakeholders including non-scientists in this debate.

2.2 Nanotechnology – a new paradigm

We are now at a threshold of a revolution in the ways in which materials and products are created. This has resulted from the convergence of the traditional fields of chemistry, physics, mathematics, biology and engineering to form the new field of nanotechnology. Nanotechnology is concerned with the fabrication and use of materials, devices and systems so small that the convenient unit of measurement is the nanometer (a billionth of a meter). At this very small scale the characteristics of molecules and atoms in the material exhibit important new properties different from the material's bulk properties. These novel properties are being harnessed to develop devices and materials, which significantly improve performance. The theme of the field is "novel performance through nanotechnology".

We can define nanotechnology as "materials and systems whose structures and components exhibit novel and significantly improved physical, chemical and biological properties, phenomenoa and processes due to their nanoscale size. The goal of nanotechnology is to exploit these properties by gaining control of structures and devices at atomic, molecular and supramolecular levels and to learn to efficiently manufacture and use these devices". The field of Nanotechnology covers a wide range of activities including fabrication of functional nanostructures with engineered properties, synthesis and processing of nanoparticles and materials, supramolecular chemistry, self-assembly and replication techniques, sintering of nanostructured metallic alloys, use of quantum effects, creation of chemical and biological templates and sensors, surface modification and films.

Researchers and technologists are approaching the field of nanotechnology from three directions:

- In physics, the field of nanoelectronics is moving towards smaller feature sizes and is already at 100 nanometer line widths. Processors in computing systems will need nanometer line widths in the future as miniaturisation proceeds.
- In chemistry, improved knowledge of complex systems has led to new catalyst, membrane, sensor and coating technologies which rely on the ability to tailor structures at atomic and molecular levels.
- In biology, living systems have sub-units with sizes between micron and nanometer scales and these can be combined with non-living nano-structured materials to create new devices and sensors.

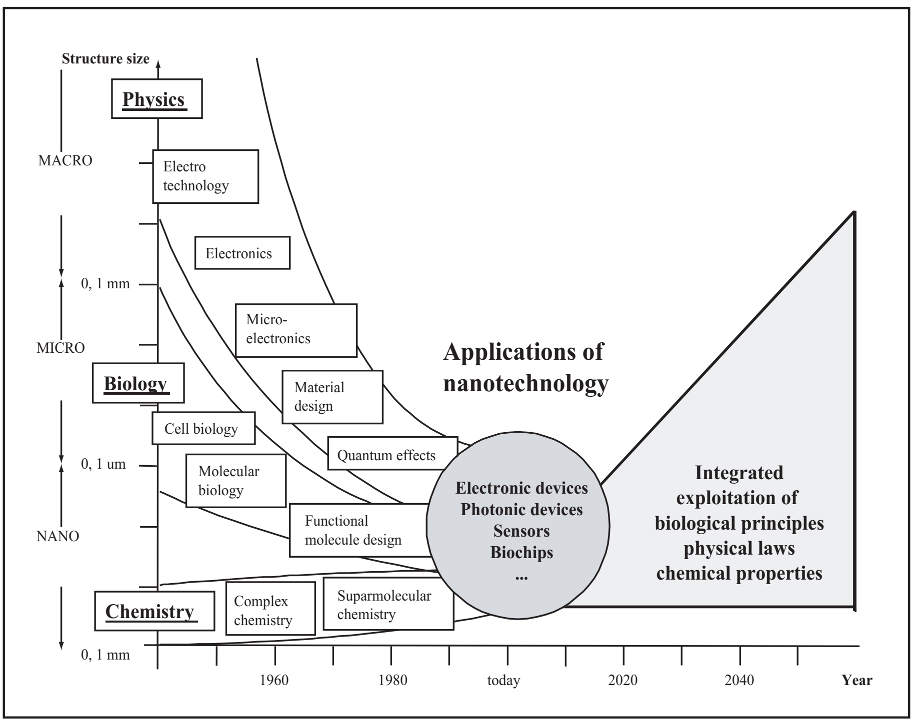
The convergence of disciplines is well illustrated in Figure 1 which also shows the scales of the areas of interaction. There is considerable debate in the scientific community about the boundaries of the new disciplines emerging from this convergence e.g. between microtechnology and nanotechnology, but it is becoming clear that, in practice, no clear division can be made. Thus, for example, sensors and biochips at the nanotechnology scale need to be packaged for commercial applications using microtechnology.

The interdisciplinary nature of nanotechnology also poses problems for researchers and institutions used to traditional disciplines with defined boundaries. Changing traditional mindsets is a major challenge and a particular need is to develop nanotechnology experts with interdisciplinary skills.

2.3 The International Effort in Nanotechnology

Virtually all industrialised countries have in development or have established a national strategy for nanotechnology.[2] The focus varies from a general science-

Fig. 1 Physics, biology and chemistry meet in nanotechnology.



Source: VDI-Technology Center, Future Technologies Division

2 See: M.C. Roco 2001 "International Strategy for nanotechnology research and development", Journal of Nanoparticle Research, 3, pp353-360.

based strategy (for example the United States and France) to industry-relevance driven strategy (for example the European Community, Korea and Taiwan), from broad spectrum of areas (as in the United States, Japan and Germany) to specific strengths. The levels of government investments in nanotechnology R&D in the United States, Japan and Europe have increased by about three times since 1997 (see Table 1)

Table 1 Estimated government-sponsored R&D (from Roco 2001).

(US$ million)

	1997	*1998*	*1999*	*2000*	*2001*	*2002*
W. Europe	126	151	179	200	Est. 225	285
Japan	120	135	157	245	410+140	753
USA	116	190	255	270	422	604
Others	70	83	96	110	Est. 380	?
TOTAL	432	559	687	825	1,577	

From the viewpoint of the present study, it is important to have a breakdown of "Others", particularly in the APEC region. Table 2 gives some recent estimates.

Table 2 Estimated nanotechnology R&D in some APEC economies (from Carl Masen Asia Pacific Nanotechnology Forum).

(US$ million)

	2001	*2002*
China	35.6	35.6
Korea	54	142
Singapore	7.5	9
Chinese Taipei	10	22
Australia	15	40

The indicators are that funding is set to increase further in the coming years. A looming problem is the education and training of a new generation of skilled workers with multidisciplinary perspectives necessary for rapid progress in nanotechnology. Assuming the current level of instrument purchasing in world markets, and that the need for trained people will be proportional to those market sizes, then the number of nanotechnology trained people needed in 2010-2015 would be 0.8–0.9 million in the United States, 0.5-0.6 million in Japan, 0.3-0.4 million in Europe, 0.1-0.2 million in Asia Pacific region without Japan and about 0.1 million in other regions. This is a major challenge for institutions used to traditional disciplines with well-defined boundaries.

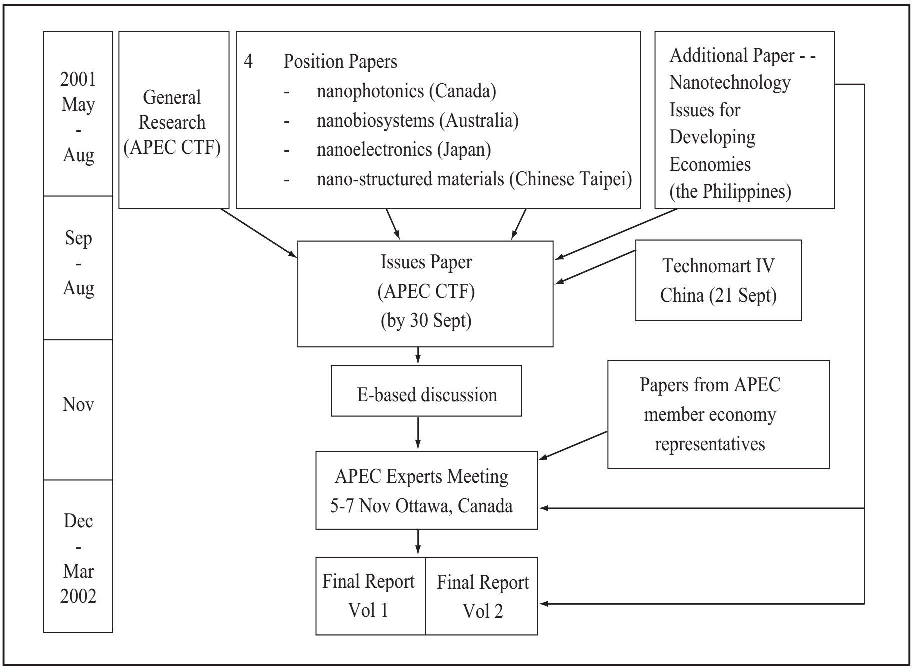
The Conduct of the Study

Given the breadth of the study and the diversity of professionals involved, APEC CTF decided to set the scene by having position papers prepared by expert teams from four economies. These were: *nanophotonics* (Canada), *nanobiosystems* (Australia), *nanoelectronics* (Japan) *and nanostructured materials* (Chinese Taipei). In addition, a paper was prepared on *nanotechnology issues for developing economies* by the Philippines. (see Section 5)

On the basis of these and independent research by APEC CTF, an *issues paper* was prepared which identified ten general issues deemed to be important for the future of nanotechnology (see Section 4). All of these materials were placed on the APEC CTF web site with a view to creating awareness of nanotechnology in the APEC region and to stimulating debate with experts around the region. These aims were also pursued at a special session on nanotechnology organised at APEC Technomart IV in Suzhou, China, in September 2001.

An Experts' Meeting was held in Ottawa from 5-7 November 2001, generously hosted and supported by the National Research Council of Canada. 26 Experts from 9 APEC economies participated in the meeting. To complement short presentations of the commissioned position papers, representatives of the economies present gave short reviews of the state of nanotechnology in their respective economies (see Section 6). Experts at this meeting were then invited to brainstorm technological opportunities in nanotechnology in the near and long term, before discussing the issues set out in the APEC CTF paper. The scenario creation technique was then used to identify possible futures for nanotechnology in the region and to draw out more clearly time scales for technological development and the policy implications. This is discussed in Section 7.

Project Process



Issues Paper

Nanotechnology: The Technology for the 21st Century

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This Issues Paper was prepared to provide a focus for the workshop to be held in Ottawa on 5 – 7 November 2001 as an essential component of the Foresight Study in Nanotechnology undertaken by the APEC Center for Technology Foresight (APEC CTF), Bangkok. The workshop was conducted by APEC CTF staff with strong support from the National Research Council of Canada.

Significant inputs to the workshop were the four technical position papers on nanophotonics (Canada), nanobiosystems (Australia), nanoelectronics (Japan) and nanostructured materials (Chinese Taipei), together with a paper on nanotechnology issues for developing countries (Philippines). These were invaluable in the preparation of this Issues Paper.

4.1 Introduction

"If I were asked for an area of science and engineering that will most likely produce the breakthroughs of tomorrow, I would point to nanoscale science and engineering".

Neal Lane, Assistant to the President for Science and Technology
to US Congressional hearing in 1998.

A useful review of the development of nanotechnology has been given by Budworth (1996). He suggests that the origins of nanotechnology go back to a talk given by the US theoretical physicist and Nobel Prize winner, Richard Feynman at the Annual Meeting of the American Physical Society in 1959. The talk entitled "There's Plenty of Room at the Bottom" comprehensively outlined the possibilities for what would now be called nanotechnology (Feynman 1961). Feynman pointed out that manufacturing things on a small scale was an area in which little had been done, but in which there was an enormous amount that could be done in principle. He suggested a number of areas:

- miniature writing
- computer miniaturisation and use of vapour methods to achieve it
- miniature engineering
- the need to make design changes because of scale effects
- the possibility of surgical and medical use of miniaturisation
- quantum devices
- direct syntheses by moving individual atoms
- the linking of biology and physics.

Feynman reviewed progress towards these in another talk in 1983 at the Jet Propulsion Laboratory at Pasadena, eventually published much later (Feynman 1993), and noted that little had happened in development of micromachines and commented on the issue of increasing accuracy, although computer components had decreased considerably in size since his first talk.

The concept and term 'nanotechnology' seems to have been coined by Taniguchi in 1974 at a conference on production engineering in Tokyo (Taniguchi 1974). He defined it as the production technology needed to get the extra-high accuracy and ultra-fine dimensions needed in such items as integrated circuits, opto-electronic devices, mechanical parts for pumps, bearings and computer memory devices and aspheric lenses, in all of which accuracies of the order of 1nm were becoming necessary. He pointed out that, at this accuracy, one was effectively speaking of removing or adding one atom at a time and he considered for a wide range of processes which enabled this to be done. His conclusion was that ion beam or molecular beam techniques were the most promising for nanotechnology.

Fig. 1 **A crude division of areas contributing to nanotechnology.**

	Inorganic	Organic
Physics	Mesoscopic physics Precision engineering Materials science Scanning electron microscopy Electronics	Molecular electronics
Chemistry	Inorganic chemistry Aerosol science Computer modelling	Supramolecular chemistry Physical chemistry
Biology	—	Biotechnology Medicine

The concept was taken up in the UK by the National Physical Laboratory in 1983 after a major international conference and a National Initiative on Nanotechnology was launched in 1986. The definition developed at that time by Franks (1987) was:

"Nanotechnology is the technology where dimensions or tolerances in the range 0.1 to 100 nm (from the size of an atom to the wavelength of light) play a critical role".

The Taniguchi approach has come to be known as 'top-down' technology ie an approach from larger to smaller.

An alternative concept was introduced in 1986 by Eric Drexler (Drexler 1986) with an approach of building larger objects from their atomic or molecular components, ie a 'bottom-up' approach. Indeed he initially used the term 'molecular engineering' and now uses 'molecular nanotechnology' to describe his approach (Drexler 1992). More limited progress has been made with this approach than with the 'top-down' approach. Although control of individual atoms is the ultimate manufacturing technology, other approaches based on self-assembly are promising. In self-assembly, the atoms or molecules needed to make the desired product are brought together in a suitable environment to arrange themselves into the product. Examples of self-assembly of large molecules which can then assemble themselves into ordered arrays are widely found in chemistry and biology and the inter-disciplinary field of supramolecular chemistry.

The variety of concepts involved in nanotechnology has led to confusion over nomenclature and to boundary disputes between researchers. We discuss these further in the next Section.

4.2 What is Nanotechnology?

In Section 4.1, we have seen that a new paradigm is emerging with the manipulation of atoms and molecules at the nanometer level (1nm = 10^{-9}m). A general definition has been given there but others have been proposed. One which perhaps captures the current thrust in the field is:

"Nanotechnology is direct control of materials and devices on a molecular and atomic scale" (adapted from Siegel et al, 1999).

Researchers and technologists are approaching the field of nanotechnology from three directions:

- In physics, the field of microelectronics is moving towards smaller feature sizes and is already at submicron line widths. Processors in computing systems will need nanometer line widths in the future as miniaturisation proceeds.
- In chemistry, improved knowledge of complex systems had led to new catalyst, membrane, sensor and coating technologies which rely on the ability to tailor structures at atomic and molecular levels.
- In biology, living systems have sub-units with sizes between micron and nanometer scales and these can be combined with non-living nanostructured materials to create new devices.

This convergence is shown schematically in Figure 1 (see page 7; Bachmann, 2000). As nanotechnology develops, it is possible that a new nanotechnological research and production paradigm will arise drawing on the laws of physics, chemical properties of materials and principles from biological systems, coupled with engineering at the nanometer level.

Not surprisingly the view of what is nanotechnology varies among experts from these different backgrounds and the direction from which they are approaching the area. A crude division of the area has been given by Malsch based in a survey of European experts (Malsch 1997) and a modified version is shown in Figure 1. This emphasises the interdisciplinary nature of the technology which appears repeatedly in later Sections. As a number of economies eg Japan, USA, Canada have realised, there is a need to gather together in one place a variety of specialists who can interact to share concepts and ideas in moving towards a new nanotechnological paradigm and we return to this issue later.

Because of this diversity of interests involved in nanotechnology, there is often confusion in the rest of society about the nature of nanotechnology. Many consider an effective public awareness program is necessary to clarify misunderstandings about nanotechnology. A threat to shaping a new understanding required by nanotechnology is posed by the temptation to re-badge old technology which has some similar characteristics as nanotechnology.

***Issue 1*: What needs to be done to increase the broader recognition of nanotechnology in APEC economies as a new interdisciplinary technology arising from a fusion of physics, chemistry, biology and engineering?**

4.3 Scientific and Technological Inputs and Implications for Facilities for Nanotechnology

As noted in Section 4.2, nanotechnology is based on inputs from different disciplines and we consider here some of these and their implication for facilities needed for nanotechnology, both in research and in production. More detail is given by Bachmann (1995) and Siegel et al (1999).

Ultra-precision machining – the best performance achieved in a general purpose machine tool of essentially conventional character is a form accuracy of about 100nm on an artefact of 100 nm diameter with a surface finish of 2-3 nm. Special tools for limited shapes and size can achieve similar surface finish and form accuracy of around 10 nm.

Microelectronics – the history of microelectronics has been one of successive reductions in line width enabling higher densities and speeds to be achieved on the one chip. Line widths are now down to 70 nm. The accuracy is set by the wavelength of the radiation used in the lithographic process – UV radiation can produce line widths to 350 nm with tolerances of about 35 nm in production while line widths less than 100 nm can be produced by X-ray lithography or by electron-beam direct writing in the laboratory. The line width is expected to reduce to 10 nm in 2010.

Microelectromechanical systems (MEMS) – the fabrication techniques of microelectronics have been increasingly applied to produce miniature mechanical, electrical and optical devices. The essential difference is that MEMS emphasises the importance of the third dimension with bulk micromachining of features, surface micromachining using thin films and substrate bonding.

Scanning probe microscopes – the invention of the scanning tunnelling microscope in 1982 opened up a new field allowing manipulation of individual atoms. It has also spawned a whole new field of scanning probe microscopes in which many physical phenomena have been used to examine the fine structure of materials. While these achievements can be considered to be the first demonstrations of 'bottom-up' nanotechnology, they depend critically on 'top-down' techniques.

Computer modelling – this is a significant feature of current scientific research and is particularly well established in chemistry. It is used as a routine tool by chemical and pharmaceutical companies with software readily available. Computer models operate at different levels from the molecular level up to assemblies of several thousand atoms in nanoparticles.

Cluster science or mesoscience – the cluster regime lies between that of single molecules and that of bulk material. Clusters consist of aggregates of atoms and molecules that are small enough not to have the properties of the bulk liquid or solid. Quantum states in clusters are size-dependent, leading to new electronic, optical and magnetic properties. One feature of clusters is that the physical arrangement of the individual constituents changes as their number is increased. This has implications for molecular manufacturing.

Nanostructured materials – these can be of nanometric size in one dimension (thin films), two dimension (fibres) and three dimension (powders) and can be produced by a variety of techniques with a wide variety of properties. Thus thin films of solids can be produced by vacuum deposition while thin films of molecules can be produced by liquid deposition techniques; fibres and powders of solids can be produced by mechanical milling or grinding or from aerosols in the gas phase. Such nanoparticles can be used individually to exploit their very high surface area/volume ratios or can be amalgamated to produce bulk materials with novel properties.

Clearly all of these require sophisticated and expensive facilities which are dispersed in different laboratories in academia, government research establishments and industry. This has implications for an economy in terms of education and training, funding, commercialisation and international links and we will discuss them in later sections.

Here however we can identify an issue as:

***Issue 2*: What mechanisms are possible for an APEC economy to assemble its resources in nanotechnology?**

4.4 Education and Training

The range of inputs and equipment needed for development of nanotechnology challenges the traditional separation of academic disciplines into physics, chemistry, biology and engineering. While there have been moves to link disciplines across boundaries and we have physical chemistry, chemical physics, biochemistry and bioengineering etc, there is a need to increase multidisciplinarity for the further development of nanotechnology.

As the position paper on Nanophotonics emphasises, academic disciplines have been separated by culture, management domains and terminology, and thus institutions will have to make significant changes to increase cross-disciplinary interaction. The challenge is then to achieve breadth and depth to produce people capable of creating new concepts in nanotechnology. Courses on surface science, molecular dynamics, quantum effects and manufacturing at a molecular level could help integration of research and education into a new paradigm of molecular models instead of microscopic approach. The supply of knowledgeable people could well be the limiting factor in the exploitation of nanotechnology.

In smaller economies and particularly in less developed economies, there is a need to bring together a critical mass of skilled people to progress nanotechnology. The approach adopted in a number of economies is to encourage the development of interdisciplinary centres of expertise within universities and then use these to link to industry. Nanotechnology centres (as virtual centres of thematic networks) can provide an environment with facilities and interdisciplinary research teams that will enable educating a new generation of young scientists. The Co-operative

Research Centres in Australia are an excellent example of bringing together academics, graduate students and industrialists into one centre with strong government funding support. There is already an active CRC for Microtechnology in Melbourne.

Beyond the education and training of a new generation of scientists and skilled workers in the multidisciplinary perspective necessary for rapid progress in nanotechnology, it is also crucial to educate, train and inform the current management and workforce. Thus nanotechnology needs to be incorporated into technical and managerial training courses.

***Issue 3:* What steps can APEC economies take to ensure that their universitites and technical institutes move rapidly to form focal points for nanotechnology research and education?**

4.5 Funding Sources

Governments which have recognised the potential of nanotechnology have supported its development in their economies by directing special funding to the area. The position paper on Nanostructured Materials gives a useful summary of initiatives around the world. Several countries notably Japan, USA and in Europe have strong national programs.

Thus, in Japan, several Ministries have supported well-funded, long-term programs on aspects of nanotechnology with strong funding support from industry. In the UK there was a National Initiative on Nanotechnology supported through research grants in academia and grants to raise awareness in industry, but this appears to have lost momentum. A major recent development in the US is the National Nanotechnology Initiative which will dramatically increase funding to US Government Departments and agencies. Overall funding had increased from US$116 mil. in 1997 to US$225 mil. in 1999, but will increase to US$422 mil. in 2001 with nanotechnology placed at the top of emerging fields of R & D in the US. In Europe, most countries have one or more research programs devoted to nanotechnology eg a national network has been set-up in France with strong funding to government research agencies; in Germany, roughly US$50 mil. was spent on nanotechnology through the Ministry of Education, Science, Research and Technology in 1997 in research institutes and four Centres of Excellence will be set up in 2001. European networks are being developed through the EU and other collaborative programs. The table on page 8 gives estimated government expenditures in US$ mil. for Western Europe, Japan and USA.

The position paper on Nanostructured Materials also contains useful data on some APEC economies, other than the USA and Japan. Thus, in Canada, the National Research Council will invest $120 million in the National Institute for Nanotechnology (NIN) to be located at the University of Alberta in Edmonton. The NIN will be a key resource to integrate a Nano-Structures Network in Canada. Other economies in Asia, particularly China and Chinese Taipei and Korea, have also put a strong emphasis on nanomaterials research. The development of nanoparticles, nanopowders, nanometals, biomaterials and nanocomposites have appeared on the top of their nano-research agenda. In China, the Chinese State Council is planning to launch a National Nanotechnology Initiative with several million of dollars in funding. This five year initiative, which is expected to start in the year 2001, will be managed by the Ministry of Science and Technology.

In Chinese Taipei, both the National Science Council and Ministry of Education have been developing a 4-year program for nanomaterials research since 2000. According to the recent information provided by the Ministry of Economic Affairs the government is expected to launch a major investment of US$300 million in nanotechnology R&D for the next 4 to 5 years.

In Korea, the focus has been mainly on the application of nanostructured materials for the IT industry. A major cooperative research venture of 76.6 billion Won (approximately US$60 million) for the development of nanotechnology-based optical materials has been initiated by the government and private groups. This ten-year project (2001-2011) will receive 45% of the funding from the government, and the rest will be provided by private companies.

***Issue 4*: Given the large amounts of funding for research and development in nanotechnology in a number of developed APEC economies, can we identify the critical funding needed for smaller and less developed APEC economies to set up their own national programs in nanotechnology?**

4.6 Regional Collaboration and Networks

As noted in Section 5, strong national programs and international networks, particularly in Europe, can be identified. Many of these operate websites and provide information to enable linking of researchers with others from outside the economy or the region. As an example, the Institute of Nanotechnology in the UK links researchers, sets up collaborative projects, organises conferences, develops databases of contacts, etc. The Institute is a virtual body with a website (http://www.nano.org.uk) and could serve as a model for networking in APEC.

For many of the APEC economies there is a need to create incentives for visits by foreign researchers to develop collaborations abroad and to build on existing strengths in industry and research through interaction and networking. The magnitude of investments in equipment will mean that all but the very largest economies will only be able to afford a limited number of centres of nanotechnology and thus it will be necessary to consider how national facilities can be made available to researchers from other less well-endowed APEC economies. The APEC Industrial Science and Technology Working Group is a logical starting point to initiate discussion of such sharing of facilities.

Issue 5: **How can APEC ISTWG be encouraged to take a leading role in developing networks of APEC researchers in nanotechnology and opening up national facilities to researchers from other APEC economies?**

4.7 Opportunities for Nanotechnology

The drive towards nanotechnology has come from scientists and technologists who have identified many opportunity areas for radically changing existing processes and devices and for creating completely new industry sectors. Some of these pick up the proposals made by Feynman 40 years ago. Examples are:

Electronics

- miniaturised data storage systems with the necessary long-term stability and a capacity comparable to the stock of national libraries
- PCs with the power of today's computer centres
- minidisks, which contain eg all classical music records
- minichips, which contain movies with more than 1000 hours playing time

Health

- perfect selective sensors for the control of environment, food and body functions
- pharmaceuticals and sera, which have long-term dosable capa-bilities and which can be taken orally
- replacements for human tissue or biocompatible foils for inner wound closure
- cheap or reusable diagnostic chips for a preventive medical survey
- sanitary facilities with photocatalytic active coatings to prevent bacteria accumulation

Manufacturing

- corrosion-free light-weight materials with high mechanical stability and a strong temperature resistance
- coated architecture panes with nearly zero adhesion for rain drops or dirt
- glass manufacturing with decorative layers without toxicity
- light weight plastic windows with hard transparent protective layers or bearings without lubricant for the automobile industry

Energy

- cheap hydrogen storage possibilities for a regenerative energy economy
- innovative solar cells on the basis of natural photosynthesis

Various estimates have been made of the economic benefits of nanotechnology, but these need to be treated with some caution. Some examples are:

***Electronics*:**

Nanotechnology is projected to yield annual production about US$300 billion for the semiconductor industry and few times more for global integrated circuits sales within 10 to 15 years.

***Improved Healthcare*:**

Nanotechnology will help extend the life span, improve its quality, and extend human physical capabilities.

***Pharmaceuticals*:**

About half of all production will be dependent on nanotechnology – affecting over US$180 billion per year in 10 to 15 years.

***Chemical Plants*:**

Nanostructured catalysts have applications in the petroleum and chemical processing industries, with an estimated annual impact of US$100 billion in 10 to 15 years.

***Environment*:**

In 10 to 15 years, projections indicate that nanotechnology-based lighting advances have the potential to reduce worldwide consumption of energy by more than 10%, reflecting a savings of $100 billion dollars per year and a corresponding reduction of 200 million tons of carbon emissions.

Despite the uncertainties associated with such estimates, these examples show that nanotechnology has the potential to significantly change a large cross-section of life in all economies in the next decades.

***Issue 6:* Can we define more clearly the time scales for development of opportunities in nanotechnology?**

4.8 Commercialisation of Nanotechnology

In order to take advantage of the opportunities discussed in Section 4.7, much of industry in many economies will have to radically change management approaches and company strategies. A recent workshop in Australia on “

Nanotechnology in Australian Industries" (McKenzie 2001) highlighted the problems with industry's approach to nanotechnology in small economies. Thus, the low level of public awareness of nanotechnology and its potential is stated to be the primary cause of apparent little interest in Australian industries' planning and long-term visioning. It is suggested that a program that generates a higher level of awareness in industry and enterprise leaders will cause an increase in the use of nano-concepts in industry visioning. "No vision, no conversation – no conversation, no vision" seems to summarise the view of the majority of Australian industry, both corporate and SMEs, who could potentially become involved.

However, even in larger economies, there are problems. Thus a recent report by UK's Department of Trade and Industry (DTI) showed that the three main issues shaping the vision of large firms in relation to nanotechnology and nanomaterials were:

- "No-one will consider 'nano' for being 'nano'; only new and improved products and processes resulting from nanotechnology"
- "Industry presently doesn't connect nano to a solution to a problem they may have"
- "All electronics will work at the nanoscale in 10-15 years"

Some firms in more developed economies have recognised the potential of nanotechnology and nanostructured materials; however, they are looking carefully for the right opportunity to become involved in this field. Although the possibilities of nanostructured materials and other possible applications of nanotechnologies seem endless, firms are facing the dilemmas of where to invest, asking what are the winning technologies, and having problems with identifying them. The current downturn in the world economy and the collapse of the e-commerce sector has dampened enthusiasm for investment in new technology ventures.

A further barrier to industry seeing itself as a participant in nano-technology is the current practice of defining an enterprise as narrowly as possible, so that 'core' business often embraces a single discipline and very few functions. Such a mental picture coupled with a limited understanding of nanotechnology and how an enterprise will engage with it explains the absence of the concepts from Australian industry vision and mission statements and ten-year strategic plans. Other small economies suffer from the same limited outlook of industrial leaders. There is an aversion to significant commitment of capital to high risk ventures.

By contrast, in USA and Europe, there is a high density of industry, many high-tech companies, enthusiastic researchers with the latest research results and venture capital organizations which are willing to support new directions. As a result, small and medium size enterprises (SMEs) in nanotechnology have been developed. Many of these SMEs are spin-offs from university research and have been established to commercialise the technologies that they have developed. In the US, a dynamic that combines entrepreneurship and vigorous industry-university relationships has been particularly important in many successful new firms. SMEs have been also powerful drivers for providing direction for further research in universities, for obtaining a better control over discoveries and for ensuring increasing income for professors, departments and universities.

In R&D in emerging fields such as nanotechnology, where new findings and innovations come up nearly every day, the need for flexible strategies is evident. Inventors need fast and unbureaucratic help to realise an idea with importance for the future, and companies must build competent networks with academia, to get the best partners for a fast transfer of the research results into products.

***Issue 7*: How can the majority of APEC economies change the mind-sets of their industry leaders and investors to apply nanotechnology in existing business and to foster entirely new enterprises?**

4.9 Nanomeasurements and Standards

The position papers on Nanophotonics and Nanostructured Materials both highlighted the importance of metrology in the commercialisation of nanotechnology. They emphasise that the establishment of standards and a metrology system is a key element in the development of an industry. Nanometrology will be an enabling tool for the development of nanotechnology; however, the challenges for developing an useful and universally-recognised standards system for nano-technology are many.

For example, maintaining or even finding positions on a surface with nanometer accuracy and precision is very challenging in a research environment, but is especially so for areal dimensions relevant to manufacturing. Reference materials (e.g. nanoparticles of known size and composition) are not available, which makes intercomparison or calibration of characterisation tools and approaches difficult if not impossible. The Department of Energy in the USA organised a workshop to deal with this problem, and a number of specific goals were set for the next 5-10 years. These included: the development of particle size calibration standards for 3 nm, 10nm and 30 nm size particles; improvements in nanomeasurements methods for nano-sized particles; and quantification of uncertainty in transmission electron microscopes. However, standards are only useful when they are accepted internationally. In the case of nanostructured materials, the standards system will play a decisive role in deciding product standards for materials, manufacturing procedures and calibration techniques.

Nanotechnology provides an opportunity to create new fundamental or secondary standards. For example, since 1990, quantised Hall resistors have been used in national standards laboratories to represent resistance. These resistors are semiconductor devices which, when cooled to 1 degree Kelvin or less in a magnetic field of several tesla, yield values of resistance which are essentially invariant, and which are multiples of fundamental constants. Optically-based atomic clocks and optical frequency synthesizers are now a reality, with a single ultrastable laser providing phase coherent references throughout the optical spectrum and down to the microwave/radio frequency domain, with the stability of the transfer process reaching the 10^{-15} level.

As an example of activity in this area, the US National Institute for Standards and Technology (NSIT) is conducting R & D for developing measurement and standards in support of the National Nanotechnology Initiative mentioned in Section 4.5. The focus of research includes:

- **New atomic scale measurements** for length, mass, chemical composition, and other properties;
- **New nanoscale manufacturing technologies** to be used by industry in assembling new devices at the atom or molecule level;
- **New standard methods, data, and materials** to transfer NIST nano-technology to industry and to assure the quality of the new nano-based commercial products.

***Issue 8*: What steps are needed by APEC governments to ensure that their national standards and metrology systems are appropriate for nanotechnology? Is there a need for APEC co-operation in this area?**

4.10 Implications for Small and Less Developed Economies

Implications of development of expertise in nanotechnology have been noted throughout this paper e.g. needs for expensive facilities, major changes in teaching and research approaches, awareness programs for industry, identification of opportunities in nanotechnology, funding allocations, networking. For small and less developed economies, these issues pose major policy decisions.

As noted in Section 4.5, the magnitude of the investments will mean that all but the very largest economies will not be able to afford to have more than a handful of sites. Therefore sharing of national facilities will be a major need. Such common laboratory settings can provide excellent fora for the mixture of ideas from one discipline to another, and from one economy to another. Indeed, it can be imagined that this may be an excellent platform for smaller and less developed APEC economies to share in the development of nanotechnology.

The position paper produced by the Philippines highlighted the need for less developed economies to use nanotechnology to build on their existing resources and capabilities, but also to identify niche areas where opportunities exist. Thus in the Philippines, the following areas have been identified: biosensors, optoelectronic devices, pharmaceuticals and polymers and composites. These have been selected on the basis of strategic importance and competitive advantage.

***Issue 9*: How can small and less developed economies assess the importance of nanotechnology to their economies and identify niche opportunties?**

4.11 Societal Implications of Nanotechnology

Scientific discoveries do not generally change society directly; they can set the stage for change that comes through the confluence of old and new technologies in a context of evolving economic needs. Nanotechnology is so diverse that its effects will take decades to work through the socio-economic systems. A major problem in anticipating its effects is that subsequent developments may be in the hands of the users and not the innovators. If nanotechnology is going to revolutionise manufacturing, health care, energy supply, communications and probably defence, then it will transform labour and the workplace, the medical system, the transportation and power infrastructures and the military. None of these latter will be changed without significant social disruption.

Initially, the impact of nanotechnology is likely to be limited to a few products and services where consumers are willing to pay a premium for new or improved performance. As a result, nanotechnology will co-exist for a long time with older technologies rather than displacing them. This may give time to assess the potential social and ethical implications of nanotechnology. Given the problems encountered in the introduction of biotechnology products, it is prudent to consider now the implications of nanotechnology. The National Science Foundation (USA) has taken a major step forward by calling together researchers and social scientists to discuss the issues (NSF, 2001).

It seems likely that the first wave of useful technologies will be in the area of detection and sensing. The capacity to detect precisely and identify viruses and even single molecules has broad applications in medical diagnosis, forensics, national defence and environmental monitoring and control. The potential benefits are obvious but what are the disbenefits?

When detection outpaces response capability – as it usually does – ethical and policy dilemmas inevitably arise. For example, it is already possible to identify genetic predispositions to certain diseases for which there is no known cure, or to diagnose congenial defects in foetuses for which the only 'cure' is abortion. Better detection through nanotechnology will increase the number of these. Another example is detection of pollutants at extremely low concentrations which raises complex questions about risk thresholds and appropriate remediation standards. Thus the presence of tiny amounts of toxic material in groundwater may justifiably raise alarm in society even if the health risks cannot be assessed and the technological capability of remediation does not exist. This may have unintended consequences of closing industry in an area, with social ramifications. In medical areas, nano-technology-based treatments may develop from the initial sensor technologies; they may initially be expensive and hence only available to the very rich, increasing the inequalities already present in societies.

It is possible to identify several general societal implications of nanotechnology as:

- Social equity: distribution of the benefits of nanotechnology
- Social purpose: the actual goals of societal development that we want to advance
- Economic and social enterprises: the structure of the institutions at the interface between nanotechnology and society.

To avoid problems in the future, it seems necessary to start considering now the societal implications, both positive and negative, of nanotechnology.

***Issue 10:* What societal implications can be envisaged and how best can ethical and moral concerns be addressed by nanotechnologists and the wider community?**

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The Position Papers

The APEC CTF is grateful for the substantial contribution of Position Papers by four economies on nanophotonics (Canada), nanobiosystems (Australia), nanoelectronics (Japan), and nanostructured materials (Chinese Taipei), and to the Philippines for a paper on issues for developing economies. The Papers were sought in advance of the Experts Meeting as background material and these proved to be substantial and valuable contributions.

5.1 Nano-Photonics (Canada)

This document has been produced with the aid and direct contributions of the following people, all of whom work for the National Research Council of Canada (http://www.nrc.ca).

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Executive Summary

The world is at a threshold of a revolution in the ways in which materials and products are created as a result of the convergence of the traditional fields of chemistry, physics and biology to form the new field of nanotechnology. The APEC Center for Technology Foresight is organizing a Forecasting Workshop that will be held in November 2001 in Ottawa, Canada. The center has identified four areas where background documents would be useful to provide an introduction to the participants prior to the actual workshop. These are nano-materials, nano-electronics, nano-biotechnology, and the subject of this paper, nano-photonics. Nano-photonics is the production, delivery, detection and interaction of light with matter in which the enabling science or technology derives its value from nanometer sized structures.

Three major segments of the marketplace today (telecommunications, memory, display) are reviewed and the crucial role that nano-photonics has already played as an enabling technology. Key to these achievements has been the capability to create new materials with exactly the electronic and optical properties needed to manufacture the required photonic components. An introduction to a limited selection of activities in the field of nano-photonics research are reviewed to provide a glimpse of what will be the foundation for nanotechnology applications in the future. These include topics such as light-emitting inorganic and organic materials, photonic crystals, and use of coherent light. Finally, some challenges for metrology, infrastructure and the educational systems are discussed.

1. Introduction

'In the year 2000, when they look back at this age, they will ask why was it not until the year 1960 that anybody began to seriously move in this direction'.

R.P Feynman, December 29, 1959

In his classic talk at the annual meeting of the American Physical Society[1], Richard Feynman introduced the public to a vision that has become known as nanotechnology. What is nanotechnology? Why is it going to be important? In the planning document *'National Nanotechnology Initiative: The Initiative and its Implementation Plan'*[2], a vision forty years after Feynman's speech can be found:

'Nanotechnology is concerned with materials and systems whose structures and components exhibit novel and significantly improved physical, chemical and biological properties, phenomena, and processes due to their nanoscale size. The goal is to exploit these properties by gaining control of structures and devices at atomic, molecular, and

supramolecular levels and to learn to efficiently manufacture and use these devices. Maintaining the stability of interfaces and the integration of these "nanostructures" at micron-length and macroscopic scales are all keys to success.'

Although progress has been slower than Feynman initially foresaw, many advances have been made in recent years. A few nations such as Japan have a long history of substantial investments and programs in nanotechnology. Certainly sufficient progress has been made that today nations are making the research and infrastructure investments necessary to ensure that both their economies and societies can reap the full benefit of what will be a key enabler in the 21st century.[3] For instance, the United States alone has committed more than $US420M to nano-technology in 2001, increased from $US255M in 1999.

The APEC Center for Technology Foresight supports the view that we are at the threshold of a convergence of the traditional fields of chemistry, physics and biology to form the new field of nanotechnology. To this end, the Center is organizing a Foresight Workshop that will be held in November 2001 in Ottawa, Canada. The Center has identified four areas where background documents would be useful to provide an introduction to the participants prior to the actual workshop. These are:

- Nano-materials
- Nano-electronics
- Nano-biotechnology
- And the subject of this paper: Nano-photonics

Photonics is derived from the word 'photon', the quantum of light or electro-magnetic radiation. The word 'photonics' has only been popularized recently, in many ways an indication of its rapidly escalating importance in the marketplace and impact on daily lives. Related or overlapping fields include 'optics' and 'opto-electronics'. One example of the application of photonics is the transmission of information by light rather than electronic technology but there are many others.

But then what is 'nano-photonics'? Certainly a review of the many recent documents (for example[4]) on nanotechnology will uncover a wealth of information in the other three thematic areas defined above, whereas nano-photonics is not a term (or category) commonly used.

For the purpose of this document, we will define nano-photonics as **the production, delivery, detection and interaction of light with matter in which the enabling science or technology derives its value from nanometer sized structures**. Not surprisingly, this still often takes us in the direction of, and results in overlap with the other theme areas. But therein lies the importance of nano-photonics, it will be a key enabler in the application of nanotechnology to a wide variety of problems.

Section 2 reviews some of the photonic market sectors where early versions of nano-photonics have already played significant roles, and can be envisioned to in the future. Section 3 examines some recent developments and breakthroughs in research ('nano-science'), which will be the building blocks for nanotechnology in the future. Finally, Section 4 discusses the continuing need for advances in metrology and the challenges facing our educational and infrastructure systems.

2. Today: Nano-Photonics in the Marketplace

This section examines the impact that nano-photonics has had on three major segments in the marketplace (telecom, memory, display), and the technology requirements that will drive future research investments.

Fibre Optic Communications

The communication of information over long distances has been revolutionized by the use of light signals transmitted in fibre optic cables, and more recently by a technology known as Dense Wavelength Division Multiplexing (DWDM). The latter technology permits multiple wavelengths (and therefore independent signals) to be sent in the same fibre simultaneously and has enabled a massive increase in the capacity without the need to lay more fibre. Simplistically, a system is comprised of the transceiver (lasers operating at different wavelengths and capable of encoding the information), the optical fibre (with *in-situ* regeneration capability) and the receiver (capability to separate the wavelengths and de-code the signals). Today modulation rates are at 10Gbit/s, with many companies developing 40Gbit/s components. Combining these rates with DWDM technology, trials by a number of companies have demonstrated capability well in excess of 10 Tbits/s per fibre.[5]

Key to these achievements, has been the capability to do 'band-gap engineering', that is to create new materials with exactly the electronic and optical properties needed to manufacture the photonic components. Deposition of thin-layered structures, literally atom by atom, has enabled precise control over parameters such as the alloy composition, the strain, thickness etc., which together with clever device design has enabled the manufacture of key components such as stable laser emitters. Quantum effects created by the extreme thinness of the layer (only one dimension) are critical to the engineering of the properties, hence the term 'quantum well' (or layer).

With a target of 25GHz (0.2 nm) spacing between adjacent wavelengths, and a hoped for wavelength region from 1490 to 1605 nm, there are significant challenges with regards to sources of the appropriate wavelength, their stability, on-demand tunability of wavelength, threshold currents, power, heating etc. The solutions to these problems are believed to lie in further advances in nano-materials. The problem of insufficient (affordable) bandwidth in the metro/access gap between the long-haul (optical internet) and the customer (LAN, SAN, etc.) is drawing much attention. Again a technology based on quantum size effects, VCSELs (Vertical Cavity Surface-Emitting Lasers), is being actively pursued because of the possibility to manufacture one- and two-dimensional arrays for coupling to optical arrays and lens arrays.[6]

Another area of intense technological interest is that of optical switching and routing of pulses, the dream of all-optical networks. The deployment of multi-wavelength systems has placed a much greater benefit in remaining as much as possible in the optical domain, rather than having to convert each wavelength signal into an electronic signal (and back!) every time some intelligence is required. Key opportunities for switching include path restoration because of equipment failure, an optical add-drop multiplexer to permit the selective addition or extraction of selected signals while allowing others to pass by the node, or the most complex, an optical cross-connect to enable a dynamic reconfiguration of the network at the wavelength level. A number of options are being pursued ranging from traditional approaches such as a Mach-Zender to NEOMS (Nano-Electro-Optical-Mechanical Systems) technology. The latter is based on a device containing hundreds of micron-dimensioned mirrors, each addressable independently that can refocus light from one fibre onto another.

The incredible demand for higher performance photonic components (and eventually circuitry) at ever lower costs in the telecommunication sector is reminiscent of the evolution of the silicon microelectronics industry. Just as the latter has enabled a wealth of applications outside the computer industry, (nano-) photonics will have a significant impact in areas such as medicine and the environment, from cost-effective wavelength-specific sources to array technologies required for imaging.

Optical Memory

At the time of introduction of the CD-ROM in the early 1980's, optical storage density was 2 orders of magnitude greater than that of magnetic hard discs. There has been a significant increase of the storage capacity of optical-based memory since then, from the CD (0.65 GB) to DVD (4.7GB) to the incoming DVR technology (22.5 GB), fueled in large part by improvements in quantum-well laser technology and improved optics. However, this improvement in performance is minor in comparison to that achieved by magnetic technology, where the density is actually higher now. This tremendous advancement was made possible by the discovery and implementation of the giant magnetoresistance (GMR) effect in nanostructured (one-dimensional) magnetic multilayers, all in less than ten years.

While the optical storage business already has certain intrinsic benefits (removability, dependability, long data life, inexpensive duplication, inter-changeability etc.) that will ensure a foothold in the marketplace, the industry is examining nanotechnology to enable a leap forward in storage density.

One next generation scheme uses a gray scale technique to store multiple bits in one spot. Using the technique of near field microscopy and a tapered glass waveguide, a lateral resolution of ~50 nm has been obtained. Another uses multilayers of organic dyes that fluoresce with different colors, but photostability is an important concern. To address this problem, research is focused on obtaining a solid understanding of mechanisms at the molecular level. Holography has been considered since the early 1970s, but again there is the requirement for a better understanding of the nanostructure of the materials. One extreme solution is the possibility of spectral hole burning in an inhomogeneously broadened line in a low temperature solid. The important parameter is the ratio of inhomogeneous to homogeneous linewidths in the material. Ratios have been measured as high as 10^7 implying a possible storage density of 10^8 Gbits/in^2. The only problem presently is the need for operation at ~liquid helium temperatures!

Just as this industry has driven development of commercially available visible lasers from 780 nm, to 650 nm to 410 nm, the pursuit of the options for the next generation memory will enable activities outside optical memories.

Flat Panel Displays

Flat panel display technology has matured to the point where it can be considered an enabling technology, rather than simply providing incremental improvement in certain display areas. Certainly the explosion in wireless communication devices has been a key driver in this sector.

Liquid crystal display (LCD), either active- or passive-matrix technology is now a major player, especially in areas such as colour displays for hand-held devices, from communication to entertainment. Of the emissive technologies, LEDs (Light emitting diodes) have made significant improvements in resolution, brightness and durability and are beginning to be more common in the marketplace. Other competitors such as field-emission displays (FED), electro-luminescent (EL), plasma and fluorescent devices have all also made important advancements.

These advances are rooted in research focused at the atomic and molecular level of inorganic or organic materials. Functional design of materials, packaging, integration with conventional electronics are all issues that have needed to be addressed by this industry, and at the same time represent significant themes within nanotechnology. Endeavors such as molecular electronics are benefiting without doubt from investments made to improve organic LED products. Flexible displays have begun to appear and are but one example of the potential for light-emitting polymer (LEP) technologies.

3. Tomorrow Today: Nano-photonics Science

This section is intended to introduce the participant to a limited selection of research activities in the field of nano-photonics, to provide a glimpse of what will be the foundation for nanotechnology applications in the future. As with the choice of activities, the references are selections from a large number of possibilities and are not meant to be a comprehensive review.

Near-field Scanning Optical Microscopy (NSOM)

NSOM is a technique which uses an optical fibre to deliver light to, or collect light from, a surface with ultrahigh spatial resolution, far beyond the diffraction limit. NSOM embodies many of the key features of nano-photonics including novel high resolution light production, delivery and detection as well as material modification all on a nanometer scale. Clearly NSOM is a key enabler in fields such as medical sensors and optical memory. Todate most NSOM experiments have been performed with ~50nm lateral resolutions.

The quest for better resolution has been hampered by poor light throughput of most probe designs ($< 10^{-3}$). An NSOM probe typically consists of a metal-coated (usually Al), tapered fiber with a small aperture at the tip. As the aperture size is reduced, light would rather leak out from the sides of the aperture through the metal rather than go through the tiny aperture. For visible light the skin depth of Al is ~7 nm placing a limit on the minimum aperture size and resolution possible of ~20 nm. To achieve higher resolution researchers have moved to a technique called "apertureless NSOM" in which as the name implies one does away with a small light delivery/collection aperture and replaces it with a very sharp metallic tip. The sample is irradiated with a focussed laser beam in the vicinity of the tip producing evanescent waves around the small structures to be imaged. The sharp tip perturbs the evanescent fields and acts as a scattering center to produce light, which is detected in the far-field. The probe is usually vibrated at its resonance frequency to permit ac detection to remove the large dc scattered background. Resolutions of 10-20nm are frequently obtained with this technique. However 1 to 2nm resolutions have been achieved using exacting conditions.

NSOM has been used to produce 50 nm lines in photoresist for niche photolithographic applications and is also being considered as a means of creating high data storage densities. Solid immersion lenses can produce 150 nm spot sizes[7] and a microscope based upon apertureless probes called a scanning interferometric apertureless microscope created bit densities of 256 Gbits/in^2.[8,9] The use of apertureless NSOM probe technology could result in data storage writing densities of Tbits/cm^2 on conventional data storage media. It may also be possible to use NSOM probes to turn molecules "on" or "off" for high-density data storage applications as well as towards the goal of "molecular switching".[10]

Research is just beginning on the use of NSOM probes as optical tweezers to trap, move and release nm-sized particles.[11] The field of "optical tweezers" is currently receiving considerable scientific interest as a means of optically controlling the construction and deployment of nano-devices such as the spin micromotor.[12]

There will likely be a continuous movement away from the classical NSOM probe to the higher resolution (a few nm) apertureless probes with tricks being developed (e.g. second harmonic detection of the modulated optical signal scattered by the vibrating tip[13]) to produce artefact free optical imaging. Such resolution will permit detailed optical imaging and spectroscopy over the surface of large molecules (e.g. DNA).[14,15] New probe designs are also emerging, for instance using a molecule attached to the tip as a point light source.[16]

Nanocrystals

Currently many different nanostructured materials are under active investigation with the aim of developing new sources of coherent radiation and components at wavelengths extending from the UV to the mid-IR. Nanocrystals and semiconductor quantum dots are particularly promising since they are expected to yield devices with advantages such as very low pump threshold, high efficiency, broad gain bandwidth etc.

The possibility of laser emission from silicon nanocrystals has attracted considerable attention following a recent demonstration of optical gain in silicon[17] for the first time. The nanocrystals, which were ~3 nm wide, were made by implanting silicon into thin silicon dioxide layers grown on silicon wafers. Optical excitation with a laser generated electrons and holes that recombined to emit at 800 nm. Measurements of the optical gain indicated that a beam passing completely through the amplifying region could experience gain as high as 10,000 cm^{-1}. The details of the process responsible for this high gain are not fully understood, but if an actual laser can be developed, and excited electrically rather than optically, it would represent a significant advance towards achieved silicon-based devices.

Another example of a nanostructured optical source is the report[18] of UV laser emission from ZnO semiconductor nanowires that were epitaxially grown on a sapphire substrate. The diameters of the nanowires ranged from 20 - 180 nm (the term wire is used normally to indicate confinement in 2 dimensions) and the well faceted hexagonal end of each nanocrystal appears to have formed a natural optical resonator. These devices were again optically pumped, and it is not clear whether a more practical excitation method can be demonstrated in the future.

In addition to the fabrication of optical emitters, nanocrystals are also finding an important role in modifying laser performance by acting as saturable absorbers. A sputtering system is being used with composite InAs/SiO_2 targets to produce SiO_2 films with a high density of InAs nanocrystals.[19] The size of the InAs crystals varies widely over a range up to 6 nm and following annealing they exhibit saturable absorber characteristics with a very fast (~100 fs) recovery time.

On a somewhat longer time scale, ceramic laser materials fabricated by sintering micron scale crystals of laser material have recently been reported[20]. In the case of Nd-doped YAG the optical and thermal characteristics are as good as those obtained with conventional single crystals grown by the Czochralski process. Ceramics offer an extremely interesting alternative for the production of laser material since they can be produced rapidly and scaling to large areas is relatively simple. Future development of such materials could lead to lower cost, easily manufactured laser media.

Self-Assembly of Quantum Dots

The term quantum dot (QD) is commonly used to describe a semi-conductor nanostructure in which electronic confinement occurs in all three spatial dimensions, not just one dimension as in the case for devices like quantum well (layer) lasers. The QD has a delta function-like density of states that depends strongly on the dimensions of the confining potential. The optical emission spectrum resembles that of naturally occurring atomic systems, displaying a series of delta-function-like lines related to filling of successive electronic shells.

Significant progress has been made employing a variety of fabrication techniques[21-26], but the most widely used strategy[27] employs the deposition of a narrower bandgap, compressively strained epilayer over a wider bandgap substrate, which results in the spontaneous nucleation (self-assembly) of coherently strained three-dimensional islands on top of a thin (5-10Å), two-dimensional 'wetting layer'. Subsequent deposition of substrate material to encapsulate the QD produces a fully three-dimensional confinement potential. Alternative fabrication strategies include the colloidal techniques[24] to provide 1-10nm QDs for II-VI materials, techniques that directly exploit changes in the surface reconstruction during growth[25] and techniques which rely on the monolayer thickness fluctuations found in thin GaAs quantum wells grown between AlGaAs barriers.[26]

Semiconductor QD lasers have demonstrated in the laboratory[28] excellent properties (extremely wide tunability, broad gain spectrum, radiation hardness) and development towards commercialization is being actively pursued. Laser emission from the visible red through to telecom-critical 1550 nm[29-32] has been achieved. This has important implications for bio-sensing and bio-diagnostics where the signature wavelength may be difficult to achieve using conventional laser diode materials. QD-based detectors have also been studied extensively[33-36] and have a number of advantages over quantum well systems, including lower dark current levels[37] and the absence of many of the coupling issues inherent in inter-subband quantum well devices.

QDs are located randomly across the semiconductor substrate and have a variety of physical dimensions, leading to significant inhomogeneous broadening (typically 30-50meV) of emission lines in comparison to real atomic systems. However, significant progress is being made in the use of techniques for spatially ordering the QD nucleation sites[38-41] and in significantly reducing inhomogeneous broadening. The ability to accurately select the sites for individual QDs, to be able to determine the strength of coupling to adjacent dots and to be able to vary the strength of coupling and the spatial symmetry of QD molecules across the complete surface of a semiconductor wafer are all critical to new device concepts.

Artificial Atoms & Molecules

A key objective in nano-photonics is to be able to predict and gain control of the optical emission from a single nanostructure. The first step is to understand the electronic structure of the nanostructure in order to be able to routinely engineer it through precise control of its composition, size, shape, number of carriers, etc. In addition, we must understand the dependence of the emission spectrum on the population of electrons and holes in the nanostructure.

Single QD spectroscopy[42-45] has been developed to the point where the optical properties of an individual QD (an 'atom') or two coupled QDs (a 'molecules') can be probed. With the use of such techniques, details of the QD emission spectrum have been revealed that were previously masked because of the large inhomogeneous broadening encountered in QD ensembles. A series of extremely sharp transition lines whose energy, intensity and behavior under external stimuli such as electric and magnetic fields have been characterized to the point where coherent control and manipulation of the emission can be considered.

For example, the dependence of the absorption spectrum has been measured[46] by varying the parameters of the QD. This study demonstrated that by injecting carriers into the levels of the dot, optical transitions into occupied levels can be blocked due to the Pauli exclusion principle.[47] Highly excited nanostructures and their light emission spectra as a function of degree of excitation have been successfully studied by a number of groups.[48-50] The latter study demonstrated the existence of "hidden symmetries" in the energy levels of excitonic molecules, which replace Hunds rules in electronic atoms. In a subsequent study[51], spectra were obtained from pillar structures which contained QD molecules with varying separation between the individual QD. The emission spectra measured as a function of the atomic' separation demonstrated the ability to manipulate the interacting dipole. Single QD spectroscopy studies have also revealed fine[52] and hyperfine[53,54] splitting due to electron-electron and electron-nuclear interactions and have led to the demonstration of optically induced exciton entanglement in a single QD system.[55]

Together these studies have demonstrated a level of understanding sufficient to begin to design and fabricate QDs with specific absorption and emission characteristics, the first step towards control and manipulation of single photons.

Photonic Crystals

The term 'photonic crystal' (PC) is used to describe a material in which periodic variations in refractive index are used to preclude the propagation of particular frequencies in chosen directions. Of interest recently are the attempts to make materials that exhibit this behavior in all 3 dimensions. In this case, when light of certain frequencies cannot propagate in any direction in the material, the term 'photonic bandgap' has been used. Many interesting properties have been predicted for such crystals.

As mentioned previously, optical fibres (or planar waveguides) play the same function for photons as metallic wires do for electron transport. However unlike electron wires, these photon wires cannot be bent, without introducing significant photon leakage. Clearly this has significant implications for the device density that can be achieved in photonic integrated circuits (PICs), or possibly limits the usefulness of integration at all. This drawback may be overcome by using a 2 dimensional PC in thin-slab or waveguide structures.[56] GaAs-based structures have been successfully made by a number of groups[57-60], a key to integrating PCs with standard optoelectronic devices.

Three dimensional structures have also been built by different groups, for example.[61,62] In principle, this is a perfect cavity into which an active emitter/absorber (e.g. QD) can be incorporated[60] permitting the control of properties such as the spontaneous emission lifetime. If the frequency of the emitter is in the gap, emission is not possible and the photon will be stored. First attempts at planarization and coupling of devices have been promising.[63] An alternative storage of photons is offered by vertically coupled QDs.[64] After photons are absorbed, electrons and holes are spatially separated by the application of an electric field. When the field is turned off, electrons and holes can recombine and photons are emitted.

Another challenge and opportunity is to apply PCs to nonlinear optics, where it is expected there will be an enhancement of effects. The group velocity of photons close to the band edge is low, thus increasing the effective interaction length for nonlinear processes within the material. The other reason is the simple concentration of light in a particular region in a PC. Placement of a non-linear material there will result in an enhanced interaction. Thus, if PCs can be made from nonlinear optical materials, or alternatively incorporate such materials, they are expected to exhibit effects such as enhanced gain, optical switching, and harmonic generation. An alternative is to incorporate QDs into these materials. QDs are saturable absorbers and could lead to strong nonlinear effects where it would be possible to open/close gaps by controlling not only the light frequency but also the intensity.[65]

Coherent Control of Light-Matter Interactions

The combination of the control of electronic structure of a nanostructure and the control of photons in a material offered by a photonic crystal leads to exciting possibilities. For example, the coherent properties of light could be used to switch a quantum or nano-device. As outlined above, a number of the preliminary steps have already been demonstrated.

Light beams with low photon numbers lead to interesting quantum interference effects. These interference effects have been termed "nonlinear optics with single photons" and offer a possibility of switching light with light.[66]

With well-ordered arrays and/or site-selected QD molecules, the possibilities for the coherent manipulation of entangled states are very real. Such coherent control experiments have already begun using single QD[53-55] although significant further development is required before the application of π-pulses can be used to flip pseudo-spin states and before gate technologies are available to adiabatically remove the coupling between coupled and entangled QDs.

Probably most attention has focused on quantum information.[67] As originally proposed by Feynman, industry will take advantage of quantum mechanics rather than be limited by it in information processing. Semiconductor QDs would seem to be a very viable option for implementation of such schemes. To choose one theme, structures are being actively pursued for their promise in the area of single photon sources. Such sources are important in certain quantum cryptography protocols[68], in which, streams of photons with a linearly polarized basis are used to encrypt a secret "key". Entangled combinations of the two polarized basis states can be used to ensure that external eavesdropping is absent, but only if one can guarantee that no extraneous photons are available to the eavesdropper i.e. only one photon at a time can be used. A number of optically active QD structures have been proposed for single photon sources, including the 'single-photon turnstile device'[69] that uses the regulated supply of single electrons and holes in a Coulomb blockade, double barrier p-n junction to regulate the emission of single photons. At present, the limiting feature of such a device is the extremely low collection efficiency and the noise background from unregulated photons. Others[70] have demonstrated an alternative source based upon spectral filtering of the multi-exciton emissions from a single QD. After excitation of multiple excitons within the QD, using a resonant, short pulse laser, energetically separate emissions can be observed from single and bi-exciton complexes. The last exciton emission from the QD can be filtered to provide a 'guaranteed' single photon source. At present, this source suffers from poor collection efficiency and a modification has been proposed in which the QD is placed inside a photonic cavity to engineer the optical mode and so improve the collection efficiency. A similar device[71] has been demonstrated based upon pulsed laser excitation of a single QD. In this structure, a single QD was embedded in a micro-cavity disk and the emission of the last exciton was again spectrally filtered to obtain single photon emission.

Organic Building Blocks

The design of active organic materials depends on the understanding of the dynamical response of materials, e.g. electron transfer, photodissociation, localization, coherence and charge redistribution. The versatility of organic materials comes not only from carbon's unsurpassed ability to make stable bonds with itself and other materials but from the ability to add functionality by combining different building blocks and the "recognition" ability of molecules where molecular interaction via a weak non-covalent interaction allows for sensing of other organic or bioorganic molecules with a conversion to either an optical or an electrical signal.

However this same weak interaction means that the electronic states of a molecule in a solid are similar to that of the vacuum states of an isolated molecules leading to narrow conduction band of the order of the thermal energy k_BT at room temperature.

The design and synthesis of novel anthracene derivatives[72] have led to demonstrations of thermally stable and highly fluorescent OLEDs with efficiencies of 10 cd/A and 2000 cd/m^2 at threshold. Much effort is going into the design of efficient electron transport materials to allow for balanced charge injection in electroluminescent cells. Using phosphorescent based emitters[73], the triplet excitations have been used to increase the device external efficiency.

The ability to tailor and process conjugated polymers has led to the realization of large-area integrated devices on flexible substrates.[74] By combining wide bandgap nanoparticle composites with narrow gap conjugated polymers, it has been possible to tune the optical constants for device applications. The challenge has been to obtain a sufficiently high refractive index contrast while maintaining effective carrier transport (current density) across the junction. Semiconducting poly (p-phenylenevinylene)-silica composites have been obtained with refractive indices between 1.6-2.7, and chemical dopants introduced to address the conductivity problems, leading to a successful demonstration of microcavity LED.[75]

The photorefractive performance of organic materials depends on the effectiveness of the charge transport which can be either band-like or hopping in nature depending on the temperature. The presence of defects and dopants introduce shallow traps which decrease the mobility while long range order favors extended electron states and a high mobility. The best carrier mobilities have been achieved in organic single crystals with flat stacks of molecules rich in π-electrons. Charge transport in oligothiophenes was highly anisotropic with in-layer coherent transport (perpendicular is incoherent and of the hopping variety because of the weak interchain wavefunction overlap) comparable in performance to amorphous Si at room temperature.

An organic solid state injection laser was demonstrated in tetracene single crystals using field-effect electrodes for efficient electron and hole injection.[76] For laser action, feedback was provided by reflections at the cleaved edges of the crystal forming a Fabry-Perot resonator. Exciton generation was greatly improved by ensuring balanced charge injection and high electron and hole mobilities in gate-controlled devices. The use of high-quality single crystals has also substantially reduced the effect of charge-induced absorption observed in electrically pumped laser made of amorphous organic materials.

Nonlinear Organic Materials

The nonlinear optical properties of organic materials depend mostly on the polarizability of electrons in the π-bonding orbitals. The addition of electron donating or accepting functional groups increases the asymmetry of the charge distribution and therefore increases the nonlinearity. Organic materials also exhibit nonlinear optical phenomena under the influence of strong electric field.[77]

Polymer waveguides can offer large nonlinear effects ($\chi^{(2)}$ ~ 100 ppm/V). The nonlinearity is provided by a non-centrosymmetric chromophore doped into the polymer matrix. The design of suitable chromophores requires push-pull molecules with an acceptor group at one end and a donor group at the other linked in a chain with sufficient electron movements to build up a large hyperpolarizability.[78] In order to change the sign of the $\chi^{(2)}$, poling or the application of a strong DC field with the polymer heated to its glass transition temperature can be used. This approach can be used for quasi-phase matching of nonlinear interactions in a waveguide.[79] Chirality can also be used to create macroscopic non-centrosymmetric structures for second order nonlinear optics. The index modulation in chiral isotropic media arise from the imaginary part of the electro-optic susceptibility. The response contains dephasing-induced terms that can lead to gain for the optical field, essential for active components in electro-optic signal processing.[80]

The host dielectric constant, the shape of the chromophore, the poling field strength and the spatially anisotropic intermolecular electrostatic interactions all play a role in determining the maximum electro-optic activity for electrically poled chromophore/polymer materials. A comparison of experimental and theoretical results point to the significant dependence of maximum electro-optic activity on chromophore shape. These suggest a new paradigm for the design of electro-optic chromophores facilitated by dendritic synthetic approaches.[81]

Two-photon absorption is a process by which a compound simul-taneously absorbs two photons at the same or at different energies, and reaches an excited state that is higher than the simple summation. Although this has been regarded as a plague in the context of all-optical switching due to resulting optical loss and damage, there is now an effort in designing molecules through structure-property relationships studies for excited fluorescence microscopy, optical limitation, optical data storage, and induced biological caging applications. A strategy for the design of molecules with large two-photon absorption cross sections has been reported based on the symmetric charge transfer from the ends to the middle of a conjugated molecule.[82]

In the last decade tremendous progress has been made in the synthesis of complex organic building blocks, including a new topology for polymers and dendrimers allowing precise nanoscale architectures (10-100nm) with interesting mechanical and optical properties. For example, the reaction of a dendrimer shell reagent with a reactive dendrimer core reagent, core-shell molecular constructions have been obtained serving as building blocks for higher order nanoscale constructions.[83] The recent progress in soft lithography[84], microcontact printing and ink-jet printing has brought us closer to the low cost fabrication of large area organic devices on a variety of rigid and flexible substrates.

Hybrid Organic-Inorganic Materials

Hybrid organic-inorganic materials can be broadly defined as synthetic materials with organic and inorganic components and are of two kinds: homogeneous systems derived from monomers of miscible organic and inorganic components, and heterogeneous and phase-separated systems with domains ranging from nanometers to micrometers in size. Integral to this definition is control over the size, composition, and topology of the organic and inorganic components, which depends upon the reaction and processing conditions used in the hybrid material synthesis. The high degree of control over the composition and structure in hybrids permits systematic investigations of structure-property relationships, which can result in improved optical properties relative to the organic or inorganic materials alone. Hybrid organic-inorganic materials are generally prepared through solution or sol-gel processing, in situ polymerization techniques, or solid-state reactions. They can be readily prepared in diverse forms such as monolithic structures, thin films, fibers, particles, or powders. This versatile and mild approach to materials with new or enhanced properties makes hybrids attractive candidates for optical devices, microelectronic coatings, sensor coatings, and structural materials.

Hybrid organic-inorganic materials are being developed in interdisciplinary fashion between inorganic chemistry, polymer chemistry, organic chemistry, and biology. Optical studies performed on organic-inorganic nano-composites have evolved toward different objectives: to investigate the fundamental spectroscopy of the dye molecule isolated in the sol-gel environment, to study dye energy transfer in solid matrices, to use luminescent molecules as probes of the sol-gel process, and finally, to develop materials with specific optical properties based on the properties of organic or inorganic chromophores.

As new hybrid-material approaches develop, one can expect new types of photonic materials to be created. One such case is the templated growth process using organic molecules and macromolecules as structure-directing agents that allow the construction of complex hybrid hierarchical architectures. The confinement of highly-dispersed nano building blocks in the form of clusters or nanoparticles in mesoporous hybrid matrices carrying functional organic groups, or the organization of such blocks on textured substrates, could provide larger concentrations of active dots and better-defined systems.

The Other Dimension: Time

To this point, focus has been on the natural size imposed by the fundamental building blocks of nature, atoms and molecules, towards which nanotechnology is evolving. However, these same building blocks of nature dictate another 'size', namely the time scale. When we learn to control responses on a time-scale (measured in attoseconds, 10^{-18}s), and to combine this capability with nano-sized devices, we truly will be able to pursue new functionalities. The evolution of technology during the past decade shows that this dream is close to being realized.

There are three categories of implications (speed, phase and intensity) of femtosecond science for nanotechnology:

Speed: Even when speed is not a direct requirement, nano-technology will often have a new hidden requirement for speed. For example, ensuring that a device performs its function before other relaxation pathways (e.g. coherence and de-coherence) can intervene will mean that rapid devices will be the most efficient. It will also ensure that there are fewer uncontrolled relaxation pathways that can lead to damage of what will undoubtedly be fragile devices.

Intensity: Ultrashort pulses give us access to extremes in nonlinear response of matter. In fact speed and intensity often go hand in hand. To gain enough photons in a beam to force the nanodevice to respond quickly requires a high intensity. This can be a major advantage because there are very efficient means of control that we can use when the pulse is very intense. Adiabatic rapid passage, chirped pulse excitation, non-intuitive pulse sequences, and induced transparency are all highly efficient, highly nonlinear processes. These should allow quantum systems to be manipulated almost deterministically.

Phase: Nanotechnology promises very high-density packing of basic devices (on a surface or in a volume) and very small devices. In either case, it will be difficult, but essential, to communicate with these devices. There are a number of options, but coherent control is the most advanced.

It is possible to deliver 100 fs duration laser pulses through 100 nm aperture NSOM probes.[85] One can anticipate that a combination of femtosecond laser pulses and apertureless probes will permit studies of femtosecond dynamics with nanometer spatial resolution. The short duration high power pulses will also permit the study of non-linear effects at surfaces again with nanometer resolution. Already short pulse duration, high peak power laser beams focussed onto a sharp tip have been used to make 10 nm cuts and pits in various materials.[86]

4. Challenges: Education, Infrastructure & Metrology

Education

Nanotechnology presents two major challenges for educational institutions and how they have been traditionally educating students.

Certainly substantial, if not the most important, advances to be gained from nanotechnology will come from true cross-disciplinary efforts, all of which will require and accelerate the convergence of the physical sciences and engineering with the biological sciences and medicine. Because these disciplines have been traditionally separated by culture, management domains and terminology, institutions will have to consider significant changes to ensure that students receive an education that at least raises their level of awareness and their ability to communicate meaningfully with other disciplines. The level of understanding that an individual has of either the technology base they hope to take advantage of, or the end application that they hope to have an impact on, is going to increase dramatically in importance.

At the same time that institutions are faced with the challenge of increasing the breadth of the education of students, so to will they be faced with increasing the depth of knowledge taught in any given discipline. For example, materials engineering may not have required a knowledge of quantum mechanics or atomic-scale characterization tools in the past but both will be essential to be able to engineer nano-materials whether for their optical properties or any other. Taking this concept one step further, theoreticians will have a role of increasing importance to play because of the necessity to be able to simulate and predict outcomes before investing heavily to provide proof-of-concepts.

These two conflicting demands (breadth and depth) on resources of both the institutions and students must be somehow met. Otherwise, the supply of knowledgeable people could easily be the limiting factor in the speed with which nanotechnology can be introduced into people's lives.

Infrastructure

The tools for the creation of materials, their investigation on an atomic scale and the development of robust fabrication processes will all demand major investments in capital equipment and laboratories. In addition, the importance of predictive simulation will require significant investment into computational infrastructure.

The magnitude of the investments will mean that all but the very largest economies will not be able to afford to have more than a handful of sites. Therefore accessibility and efficiency of operation will be keys to success. This style of operation is common to some areas of research (e.g. synchrotron radiation) but will present a new challenge to the majority.

However, the requirement for major, central facilities may actually assist in addressing the challenges discussed in the previous section. A common laboratory setting can certainly provide an excellent forum for the mixture of ideas from one discipline to another. Indeed, it can be imagined that this may be an excellent platform for APEC economies to share in the development of nanotechnology through the sharing of access to national facilities.

Metrology

The rapid advances in nanotechnology being witnessed today have been enabled by our fledgling abilities to assemble, measure and manipulate structures on the nanoscale. Certainly much development is left to be done, but one of the keys to moving from the laboratory to manufacturability will be a significantly improved capability in metrology.

For example, maintaining or even finding positions on a surface with nanometer accuracy and precision is very challenging in a research envioronment, but is especially so for areal dimensions relevant to manufacturing. Reference materials (e.g. nanoparticles of known size and composition) are not available, which makes intercomparison or calibration of characterization tools and approaches difficult if not impossible.

On the other hand, nanotechnology will provide an opportunity to create new fundamental or secondary standards. For example, since 1990 quantized Hall resistors have been used in national standards laboratories to represent resistance. These resistors are semiconductor devices which, when cooled to 1 K or less in a magnetic field of several tesla, yield values of resistance which are essentially invariant, and which are multiples of fundamental constants. Optically based atomic clocks and optical frequency synthesizers are now a reality, with a single ultrastable laser providing phase coherent references throughout the optical spectrum and down to the microwave/radio frequency domain, with the stability of the transfer process reaching the10^{-15} level.

5. Summary

Through devices such as quantum well lasers and their enabling roles in applications ranging from telecommunications to home entertainment, it is evident that nano-photonics has and is having a major impact on our daily lives. Given the exciting developments outlined in section 3, and remembering that those are only representative of the field, it is clear that the impact of nano-photonics technology has the potential to grow significantly. Tremendous scientific advances have been made but there remain many challenges to their implementation.

APEC could play a significant role in a number of areas:

- **Critical Research Areas.** The convergence of physics, chemistry and biology will actually lead to an explosive increase in possibilities of R&D directions. Choices will be difficult, and sometimes limited by the breadth of expertise available. Encouragement of multi-diciplinary and multi-national collaborations would accelerate progress to the benefit of all. For instance, the number of organizations contributing to section 3 is relatively small. Means to increasing the participants must be found.

- **Physical R&D Infrastructure.** The magnitude of the financial investments required to create R&D centers in nanotechnology will mean that none but the very largest economies will be able to afford to have more than one or maybe two sites, and even these cannot possibly cover all areas. Access to major facilities in other countries would lead to efficient operation of any one facility and allow member nations to broaden their R&D programs. It will have the added benefit of permitting more long-term research to be undertaken, from which everyone will benefit.
- **Technical Workforce.** The supply of knowledgeable people could easily be the limiting factor in the speed with which nanotechnology can be introduced into marketplace. There is a need for the development of new curriculum in the universities, which could be shared amongst the member economies. Access to facilities mentioned above would also augment the training of students.
- **Metrology.** One of the keys to moving nanotechnology from the laboratory to the factory will be a significantly improved capability in metrology, and ensuring international accepted standards to avoid the waste of resources through parallel and counter-productive investments.

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5.2 Nanobiosystems (Australia)

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1. Introduction

Nanobiosystem, as defined in this discussion paper, is not the use of nanotechnology as applied to biology but rather the use of biology to aid in the development of nanotechnology. The basic premise of nanobiosystems is to utilize biology at two levels. Firstly, it is to use biological materials that already exist as ready-made devices or functional materials with the appropriate size and properties. For instance, enzymes with their highly evolved specificity and catalytic powers may be useful building blocks in the design of nano-fuel cells as power sources (Chen et al 2001) or as bioelectronic materials (Willner & Willner, 2001).

Secondly, it is to look at biology in order to understand, and then apply, the fundamental principles that biology uses in order to produce nanodevices. For instance, by understanding the chemical sensing mechanism based on ion-channels that is a common motif used in nature and then developing biomimetic analogues with the appropriate properties and structures, functional sensing nanodevices have been built (Cornell et al, 1997).

Biology has some obvious advantages in terms of producing complex structures ranging in size from nanoscopic molecular motors (Soong et al, 2000) to the gargantuan (e.g. consider the Great Barrier Reef coral structures). These structures are synthesized at room temperature, using benign aqueous solvents in a self-assembly process. Current drawbacks in biology center around stability issues and the complexity of some biological systems. Understanding these processes could be of immense value in producing nanotechnology not just for biotechnology, medical or healthcare applications, but in far broader areas such as environmental, food, general manufacturing, energy, communications or transport.

Due to the nature of nanobiosystems research, i.e. the application of biology towards nanotechnology, the applications and directions are necessarily less focused in terms of applications and outcomes than the areas of nanophotonics or nanoelectronics. A brief overview of some areas of current research will be given in order to give an indication of the type of research, applications and directions being investigated, rather than an attempt at a comprehensive review.

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- applying basic concepts derived from biology to traditional areas
- bio/chemical sensors based on nanobiosystem
- bioelectronics
- opto-nanobiosystems
- nanoscale machinery
- nanoscale building blocks
- complex biomimetic systems such as artificial organs, muscle

2. Overview of Selected Areas of Research:

2.1 Applying Basic Concepts Derived from Biology to Traditional Areas

One of the main benefits of research into nanobiosystems may well be the integration of basic biological concepts into nanotechnology. By understanding and trying to apply the principles of how biology functions, into artificial structures, basic paradigm shifts in terms of our thinking and our technology may occur.

For example, if we wish to produce nano-scale information processing devices, are the accepted computer methodologies based on lithography and hard-wired digital electronics the most appropriate? Would there be advantages in using systems based on dispersed information processing such as enzyme transistors or whole cell biocomputing (Simpson et al, 2001), or DNA computers (Adleman, 1994) etc.? These systems rely on carrying out sophisticated computations using biochemical interactions in aqueous solution without the need to build complex circuit boards or integrated circuits. Even if the ability to build practical devices for the consumer market may not appear feasible at this stage (Cox et al, 1999), this type of fundamental research shows that it is possible to (1) devise sophisticated computational systems that function with nanoscopic biological materials and (2) that it is possible to build information processing devices that do not need to be hard-wired like a conventional digital computer.

Another example of looking to nature for basic concepts is the use of self-assembly in biology. Biological systems invariably are assembled through the interaction of simpler sub-units that self-organize into ever more complex structures. The structure of the sub-units is the in-built program that forces them to organize into quite specific nano- and macro-structures without the need to use lithography or other external structuring input. Lipids, and other amphiphilic molecules, for example can be used to form well-defined structures such as lamellar, hexagonal, cubic etc phases in water where the final structure depends only on the initial structure of the lipid molecule (Ringsdorf et al,1988; Liu et al,1998, Brinker et al, 1999). These structures can then be further used as templates. For instance, in tubular lipid/water structures, the water can be replaced with inorganic or metallic material yielding shaped nanoparticles such as nanorods (Nikoobakht et al, 2000). These structures can in principle be used to build three-dimensional nanomaterials, such as filter systems described by Lu (Lu 2001, Lu et al 2001). Self-assembled monolayers as protective and "smart" or functional coatings for surfaces also derive their properties from nature's method of protecting cell contents, namely the biological membrane (Ullmann, 1996). Taking nature's examples further, the incorporation of phytanyl groups, such as those found in extremophiles which exist in harsh environments, improve the protective properties of the self-assembled monolayer. (Braach-Maksvytis & Raguse, 2000). The increased electrical resistance imparted by these molecules to the self-assembled monolayer stem from using the cell's concept of liquid crystalline phase, rather than crystalline phase, to provide a "self-annealing" surface.

2.2 Chemical Sensors Based on Nanobiosystems

The development of chemical sensor technology is an area of intensive research and is widely seen as one of the first and most promising areas of application for nanobiosystems (Göpel, 1996). The biochemical sensing industry is used to dealing with biological materials that may have limited stability and limited shelf-life and hence a number of issues such as product stability do not have the same stringent requirements as do for instance the shelf-life of a digital computer or flat panel display. However, other issues such as reliability of test results (especially in medical test situations), sensitivity, speed, specificity, interference from other substances etc give rise to other challenges in developing sensing devices.

At this stage of nanobiosystems research, the most sensitive and specific, portable chemical sensors are still attached to noses and other sensory organs of animals. These sensors invariably rely on the fact that a binding event of the analyte molecule of interest, to a biological receptor within the organ, results in the closing or opening of an ion channel that is embedded in an insulating cell membrane. In the open state, ion channels routinely allow a flux of several million ions per second to pass through their hollow interior from one side of the cell membrane to the other side. Thus if a single analyte molecule causes the closing of a single ion channel an immediate amplification factor of several million results by preventing further ion flow.

Major efforts in biosensor technology can be broadly divided into 3 areas: (1) use of biological receptors with physical sensing/amplification techniques (2) biomimetic sensors that attempt to use both biological receptors and biological signal amplification using ion channels (3) systems that use whole sensory cells or organs of organisms. Of these only the first two areas fall within the category of nano-biosystems research.

Examples of the use of biological receptors with physical amplification techniques have been investigated for a number of years (Göpel, 2000). These devices generally consist of biological receptors such as antibodies or antibody fragments that are immobilized onto the surface of a transducer device. The binding of the analyte causes a change in a physical parameter at the surface of the transducer device that can be measured. Physical parameters that may be measured are changes in mass using quartz crystal microbalances or surface acoustic wave devices, changes in the surface plasmon characteristics of metal (gold or silver) surfaces, changes in refractive index or thickness of the surface layer using ellipsometry. One of the main drawbacks of these methods is the fact that non-specific binding of molecules, other than the one that is being detected, is also difficult to prevent when these techniques are used in complex biological media. Other limitations may be the sensitivity, rate of response and cost of the transducer. Hence the main application to-date has been in the development of gas or vapor sensors, in particular the development of "electronic noses" (Göpel, 1996; Göpel, 2000). These function by using arrays of relatively non-specific sensor elements and using pattern recognition software to identify different odors, gases or vapors in what is believed to be an analogous process to that occurring in the nose.

A recent novel example of using hybrid nanoscale technology was developed by the Mirkin group to develop a sensitive DNA sensor technology based on the optical properties of nanoparticles (Storhoff & Mirkin, 1999). In this technology DNA is modified with a thiol group at one terminus. The modified DNA is then attached to gold nanoparticles (some 15 nm in diameter) via strong gold-sulfur interactions. A sample of test solution that contains complementary DNA to the DNA that is attached onto the gold nanoparticle is now added and hybridization (cross linking) of the DNA strands occurs. In this manner the complementary DNA strand causes the nanoparticles to aggregate. Dispersed, isolated 15 nm diameter gold nanoparticles display a burgundy-red color due to surface plasmon adsorption. However, aggregation of the gold nanoparticles causes a shift in the color and the solution turns blue-black. This color change can be readily detected and only occurs in the presence of the appropriate DNA complements.

A generic nanobiosystem sensor that uses both biological receptors and signal amplification using ion channels has been described recently (Cornell et al, 1997). In this particular system a complete biomimetic sensor structure was produced consisting of receptors, ion channels, and lipid bilayer membranes. The lipid membrane was developed with the required two-dimensional fluidity such that the ion channels could incorporate and function properly. Four nm long tetraethylene oxide groups were incorporated into the lipid molecules in order to create a space between the lipid bilayer and the electrode surface. This space created a reservoir region for ions flowing through the conducting channels. Antibody fragments where attached to the ion channel as receptor molecules and a novel switching mechanism was developed to enable the sensor to respond to both low molecular weight analytes as well as larger proteins, enzymes, DNA or micro-organisms. The whole structure was based on biological principles but used synthetic molecules and modified ion-channels. Although a complex structure, one of the advantages of the approach was that the sensor architecture basically self-assembled and could be formed within minutes with no complex apparatus. Another advantage was that by using structural motifs found in nature the response towards interferents found in blood, serum or plasma was minimal. Stability of the systems was enhanced by mimicking chemical structures found in thermophilic bacteria (archaebacteria), that is, bacteria that thrive at extreme temperatures.

Such sensing technology is the most commercially advanced nanobiosystems technology with the formation of several start-up companies having been formed and it is probable that such ventures will form some of the first commercially viable examples of nanotechnology.

2.3 Bioelectronics

Bioelectronics may be defined as the integration of biomaterials and electronics. This simple definition leaves considerable leeway as to the amount of biomaterials (e.g. enzymes, antigens/antibodies, DNA) versus the amount of electronics, or the complexity of the device, that are used in defining research as being bioelectronic.

An active area of relevant research in bioelectronics is the structuring of biologically active components onto electrodes and the direct electrical contact of enzymes to electrodes. This is a non-trivial exercise as enzymes generally function with soluble i.e. mobile chemical electron-transfer species. However, in order to utilize the electro- catalytic power of enzymes efficiently, the active center of the enzyme as well as any enzyme substrates and co-factors need to be positioned appropriately on the electrode interface. Nanoscale control of the structures is being sought after in order to optimize the electron transfer efficiency and to avoid denaturing the enzyme. Some interesting results are being obtained through the use of hybrid systems consisting of enzymes attached to metal nanoparticles and carbon nanotubes. Potential outcomes of such research are biosensors (Willner & Willner, 2001), miniature biofuel cells (Chen et al, 2001), or biomaterial based electronic circuits (Wei, 1998; Willner et al, 1999; Hirsch et al, 2000).

Other relevant examples of nanoscale bioelectronics are the use of DNA as a wire template (Braun et al, 1998). In this work two macroscopic electrodes with a12 micron gap between them are first coated with a short, thiol fictionalized DNA oligomer. A long complementary DNA strand is then allowed to hybridize with the short DNA oligomer. This forms a DNA bridge from one electrode to the other. The DNA strand is then used as a template for electroless silver plating of the DNA strand. The silver plating occurs preferentially on the DNA and the two macroscopic electrodes are bridged via the thin conductive silver wire. The work opens up the possibility of using different types of DNA to wire up two or three dimensional nanoscale circuits.

2.4 Opto-nanobiosystems

Brief mention should be made of the research being carried out exploiting the optical and photoactive properties of biological molecules. For instance the optical properties derived from structural organization of biological materials (Srinivasarao, 1999) is of current interest in the photonics area. Nature abounds with brilliant iridescent colors found on the bodies and wings of many birds, butterflies, moths and beetles. This color production is mainly produced by physical means such as diffraction, interference, and scattering based on complex micron and sub-micron structures. Gaining an understanding and subsequently mimicking such structures using self-assembly techniques is still a major challenge.

The use of photostimulation to modulate or switch some properties of the nanomaterial is an active area developing biocomputers (Birge, 1995) and optobioelectronics (Willner, 1997). In the first case, the photostimulated switching of a naturally occurring protein, bacteriorhodopsin (bR), into various meta-stable adsorption states has been used to develop a three-dimensional memory device. The second case uses photoactive compounds adsorbed onto electrodes, to reversibly switch the electron-transfer from an enzymes to the electrodes, on or off. AMES in NASA is looking at extremophile donut shaped molecules to attach metal at centre for photon acceptance leading to device that can read and write at the molecular level. The storage implications brought NASA's attention to the convergence of biology and how it affects information technology.

A third example is the development of photochemical energy conversion systems that mimics the photosynthetic process. These can be purely synthetic, having taken the original inspiration from nature but having evolved into systems that no longer contain any biological materials (Graetzel, 2001), or they may attempt to mimic the natural system more closely and attempt to produce chemical energy by incorporating the appropriate light adsorption complexes and enzymes into lipid vesicles (Steinberg-Yfrach et al, 1997, 1998).

2.5 Nanoscale Machinery

The concept of designing and building nanoscale machinery, such as a functional nano-motor was probably deemed to be something that would not be achieved in the short term by most researchers. In a series of reports Noji (Noji et al, 1998) and Montemagno (Soong et al, 2000) have demonstrated that the biological protein complex F_1- ATPase, which is known to function as a biomolecular motor, can be used to construct primitive, functional nanodevices. The F_1- ATPase molecule is approximately 8nm in diameter and 14nm in length. The rotating shaft in its center is capable of producing 80 to 100 pN.nm of rotary torque and can rotate at approximately 17 revolutions per second. The Montemagno group were able to specifically attach the F_1- ATPase molecule onto a nanostructured post via one end of the F_1- ATPase molecule, and subsequently attach a 750-1400nm long nanopropeller onto the shaft. On addition of the enzyme substrate, ATP, rotation of the propeller could be observed. Powering nanomachines with molecular motors such as these is the focus of one of the research programs of the new Nanobiotechnology Centre, made up of the Cornell-based consortium involving Princeton and Oregon Health Sciences universities, with director Harold G. Craighead. By converting the chemical energy of adenosine triphosphate (ATP) molecules into mechanical energy for biological molecular motors, researchers hope to develop implantable probes, drug-delivery systems and nanomachines that mimic biological functions, such as active valves in microfluid devices.

Given that a number of other enzymes such as kinesin, RNA polymerase, myosin also function as linear motors or rotary motors it is quite conceivable that the advent of nanoscale devices with moving parts, powered by chemical or electrochemical energy is nearer at hand than expected and could hasten the development of nanoelectromechanical systems (NEMS).

It is the integration of ideas from natural systems with inorganic devices that form the exciting hybrid systems and a new class of nanomechanical devices. Nanomachines powered by chemically fueled molecular motors could be coupled to devices with integrated valves, pumps, and sensors that can react to changes in the body and the environment. One can imagine, for instance, miniaturized, self-powered machines that sense and identify oil or chemical pollutants in soils and map their distribution and concentration, or medical implants that sense and dispense drugs or hormones in response to body changes (see IWGN Research Directions 1999, and www.nano.gov for further discussions).

2.6 Nanoscale Building Blocks

Complex biological systems provide models from which to design components that can come together in only one way to form the desired three-dimensional nanoarchitectural system. For example, spider silk is one of the strongest materials known. Its molecular structure is being used to design better composite polymer systems of increasing strength and utility.

A major challenge and opportunity for nanobiosystems is the ability to form such two and three dimensional structures and architectures based on the self-assembly of biologically derived molecules. In terms of structural building blocks two of the materials that are being pursued are amphiphilic compounds (e.g. lipids) and DNA.

As mentioned above amphiphilic compounds can form a large variety of bulk structures in the presence of water, based on the shape of the molecule (Ringsdorf et al, 1988; Liu et al, 1998; Lu et al 2001). The structures that can be formed can be planar sheets, tubules of water, spongelike water-in-oil or oil-in-water phases, or even microtubules of lipid. These structures have precisely defined architectures at the nanometer scale and most importantly the structures self-assemble. This self-assembly property makes it possible to use such structures as templates for the synthesis of non-biological materials, by, for instance, precipitating inorganic materials into the aqueous regions of the lipid/water structures (Soten & Ozin, 1999). The lipids can then be removed by dissolving it in an organic solvent, leaving a precisely templated inorganic skeleton. Potential applications include the synthesis of uniform nanoparticles, nanorods, catalysts, or membranes with defined porosity.

Other biological material such as DNA is being used as smart glue in order to couple nanomaterials such as nanoparticles together (Storhoff & Mirkin, 1999) and to construct geometric shapes such as nanoscale cubes or octahedral (Seeman, 1997). The utility of DNA in this regard stems from the fact that individual DNA oligomers can be produced that will only hybridize with their specific complement and that it is possible to automatically synthesize oligomers with virtually any combination of DNA base sequences.

In work that bridges the simply structural use of DNA and incorporates active functionality the group of Seeman has recently synthesized a hinge made from DNA strands that is capable of reversibly rotating from one form to the other on addition of hexa-aminecobalt (III) chloride to the bathing solution (Seeman, 2001). The ability of DNA to undergo highly controlled and hierarchical assembly makes it ideal for applications in nanobiosystems. For example, DNA has been used to design lattices that readily assemble themselves into predictable, two-dimensional patterns. These arrays are composed of rigid DNA tiles, about 60 nm2, formed by antiparallel strands of DNA linked together by a double-crossover motif analogous to the crossovers that occur in meiosis. The precise pattern and periodicity of the tiles can be modified by altering DNA sequence, allowing the formation of specific lattices with programmable structures and features at a nanometer scale. This approach has the potential to lead to the use of designed DNA crystals as scaffolds for the crystallization of macromolecules, as materials for use as catalysts, as molecular sieves, or as scaffolds for the assembly of molecular electronic components or biochips in DNA-based computers. Similarly, biological-molecule-based scaffolding could take advantage of the unique structural characteristics of RNA molecules, of polypeptide chains, or of the highly specific interactions that occur between DNA and proteins or between RNA and proteins. Devices that are currently in use to control the interactions of DNA on surfaces can have broader applications for controlling nanoassembly. These devices use electric fields to control the movement of particles toward or away from microscopic sites on the device surface. Charged biological molecules (DNA, RNA, protein) and analytes, cells, and other nanoscale or microscale charged particles can be precisely organized.

2.7 Developing Nanobiosystems That Mimic Biological Systems

Although not at the stage where true nanobiosystems exist, research into the development of artificial or mimetic organs is continuing. It is expected that as understanding of biological systems such as organs is developed and as the ability to manipulate materials at the nanoscale progresses, it will be possible to create materials and devices that could function in analogous manner to the real organ. This area could lead in at least two directions. Firstly, there is the mimicking of tissue for non-medical applications such as developing artificial muscles as linear actuators for robotics applications (Bar-Cohen, 2001). Secondly, there is the development of artificial devices to replace or aid damaged tissue such as nerve tissue, artificial retinas, artificial ears (Cochlear, 2001) etc. Such implantable devices will not be easy to produce due to the corrosive nature of the body but will certainly require advances in nanobiosystems.

3. Outlook

This overview of areas of nanobiosystems research is by necessity limited in scope and not meant to be all-inclusive. It is however meant to give an indication of the broad scope of using biology in various nanotechnology applications. In fact examples of using biologically derived principles, structures or molecules can be found that are of relevance to the other discussion papers on nanomaterials, nanooptics or nanoelectronics. As such nanobiosystems research can be viewed as an enabling technology for a number of nanotechnology areas.

Nanobiosystems research has the ability to impact nanotechnology on a number of levels. At its most basic, biology has produced some of the most striking examples of functioning nanotechnology to-date. If nothing else, then this should allow us to use biology as inspiration of what is possible and to confirm that the basic concepts behind nanotechnology are scientifically valid. Research at this level may yield answers into how it is possible to design self-assembling systems that yield complex multi-level structures from relatively simple sub-units. As with all such research the eventual outcomes are difficult to predict.

One possible outcome may however be a change in how the research of nanotechnology is approached. While some researchers argue that only through the use of ever more complex and expensive infrastructure will it be possible to make an impact in nanotechnology, an important lesson from biology may be that it is possible to create complex functional systems and technologies from relatively simple materials. It is also quite likely that even if the initial research is relatively costly, the final process may be quite simple. In this case the supply of the knowledge rather than infrastructure will determine who will be able to utilize the technology.

However, it should also be possible to make use of what nature has already given us in order to develop nanobiosystems that are of technological relevance in the nearer future. Applications such as chemical and bio-sensors are likely to remain some of the first commercial applications. It is, however, more difficult to judge what other technological applications had their initial inspiration derived from biology. For instance the photoelectrochemical cell developed by Graetzel is biomimetic in nature and is an example of nanoscale engineering par excellence but no longer contains any biologically derived material (Graetzel, 2001).

In the longer term technological impact is more difficult to predict but areas such as, environmental protection/remediation, CO_2 reduction, solar energy conversion, biofuel cells, models of artificial organs or tissue, implantable devices and sensors, bioelectronics, new catalysts and separation techniques based on biomembranes, shifts in information processing paradigms, NEMS, materials manufacturing based on biomimetic principles using low temperature, aqueous, environmentally benign principles are all possibilities that are in the fundamental research phase at the moment.

One of the more interesting aspects of the research into nanobiosystems may in fact be the way that research is organized. A large amount of the research carried out in nanotechnology and in nanobiosystems in particular has to be carried out by multidisciplinary research teams involving scientists trained in the biological, chemical and physical sciences. This has involved moving out of the traditional discipline areas and exploring the fringes and intersections between disciplines. Researchers in these areas may find that it is no longer possible to be neatly categorized by departments and that the more successful institution develop systems that help rather than hinder the breakdown of traditional barriers.

Self-assembly, self-diagnosis, self-healing are all processes that the biological world knows how to do very well. To be able to incorporate just a fraction of the knowledge of these processes into materials and devices, holds enormous promise, not just in the new materials and devices that will unfold, but also the radically different manufacturing processes that nature uses – a handful of building blocks, sun, air, water and ambient temperatures. Mimicking these processes would sweep away the prohibitive cost barriers which exist with today's manufacturing methods, and create a truly new paradigm for our future world.

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5.3 Nanoelectronics (Japan)

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Nanoelectronics – Background and Summary

The performance of an information processing system P under von Neumann architecture is expressed as, $P = k\,n\,f$, where n is number of elements in the system and f is operation frequency. Thus, the guiding principle is “the larger the better, and the faster the better”. Therefore, semiconductor technology has been evolved to make computers faster and larger, as indicated in Fig. 1, by “mainframe” and “microprocessor” trends. It takes about five years to improve the performance of computers by one order of magnitude. The progress has been accomplished by down-scaling the transistor size, by following the “scaling principle” proposed by Dennard, et al. (IBM) in 1974. Thus, the transistor size has been shrunk by x0.7 and the integration quadrupled every 3 years, for more than 30 years as shown in Fig. 2. Since the limitation of the present silicon paradigm is foreseen within 10-20 years, which lies somewhere around 20-70 nm, at least two to three orders of magnitude higher performance is required for the computers in the next paradigm of information technology, and advanced high performance devices have been investigated.

This section will cover nanoelectronics, placing emphasis on nanoscale electronic devices, which are expected to supersede the present system. Mainly due to the constraints with the limited space, the topics are focused on the following five items.

1. Nanoscale Silicon ULSI Devices
2. Novel Compound Semiconductor Devices, Including III-V And IV-IV.
3. Novel Functional Nanoelectronics Devices Employing Such Quantity As Spin And Polarity
4. Nanostructure Devices, Including Single Electron Devices And Quantum Dot Devices
5. Novel Nanoscale Devices

Down-scaling of silicon devices will continue at least another decade, because the performance of MOSFETs (metal oxide semiconductor field effect transistors) becomes higher as the dimensions are made smaller, until it reaches the physical limitations, which lie somewhere around 50 nm. Whether nanoscale silicon devices would survive below the limitation depends on the findings for clever solution. The impact of compound semiconductor devices is mainly focused on ultra fast devices, for communication and transmission. Thus, it is also stressed that smaller dimensions are essential for higher performances. Novel functional devices could overcome the limitations of the silicon ULSI devices in 5-10 years of time. Nanostructure devices, such as single electron devices and quantum dot devices, and novel nanoscale devices such as molecular devices would supersede the present paradigm of silicon-based electronics in the future, 10-20 year range. Other electronics related items such as storage, display and communication devices would also be benefited by the advancement of nanotechnology.

1. Nanoscale Silicon ULSI Devices

- Impact of ULSI Technology Progress on Nanotechnology -

(1) Introduction

Current ULSI technology is going toward further miniaturization at a higher speed. The technology roadmap accelerates this speed, and now the world record planar MOSFET has a 20nm gate length, as shown in Fig. 3 by Chau (Intel) in 2001. The gate oxide of the device is thinner than 1nm and the junction depth is several tens of nm. In fact, every device parameter is in the nanometer technology region. More surprisingly, the device shown in Fig. 3 has been fabricated by the conventional ULSI fabrication technology. It is really important to note that the ULSI technology likes a technology continuity of the previous generation rather than a complete revolution. In the nanotechnology field, something revolutionary rather than something new is favored in the starting point, though a resultant achievement is so far the same or poorer switching function, as compared with that of the current conventional semiconductor devices. However, if those new switches are integrated by the conventional LSI integration methodology, the 20nm MOSFET will be superior to any new nanotechnology devices for many applications up to the present. The other example of a conventional but very advanced MOSFET is a vertical device by Hergenrother (Lucent) in 1999, as shown in Fig. 4, in which the epitaxially grown silicon pillar is surrounded by gate electrode. The channel length is not defined by any lithographic technology but by the film thickness control. An MOSFET with a monolayer (sub-nm) thickness channel length can be achieved in principle. Those kinds of advanced silicon LSI technologies will be successfully applicable to devices/materials in nanoelectronics as well.

(2) Technology Issues

Nanotechnology is defined as the direct control of materials and devices at a molecular and atomic scale. As a matter of fact, the silicon oxidation process has been intensively studied in terms of the atomic level at the Si/SiO_2 interface. Now the gate insulator of the advanced MOSFET in Fig. 3 has only a few molecular units of silicon dioxide between gate and channelregions. Furthermore, the atomic layer deposition (ALD) is investigated for growing method of high-dielectric constant materials as the next generation gate dielectrics, where the layer-by-layer film growth is anticipated. The layer-by-layer etching could be also possible. The atomistic simulation has been utilized to evaluate the impurity diffusion or the interface defect formation at the Si/SiO_2. It has also been reported that a sub-10nm gate electrode was delineated by the electron beam lithography in the research level by Ochiai (NEC) in 1999, in conjunction with a molecular level design of the resist material. From those viewpoints, it can be claimed that the process and materials control in the current ULSI technology is already in the nanotechnology region.

(3) Cost Issues

There are a number of hardships for the current and future ULSI technology. A big concern of small devices in the ULSI is how to keep each property robust, reliable, homogeneous and uniform in terms of the integrated circuit. On the other hand, a real challenge in the ULSI technology is to keep the actual chip cost low, including everything from purchasing raw materials to selling commercial products. It is worried that the economical challenge might stop the simple miniaturization way of the ULSI roadmap from now. In those cases, can the nanotechnology resolve those challenges encountered in the current ULSI technology? Before considering the possibility, it is necessary to clarify how the nanotechnology is different from such advanced fabrication technology in ULSI. One of the big differences is between the bottom-up and top-down way for the achievement of a product's functionality. In the top-down scenario, it is now of a great concern that the finer lithography will make the cost/function in a chip much higher with the progress of technology node, though the reduction of the cost/bit in memory and the cost/switch in logic have been driving forces of the device miniaturization in ULSI systems. On the other hand, in the bottom-up scenario, it is expected that a complex chemistry such as a molecule design or self-organization can be utilized to make a functional building block in principle. An issue is whether the uniformity or homogeneity of a system can be guaranteed by using the bottom-up technology. If not, the replacement of the current semiconductor electronics with nanoelectronics will not be practical, as long as the present system architecture is employed. If yes, the nanoelectronics will be greatly appreciated. Electron or atom manipulation seems very attractive in terms of the miniaturization, but it seems tremendously difficult to be robust or highly reliable in terms of the integrated circuits. Typically, a statistical fluctuation control is essentially in doubt.

(4) Application Issues

From the application point of view, a value-added point is not the fabrication method but the system performance or functionality. In the ULSI system, a large number of transistors make a single chip very functional. The most advanced MPU chip has more than 1G (10^9) transistors in a chip and all of them are basically synchronized. On the other hand, in nanoelectronics, the functional element or block might be much more versatile, but the system architecture for communicating between the block elements may have been very poorly considered. This would be a real roadblock in the case of integrating the nano-scale building blocks. In fact, this issue is also a big problem even in the current ULSI system in terms of the speed and the power consumption in a chip. The nanoelectronics has a same problem as long as the same system architecture is employed, though a number of techniques employed for the ULSI fabrication process can be used for other nanotechnology fields as MEMS, DNA chips, healthcare devices, etc, in making nm or μm designed structures.

(5) System Issues

As shown in Fig. 5, there is a kind of technology hierarchy from system to fabrication process/materials in the ULSI system development. Each section has a proper specialty or literacy, and a technical community. On the other hand, there is no counterpart in the nanotechnology development. This would be good for the nanoelectronics, because a fixed hierarchy has been efficient for developing the existing technology, but makes further progress too rigid and conservative. The nanoelectronics should be developed in an interdisciplinary or a chaotic way. Nonetheless, the nanometer fabrication technology is certainly useful and powerful for realizing the nanoelectronics. Thus, there will be two ways that the nanoelectronics will go as an advanced electronics over the current CMOS LSIs. One is to make the current dry LSI chips more human-friendly and more versatile by adding the nanoelectronics to the existing semiconductor ULSI systems. By doing so, a drastic fusion is anticipated between different technologies such as the semiconductor technology and the biotechnology, or between different business categories such as the semiconductor and the medicine industries. As a matter of fact, it is expected that the SoC (System on a Chip) will include various materials, device and components as well as semiconductor devices. If the cost/performance is admitted and the process interference each other is quite low, any systems can be implemented into the conventional ULSI systems. This will open a way for the nanoelectronics to take an active part in the future information technology and business, because a variety of material will be able to enter the SoC business and a new design of the system architecture will be required. A graceful assimilation of both top-down with bottom–up technologies will be beneficial to not only technology but also to the world economy in the future ubiquitous information society. The other way is to utilize a new architecture, though no one knows right now, for making the most of functional blocks in the nanoelectronics. In that case, it is necessary that a small number of functional blocks should be superior to a highly integrated CMOS LSI system. Otherwise, it will be no hope for nanoelectronics to survive on a main stream of the electronics.

A final remark is on the impact of nanotechnology on the ULSI technology. As mentioned repeatedly in a relationship between ULSI technology and nanotechnology, nanotechnology will increase the spectrum of ULSI technology application from two points. One is that the nanotechnology makes the current ULSI more applicable to versatile products. The other point is that the nanoelectronics might achieve new functionality or performance, which will not be realized by the current ULSI systems. Lastly, a helpful and really beneficial point of the nanometer scale metrology should be addressed from a viewpoint of constructing the technology standards for the present.

(6) Conclusion On Nanoscale Silicon ULSI Devices

1) The current semiconductor fabrication technology is now in the nanometer-controlled region.
2) The nanotechnology should learn the current ULSI technology more but should not mimic it. The functional blocks in the nanoelectronics will be built up by using both the top-down and the bottom-up technologies complementarily and cooperatively.
3) It will be important how to harmonize the functional blocks in the nanoelectronics with the current semiconductor devices.
4) The application filed of nanoelectronics will be tremendously big in the ubiquitous IT society, as versatile human friendly hardware.
5) Both R&D of top-down and bottom-up nanotechnologies will be needed to build up a big market and scientific field.
6) The nanometer/sub-nanometer scale metrology is fundamentally useful for characterizing the ULSI technology standards.

2. Novel Compound Semiconductor Devices, Including III-V And IV-IV.

Among the compound semiconductor devices, GaAs/AlGaAs heterostructures were used at the early stage of the development of the high electron mobility transistors (HEMT), which was invented by Mimura et al. (Fujitsu) in 1980. In the

GaAs/AlGaAs HEMT devices, the achieved electron mobility was around 5,000 cm^2V/s. Recently, however, the InP/InGaAs HEMT devices were developed, where the electron mobility over 10,000cm2V/s was realized and the cut off frequency (f_T) exceeded 350GHz in the HEMT with the shorter gate than 30nm reported by Suemitsu et al. (NTT) 1998. In the year 2000, f_T of 362 GHz was achieved by the joint research group of Fujitsu Ltd., Communications Research Laboratory and Osaka University. In addition, the monolithic microwave integrated circuit (MMIC) with a gate length of 150 nm was demonstrated by Fujitsu in 2000 for the automobile radar system operating at 76 GHz. Technological key issues are (1) to form the heterostructures with good quality by high electron mobility materials, (2) to shorten the gate length for higher speed operation, and (3) to develop a new system design and packaging method in order to reduce the stray capacitance, which becomes very dominant in the high frequency region.

On the other hand, heterojunction bipolar transistor (HBT) devices were also developed, by using both lattice matching materials like InGaP/GaAs and mismatching materials like InGaAsN/GaAs. Especially in the InGaP/GaAs HBT with a very thin base layer (~15nm), f_T over 150GHz was achieved by Oka et al. (Hitachi) in 1998. These devices can be applied to power amplifiers of the optical communication system, the cellar phone system, the automobile radar system, and so on.

By using SiGe materials for the HBT devices, f_T around 100GHz was obtained with a thin base layers of 50~100nm in thickness. Especially, f_T over 150GHz was reported by Oda et al. (Hitachi) in 1998. An advantage of the SiGe devices is compatibility with the production processes of the conventional Si technologies, leading to the possibility of integrating SiGe HBT devices and Si CMOS circuits on a same chip. Technological issues are to reduce the number of defects in SiGe layers and to obtain a highly doped base region of Ge by the epitaxial growth.

Although the devices should be miniaturized more and more for the high-speed operation, we cannot decrease the operation voltage proportional to the device size because the signal level must be higher than the thermal noise. As a result, the electric field in the device becomes very high in the nanoscale devices. Therefore, high voltage tolerance is required for the future device materials. From this point of view, the wide band gap materials like GaN, which have attracted great attention as a material for the short wavelength optical devices, are very promising for high-speed electronic devices as well. However, since we don't have suitable substrates for the GaN epitaxial growth at this stage, the sapphire substrates, whose lattice constant differs very much from that of GaN, are unwillingly used with the low temperature grown buffer layers to reduce dislocations, otherwise very expensive SiC substrates should be used. To realize the GaN electronic devices, it is very important to find suitable substrates for improving the quality of the epitaxially grown layers and to reduce the cost for the substrates.

3. Novel Functional Nanoelectronics Devices Employing Such Quantity As Spin And Polarity

As modern portable electronic devices such as mobile phones and notebook computers become more and more popular, there is a confirmed increase in the demand for nonvolatile random access memories. FeRAM (ferroelectric RAM) and MRAM (magneto-resistive RAM) are the most promising candidates for this application.

(1) FeRAM (ferroelectric random access memory)

The ideas of ferroelectric memories were first presented from Bell Laboratory in 1955 as a series of patents, in which a prototype of the current ferroelectric-gate FET (field effect transistor) is also included. However, formation of a good ferroelectric-semiconductor interface was very difficult, because of interdiffusion of constituent elements of the film and substrate and no commercially available device has been fabricated.

Meanwhile, a new type of ferroelectric memory, in which each unit cell is composed of ferroelectric capacitor(s) and switching MOS (metal-oxide-semiconductor) transistor(s) and the stored data are read-out by detecting the polarization reversal current, was proposed in late 1980's and rapidly developed in the following years. Now, research and development of this type of FeRAM are being conducted actively in many semiconductor companies. FeRAMs with capacities up to 256 kbits have already been mass-produced for smart tag and computer game applications. The most important feature of FeRAM is that power consumption is lowest among various random access memories. Furthermore, if FeRAMs with several hundreds megabits are produced in the future, they may replace all memories such as DRAM (dynamic RAM), E^2PROM (electrically erasable programmable read only memory), and flash memory, except for high speed SRAM (static RAM).

Recently, studies on the ferroelectric-gate FET and related devices have become popular again. These FET-type devices have a feature that the stored data can be read-out non-destructively and thus high-speed operation can be expected. Fig. 6 shows comparison of the cell structure between 1T1C-type FeRAM (a) and 1T-type FeRAM (b), which is composed of a single ferroelectric-gate FET. Ferroelectric-gate FETs can also be implemented in a logic circuit and compose a reconfigurable LSI, in which the logic function can be changed in real time.

(2) MRAM (magneto-resistive random access memory)

MRAM has an advantage that the access time is as fast as that of SRAM. In the original idea of MRAM, GMR (giant magneto-resistance) phenomenon was used. However, the resistance change in this type of cell was as small as a few % and it was difficult to integrate the GMR cells in a large scale. Recently, TMR (tunnel magneto-resistance) phenomenon was discovered in a junction structure with the upper and lower ferromagnetic materials, in which the resistance change was as large as several tens of %. In order to write a datum “1” or “0” in this cell, DC current is flown to produce magnetic field and to direct the magnetization of the upper ferromagnetic material, while the magnetization direction of the lower material is kept constant during the write operation. In the readout operation, such a phenomenon that the current through the tunnel junction is much different between the parallel and anti-parallel conditions of the magnetization directions of the ferromagnetics is used.

Fast readout operation of 1 kbit MRAM has already been demonstrated. Fabrication and normal operation of 256 kbit memory has also been demonstrated. The future issue of MRAM is how to reduce the power consumption, which is usually the most important characteristics in current-driven devices.

4. Nanostructure Devices, Including Single Electron Devices And Quantum Dot Devices

Nanoscale semiconductor structures utilize various phenomena based on new physics that are not observed in large-scale structures. Application of these new phenomena to electron devices such as transistors and memories is one of the most important topics in the field of nanoelectronics, because the new devices would break the limit of the conventional VLSI devices. The typical phenomena in nanostructures are the quantum effects that are caused by the wave nature of electron, and the single electron charging effects that are caused by the discreteness nature of electrons. The devices that have been already developed include resonant tunneling device that utilizes the quantum effect, three terminal surface junction tunneling devices that utilizes the Esaki tunnel diode, and single electron transistor that makes use of the single-electron charging effect.

One of the disadvantages in these types of devices is that they operate only at very low temperature such as the liquid helium temperature (4.2 K). Theoretically, the operating temperature will increase by miniaturizing the device size. Although the research of these devices first started using III-V semiconductors such as GaAs, devices using Si have also reported recently. Generally, silicon nanodevices can operate at higher temperature than III-V semiconductor devices because silicon structures can be miniaturized by thermal oxidation. Some silicon nanodevices that operate at room temperature have also been reported. The typical characteristics of these new nanodevices are negative transconductance and drain conductance, which are not observed in conventional semiconductor devices such as MOSFETs. New circuits and architectures that utilize these characteristics have been also studied. As typical examples of nanodevices, characteristics of a single electron transistor (SET) and a silicon dot memory are described in the following sections.

(1) Single Electron Transistor (SET)

Fig. 7 shows a schematic structure of a SET. The operation principle is as follows. A quantum dot is connected to source and drain via tunnel junctions, and the potential of the dot is controlled by the gate electrode, which is separated from the quantum dot by a gate insulator. When an electron is injected to the quantum dot from source by tunneling, the potential of the dot is raised by the Coulomb potential of the electron. Therefore, the second electron cannot tunnel to the dot by the Coulomb repulsion, and the current does not flow. This phenomenon is called “Coulomb blockade”. Since the dot potential is controlled by the gate, the drain current oscillates as a function of the gate voltage as shown in the figure.

The SET characteristics were reported by many research groups in early 1990’s, but the materials were mainly III-V semiconductors or metals, and they operated only at very low temperatures. Takahashi et al. (NTT) first reported a SET that operates at room temperature in 1994. The material was silicon, which enabled microminiaturization of the quantum dot. Since then, the silicon SET has become one of the most promising devices for future low power VLSIs. Integration of SET has been reported. Ono et al. (NTT) demonstrated the arithmetic operation using silicon single-electron transistors in 2000. Uchida et al. (Toshiba) reported a room temperature multifunctional SET logic in 2000.

(2) Nanoscale Memory Devices

The memory device is also a good target of nanoscale semiconductor devices. Yano et al. (Hitachi) first reported single-electron memory using extremely thin polysilicon channel in 1993. A quantum dot is naturally formed in polysilicon film and acts as a storage node. The storage node is so small that the number of electron in the node is exactly controlled by the Coulomb blockade. Tiwari et al. (IBM) also proposed a memory device that utilizes silicon floating dots in 1995. Fig. 8 shows a schematic of the memory device and hysteresis current-voltage (I-V) characteristics. The floating dots act as storage nodes, and the device operates as a memory device. This structure is the modification of the present FLASH memory structure, and fast write/erase and low-voltage operation is expected since the storage node is composed of silicon quantum dots instead of one polysilicon floating gate.

5. Novel Nanoscale Devices

This section mainly deals with novel nanoscale devices, placing emphasis on nanoscale organic molecular devices which include thin film molecular devices, such as organic electro-luminescence (OEL) devices and thin film organic field effect (TFOF) devices, nanotube-based devices and “single molecule electronics” devices, which are anticipated to supersede the current “solid state electronics” based devices in the future. The first commercialized molecular device is the OEL device, which broke down the superstition that organic materials cannot be used in active electronic devices. Of course, the trend for practical active organic electronic device development was created by the Novel Prize discovery of conducting conjugated molecules by Shirakawa, et al. in 1977.

(1) Organic Electro-luminescence (OEL) Devices

Light emission from organic single crystal was first observed by J. Pope et al. in 1963, and enormous works have been conducted to explore good light emitting organic molecules, and finally, high efficiency OEL device, with a hetero structure was demonstrated by C. W. Tang (Kodak) et al. in 1987 using nanometer thick amorphous multilayers. Since then, lots of works have been accomplished to improve the efficiency and lifetime of OEL devices using conjugated oligomers (low molecular weight) or polymers (high molecular weight). Now, most of the companies in audio-visual equipments field are trying to bring OEL products into market, the first one being Pioneer Co. Ltd. of Japan in 2000 using conjugated oligomers. Current direction of product development would be three-fold, high efficiency active matrix OEL display to replace LCD, high efficiency white color illuminating devices to replace fluorescent lump, and flexible, low power low cost display for portable use. Currently, Japan is the leading country in the mass-production regime followed by Korea, Taiwan, U.S.A. and other countries.

(2) Thin Film Organic Field Effect (TFOF) Devices

Thin film organic field effect (TFOF) characteristics were first demonstrated by F. Ebisawa (NTT), et al. in 1983 and K. Kudo (Chiba U.), et al. in 1984 both from Japan. Since then, lots of improvements were demonstrated in carrier mobility by synthesizing appropriate molecules and also in device structures, and field effect mobility almost reached 1 cm2/V s. It is anticipated that TFOF transistors would be replacing amorphous silicon (a-Si) transistors in active matrix display for lower cost. Combined with liquid crystal displays and organic EL devices, it would be made possible to fabricate displays with almost all organic materials, which would lead to ecology-friendly displays. Small scale circuit using TFOF transistor has been demonstrated by B. Crone (Lucent) et al. in 2000, operating at 1 kHz, which would be high enough for the above purposes. Mass production of TFOF transistors/integrated circuits would be accomplished very soon in the display area.

(3) Nanotube Devices

Carbon nanotube was discovered by S. Iijima (NEC) in 1991, and lots of works have been conducted to investigate the properties as well as to understand the physics behind them. Quantum transport and nanotube field effect transistor (FET) characteristics were both first demonstrated by C. Dekker (Delft U.) et al. in 1997 and 2000, respectively. In addition, a "random access memory" based on nanotubes was proposed by C. M. Lieber (Harvard) in 2000. However, the characteristics of these devices were far behind those of silicon FETs. The major reason is that the resistances associated with the nanotube device structures, including contact resistances with metal leads, are several orders of magnitude higher than those of silicon devices, which would hinder the possible superior characteristics of nanotube devices. Very attractive quantum electronics and spintronics application of carbon nanotubes were demonstrated in 1999, about 100 nm long spin coherence by K. Tsukagoshi (Hitachi) and magneto-resistance effect (MR) by R. Saito (Electro Communication U.). The first commercialization of nanotube device would be the field emitter display, and commercial products are already demonstrated by Ise Denshi, Japan, followed by several Japanese and Korean companies.

(4) Atom Scale/Single Molecule Devices

The first single molecule device concept, "molecular rectifier", was theoretically proposed by A. Aviram (IBM) et al. in 1974, followed by an experimental demonstration of single molecule photodiode by M. Fujihira (Tokyo Institute of Technology) et al. in 1975. Then "molecular electronic device" concept was proposed by F. Carter (NRL) in 1980, which attracted attentions of academia, however, mainly due to inaccessibility to single molecule and poor switching characteristics of the proposed "devices", the interest rapidly faded away. In the latter half of 1990s, the serious limitations of semiconductor scaling were made clear for higher performance information technologies, the "single molecule device" concept was revisited and several advanced devices were proposed. This time, due to rapid progress in such technologies as scanning probe, electron beam nanofabrication and computer simulation, various experimental demonstrations as well as theoretical predictions were made. They include, "single molecule resistance measurements" by P. Weiss (Penn State) in 1996, "resonant tunneling" measurements by M. Reed (Yale) in 1998, three terminal device proposal by J. Tour (Rice U.) in 1997 and Y. Wada (Hitachi) in 1993. In addition, coherent conduction of electron within single molecule is theoretically predicted M. Tsukada (U. Tokyo) in 1999. Other possible single molecule device proposals include, light emitting device and sensor device by Y. Wada (Hitachi) in 1994, single molecule storage device by K. Matsushige (Kyoto U.) et al. in 1995. The performances of these devices would far exceed those of the present devices by several orders of magnitude, and would fulfill the requirements of advanced information technologies in the future. Thus, "single molecule electronics" would be replacing the current "solid state electronics" in 10-20 years of time.

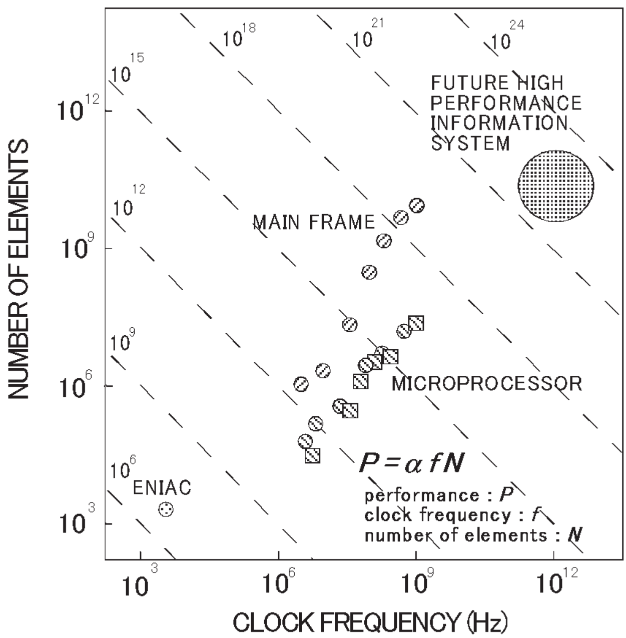

Fig. 1 Number of elements and clock frequency relationship of historical information processing systems.

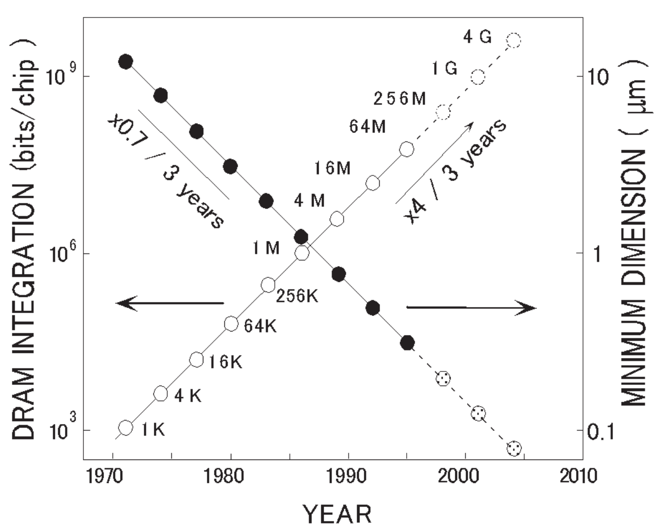

Fig. 2 Trend curve of silicon ULSIs: the minimum dimension has been shrunk by a factor of 0.7 while the integration quadrupled every 3 years for more than 30 years.

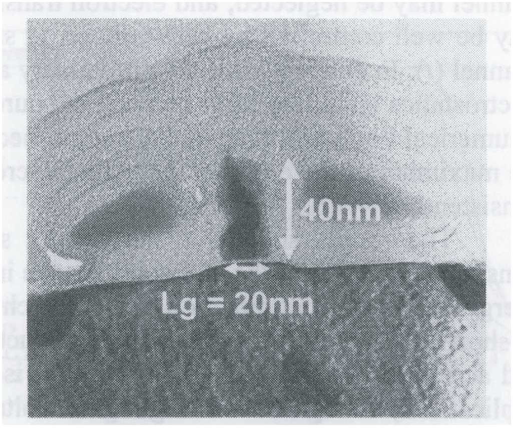

Fig. 3 TEM image of Lg=20nm MOSFET. (R. Chau, Abst. Si-Nanoelectronics Workshop, p. 2, (2001).

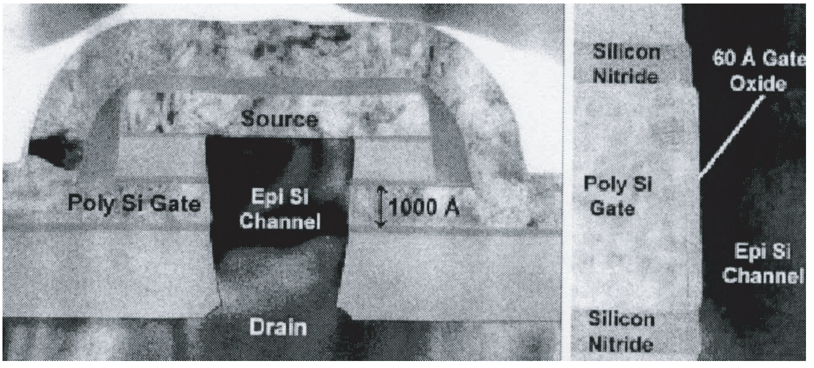

Fig. 4 VRG(Vertical Replacement Gate) MOSFET. (J. M. Hergenrother et al., Tech. Dig. IEDM'99, p. 75, (1999). (© 1999 IEEE).

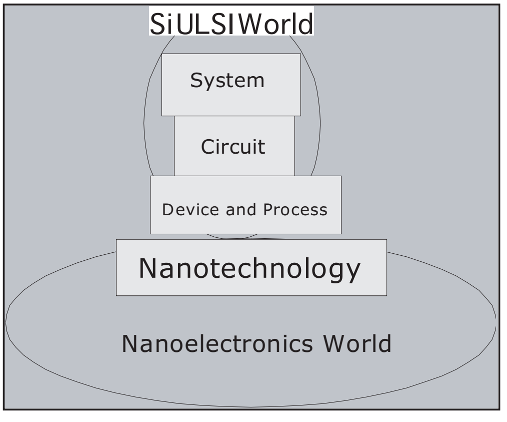

Fig. 5 A technology hierarchy. for ULSIs. The most advanced device size of ULSI world is in a nanotechnology region.

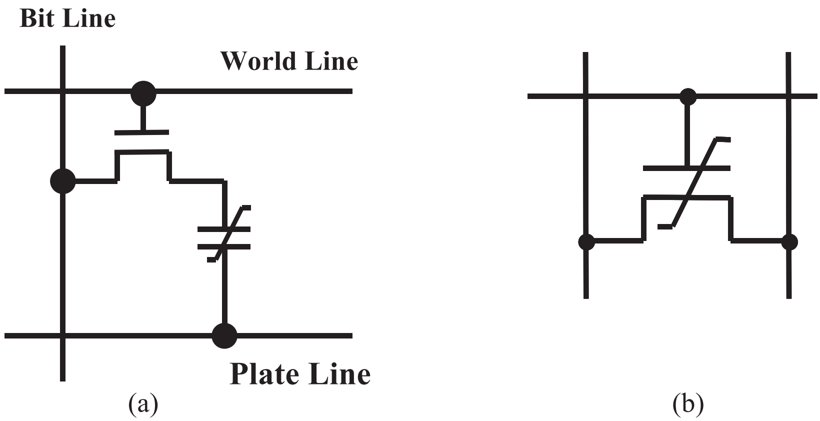

Fig. 6 Classification of FeRAM. (a) 1T1C-type (b) 1T-type.

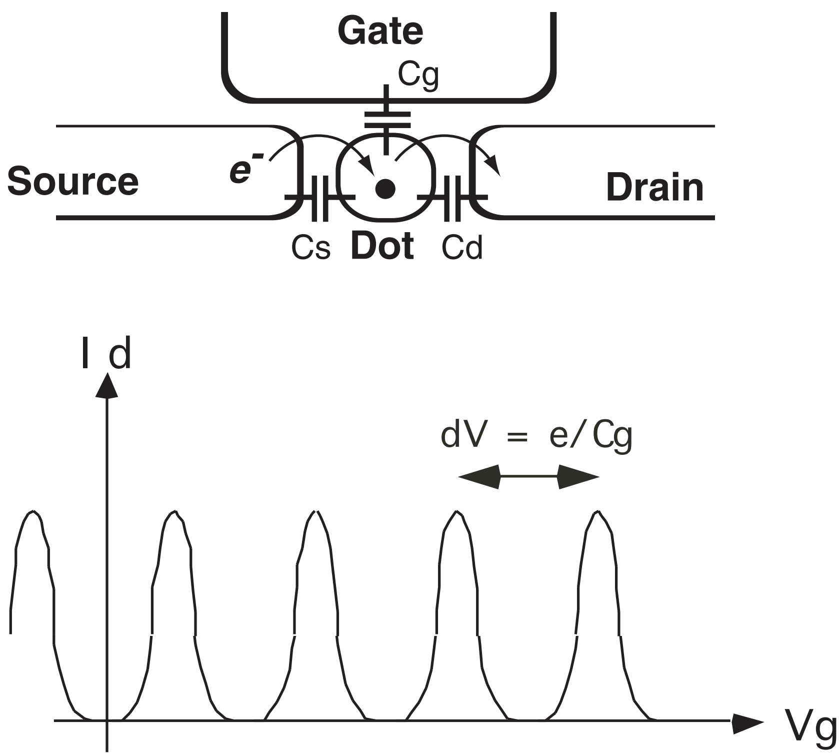

Fig. 7 Schematics of a single-electron transistor and Ids-Vds characteristics.

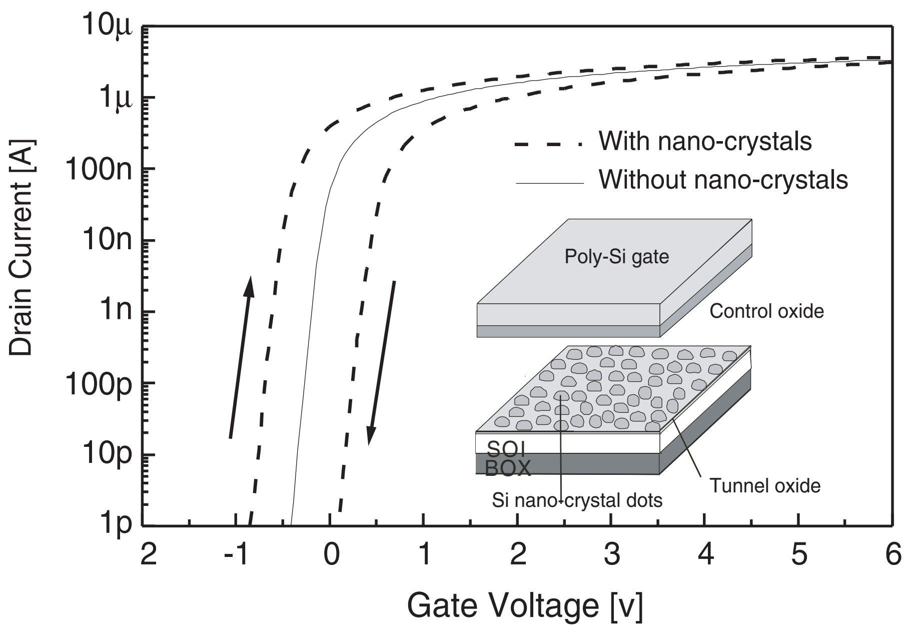

Fig. 8 Characteristics of silicon quantum dot memory. The inset shows a schematic of device structure.

5.4 Nanostructured Materials (Chinese Taipei)

Prepared by Science and Technology Information Center (STIC), National Science Council, Chinese Taipei.

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This position paper has been prepared as a document base for the APEC Technology Foresight Nanotechnology Project by the Science and Technology Information Center, National Science Council (STIC-NSC), Chinese Taipei. The area of Nanostructured Materials was assigned to Chinese Taipei, which is a co-sponsoring economy of the APEC Technology Foresight Nanotechnology Project. The report follows the format suggested by the Foresight Nanotechnology Project and is divided into five sections: background and definitions, contributory disciplines, current status of nanostructured materials, emerging opportunities and potential applications for nanostructured materials and nanomeasurement and standards. An appendix containing some relevant data is also attached.

The objective of this paper is to provide detailed and updated information on nanostructured materials and also highlight the general issues concerning the development of these materials.

In the process, the paper identifies the main characteristics of nanostructured materials both as a rapidly growing research field and as a platform for revolutionizing the manufacturing sector. Challenges, opportunities and potential applications of nanostructured materials are also discussed in detail. Finally, the issue of establishing international standards and its implications in the manufacture of nanostructured materials is described.

1. Background and Definitions

The cover page of the 1997's July-August issue of the American Scientist showed an incredible "space elevator" tethering a geostationary satellite to earth. This science-fiction idea popularized by Arthur A. Charles in his 1978's novel *Fountain of Paradise* was simply not possible because no material ever developed had anything near the required strength for such a tether. The tensile strength required for this space elevator, 62.5 GPa[1] , would make the best stainless steel collapse like a spider thread. This futuristic tale was used to introduce a promising nanostructured material, the carbon nanotube, which in the form of SWNT has a tensile strength of 200 GPa, more than 100 times that of steel! Carbon nanotubes,

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[1] Giga Pascal

however, are not only extremely strong and stiff but also behave like metals and semiconductors, and offer excellent thermal conductivity.

In April of this year, it was reported that the solution to California's energy crisis could come from a revolutionary co-polymer based plastic brick developed by Korean scientists called "light bricks".[2] These "light bricks", which are the result of cutting edge manufacturing using nanomaterials has the potential to save incredible amount of energy and are also environmentally friendly. The estimated US $4 billion/ years saving in electricity motivated a top-level meeting between US energy officials and the company manufacturing the bricks.

Similarly, other nanostructured materials are expected to create radical changes in diverse fields. From electronics, by providing materials for the next-generation of computer chips; to energy technologies, where novel materials may have a critical impact on new types of solar cells and rechargeable batteries. Nanostructured materials have a tremendous potential to reinvigorate traditional sectors, revolutionize high tech industries and create new knowledge-intensive firms. For products in industries such as coatings, steel, medicine, optics, electronics and energy, nanostructured materials will provide a new set of possibilities for fundamentally improving the performance, applicability and lowering manufacturing costs.

The development of nanostructured materials is a research-intensive field. Although, the first research on nanostructured materials started some 20 years ago, it has received widespread interest only since the 1990s. While many aspects of the field existed before, the science and technology of nanostructured materials has only become definable during the past decade. Recently, it has grown to be a coherent field of endeavor through the confluence of three crucial technological streams:

- new and improved control of the size and manipulation of nanoscale building blocks;
- new and improved characterization (e.g., spatial resolution, chemical sensitivity) of materials at the nanoscale;
- new and improved understanding of the relationships between nanostructure and their properties; and how these can be engineered.

The vast commercial potential of nanostructured materials has attracted the interest of the industry, academic institutions and government laboratories.

The research and development in nanotechnology has become a national task force for countries such as the US and Japan, and nanostructured materials stand out as one of the key areas in many national programs. It is believed that by the first decade of the 21st century, nanotechnology will be a multibillion-dollar industry and nanostructured materials will share a high percentage of this market. In fact, as Table 1 shows that only the 1996's global market value for nanostructured materials was already over US $9 billion and it is expected that its value will exceed US $20 billion by the year 2001. Ceramics and coatings would represent more than 80% of this global market.

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[2] See "Light Bricks" to save Electricity http://www.scienceagogo.com/news/20010230190630data_trunc_sys.shtml

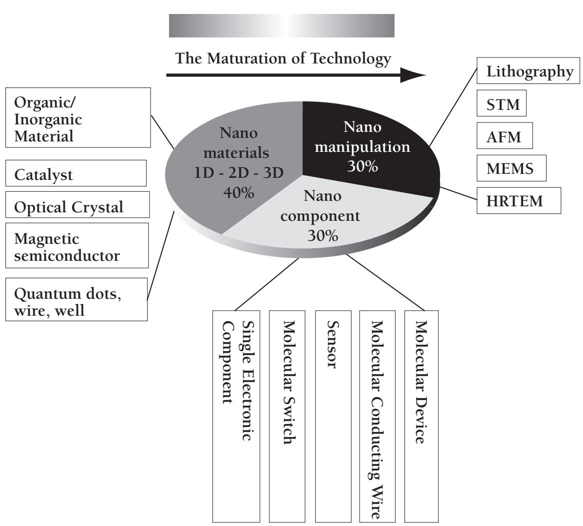
As detailed in section 4, the possible applications of nanostructured materials are endless. While scientists are only beginning to grasp many of the functionalities of nanostructuring materials, its incredible potential for changing radically the way in which materials are created and manufactured is already quite clear.[3] Figure 1 shows some of the potential applications.

Table 1. Expected global markets for nanostructured materials (US $million)

Year	1996	2001
Ceramics	5,912	8,811
Coatings	2,103	8,811
Pigments	568	1,137
Solar cells	454	795
Sunburn lotion	227	284
Polymer composites	-	1,023
Total	**9,266**	**20,864**

Source: Ten Wolde (1998) Nanotechnology: towards a molecular construction kit. Original data from BMBF (German Ministry for education, science and technology) Innovatiosschub aus den Nanokosmos, report BMBF/624, Analge, 1, 19 December, Germany.

Fig. 1 Nanotechnologies: Areas of application and level of maturity.



Source: Data provided by Prof. Chung-Yuan Mou, Department of Chemistry, National Taiwan University.

[3] Richard W. Siegel (1998). Chap 1. Nanostructure Science and Technology. A world wide study. WTEC, Loyola College, Maryland.

1.1 Key Definitions

A number of key terms commonly used in the science and technology of nanostructures should be clearly defined to facilitate discussion. These definitions tell us much about the fundamental differences between nano and micro structured materials.

Nanostructured materials

The term nanostructured materials usually refers to "solids or thin film in which either the fundamental building block or the microscopic order are nanostructured". The much finer grain size can produce denser materials with greatly improved mechanical properties, nearly three times better than the microstructured version.[4] Materials often behave very differently when they are nanostructured. For example, aerospace and defense will benefit from much higher performance, e.g. light weight, high strength nano-composite materials and ceramics. Stronger, improved life hip prostheses is just one of many benefits offered in the biomedical field.

A more general concept of nanostructured materials, taken from the Handbook of Nano-structured Materials and Nanotechnology, starts from the definition of nanostructures as particles, grains, functional structures and devices with dimensions in the 1-100 nanometer range. Nanostructures include quantum dots, quantum wires, grains, particles, nanotubes, nanorods, nanofibers, nanofoams, nanocrystals, nanoprecision self-assemblies and thin films, metals, intermetallics, semiconductors, minerals, ferroelectrics, dielectrics, composites, alloys, blends, organics, organo-minerals, biomaterials, biomolecules, oligomers, polymers, functional structures and devices.

What is novel about these materials is that the fundamental physical and biological properties are altered dramatically as the size of their constituent particles becomes near to the nanosize. In other words, when a material is nanostructured or is synthesized in such a way that its fundamental components are particles or grains with nano dimensions, it offers an unique and entirely different range of properties from chemical reactivity to electrical, optical and mechanical behavior.

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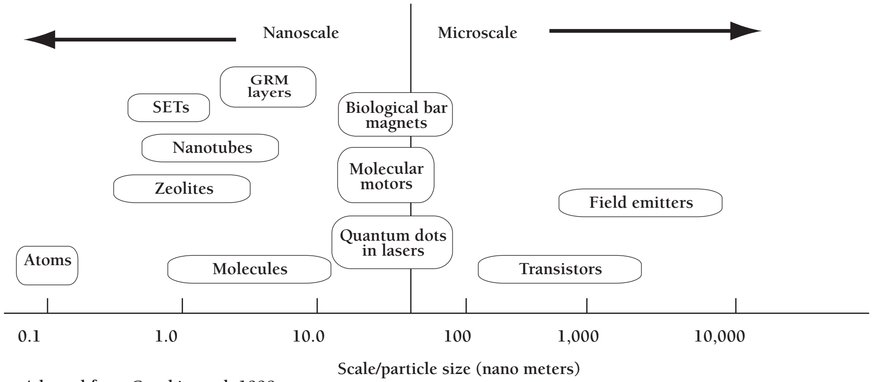
4 http://www.cordis.lu/growth/calls/top-3.32.htm

Fig. 2 Scale of some nano-scale products and applications.



Adapted from Gorokin et al, 1998

However, these properties depend critically on the reproducibility of the size of identical nano particles or grains[5] ; this is one of the major challenges facing the synthesis of nanostructured materials.

Factors determining the properties of nanostructured materials

Research on nanostructured materials is driven by the idea that the ability to manipulate the building blocks at nano scale can produce materials with enhanced properties at the macroscale. Generally, there are two type of effects induced by nano-scale. Firstly, the size effect, mainly the quantum size effects. Here, the fact that a series of discrete electronic levels replace the normal bulk electronic structure has important implications for the physical properties that the material may exhibit. Secondly, the *surface effect;* the increased specific surface in systems which structure is based on nanoparticles or grains may play a fundamental role affecting radically some physical and chemical properties. This is the case of chemical reactivity; the implications are obvious for fields such as heterogeneous catalysis.

Goncalves et al (2000) distinguished four common microstructural features that determine the properties of nanostructured materials: (i) fine grain distribution; (ii) chemical composition of the constituent phases; (iii) the presence of interfaces, more specifically, grain boundaries, heterophase interfaces, or the free surface; (iv) interaction between the three constituent domains. The presence and interplay of these four features mainly determine the distinctive properties of nanostructured materials. Some of these distinctive properties are listed as follows:

Mechanical properties

- Lower elastic moduli than conventional microstructured materials by as much as 30%~50%;

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5 The size variances must be reduced from 20% to less than 5% to achieve a measurable enhancement of the quantum effect, Murray et al (1993)

- Increased hardness and strength—hardness values for nano-crystalline metals are 2 to 7 times higher than those of conventional grain-sized metals;
- Ductility the superplastic phenomena were observed for ceramics with nanoscale grain size;

Thermal properties

- Melting point decreasing significantly, for example, the melting point for gold with conventional grain size is 1064 C. However, the melting point for gold with nanoscale grain size is decreased 27 C.

Optical properties

- The unusual linear properties of some nanostructured materials, such as Au-colloids, Ag-colloids, are ascribed to surface plasmon resonance of the conducting electron induced by light, which dramatically increases the local fields.

Electrical properties

Several electrical properties of nanostructured materials have been investigated:

- Varistors with non-linear dependence of electrical conductivity on electric field.
- Cermets with non-linear behaviors due to single electron tunneling currents over Coulomb barriers between adjacent clusters.

Magnetic properties

- Giant Magneto-Resistance (GMR) was observed in 10 nm thick multilayers of Fe separated by a suitable thickness of non-magnetic layers of Cr.

Synthesis and Assembly of nanostructured materials

Synthesis and assembly of nanostructured materials include sourcing of the necessary precursors from liquid, solid or gas phases and the use of chemical, physical (or other) deposition techniques to deposit atoms and molecules in the suitable substrates. Thus, chemical reactivity or physical compaction is used to integrate nanostructure building blocks to form the final structure.

Goncalves *et. al* (2000, p.2) summarize four methods that are commonly used in the synthesis and assembly of nanostructured materials.

- Production of isolated, ultrafine crystallites with uncontaminated free surfaces, followed by a consolidation process at a range of different temperatures. The isolation of nanostructured materials is done by methods such as precipitation from original solutions, inert-gas condensation and decomposition of the chemical precursors.

- Deposition of atoms and molecules in suitable substrates by chemical or physical vapor deposition.
- The introduction of defects in a perfect crystal. New types of nano-structured materials can be synthesized by producing defects such as dislocations or grain boundaries. Ball milling and other high-energy techniques have been used for producing these deformations.
- The crystallization or precipitation of unstable states of condensed matter such as supersaturated solid or liquid solutions.

The concepts of top-down and bottom-up syntheses have been used to describe how the building blocks are assembled. Top-down synthesis refers to the approach that begins with an appropriate starting material (or substrate) that is then çsculptedé to achieve the desired functionality. This method is quite similar to that used by the semiconductor industry in fabricating devices out of an substrate by the methods of electron beam lithography and reactive ion etching (Hu and Shaw, 1998). Another typical top-down approach is the çball-millingé technique, which involves the formation of nanostructure building blocks via controlled, mechanical erosion of the bulk starting substance (Koch, 1989). Those nano building blocks are then subsequently assembled into a new bulk material.

In very simple terms, “bottom-up” based nanostructuring means building larger objects from smaller building blocks. Contrary to the top-down approach, çbottom-upé synthesis involves the initial formation of the nanostructured building blocks and then their assembly into the final material. An example of this approach is the formation of powder components through aerosol techniques (Wu *et al.*, 1993) and then the compaction of the components into the final material. Bottom-up approaches usually take place (and are inspired by) chemical and biological systems. Recently, there has been a considerable shift in the research of nanostructured materials assembly from top-down to bottom-up approaches because the later seems to be offering more potential for future applications and development. Its potential impact on food production, medicine, environment protection and even in energy production might be enormous (Mertz and Ellis, 1999, p154).

Self-assembly is one of the most bottom-up ways of creating nano-structures. Self-assembly consists of the spontaneous integration of the components bouncing in a solution, gas phase or interface until a stable structure of minimal energy is reached. Components in self-assembled structures find their appropriate location based on their structural properties (or chemical properties in the case of atomic or molecular self-assembly), with an energy difference between the starting and finished state being the driving force. Self-assembly is by no means limited to molecules of nanoscale and can be carried out on just about any scale, making it a powerful bottom-up method for nanotechnology.

Common enabling technologies

The development of nanostructure science and technology depends strongly on the advancement of a number of enabling technologies. The measurement and control of the phenomena that occur at the nanoscale as well as the identification and characterization of the resulting materials and their properties are only possible if advanced equipment, techniques and modeling and simulation methods are available. Important advances in nanostructuring materials is very much attributable to sophisticated measuring technologies; from transmission electron microscopy that helped earlier researchers to relate properties of nanostructures, to the recent scanning probe and tip technologies which have had a tremendous impact on the synthesis and assembly of nanostructured materials. Similarly, modeling and simulation have helped not only to visualize the complexity of processes that take place at nanoscale but also to handle complicated calculations with accuracy. The advance in the enabling techniques (listed below) will have a huge impact in the development of nanostructured materials.

- Supramolecular Chemistry
- Nanoprobes (STM/AFM)
- Electron Microscopy(TEM/SEM)
- Nanolithography
- Micromachining
- Molecular Design/Modeling
- Thin Film Technology

2. Contributory Disciplines

There is much uncertainty about many of the characteristics of the science and technology of nanostructured materials, but there is no doubt about its truly interdisciplinary character. Increasing number of researchers from diverse disciplines are entering into the field of nanostructured materials, bringing a breadth of new ideas and innovative solutions. In the integration between the various disciplines is where much of the novelty resides, and this activity is growing in importance. Many laboratories working on nanostructured materials (with long tradition in particular fields such as solid state physics or organic chemistry) have seen the urgent need to integrate professionals from different disciplines to form multidisciplinary teams. The reason is because the solutions to problems at nanoscale are coming from all different angles and perspectives. This motivates the sharing of solutions and findings crossing boundaries of traditional disciplines. In other words, nanotechnology has a cross-disciplinary, transdisciplinary and multidisciplinary character. For example, improvements in identification techniques or developments of innovative experimental designs often require an intimate knowledge of disciplines such as quantum physics, molecular chemistry, physical-chemistry, electronics, biology, etc. Critical applications such as nanotubes, DNA computers, etc, will require sophisticated synthesis and assembly techniques and characterization methods that are not restricted to a single field. While individual fields have a plethora of available information from a macroscale perspective, "there is plenty of room" for their development with respect to the nanoscale. The integration between two or more of these fields promises new and exciting ways to tackle problems and visualize solutions.[6] A diverse and multidisciplinary background will give nanoscientists the ability to communicate with colleagues and find appropriate methods for a particular project. On the other hand, nanostructure science and technology is developing its own language. This language would be a powerful tool making it possible for scientists to communicate with accuracy and precision the diversity and complexity of the knowledge and information associated with the phenomena and processes at nanoscale.

2.1 Current fields

Nanostructuring materials is a new area but it has many elements common to various well-established disciplines. Nanostructures enclose many of the wonders and mysteries of physical and biological worlds. Nanostructures are the natural habitat of quantum effects, they allow access to the quantum behavior of molecules which are otherwise inaccessible. Although, the enormous potential of studying nanostructures is quite clear, building real technologies based on the complexities of nanostructures will demand an in-depth knowledge of the essence of the fundamental science (Whitesides and Alivisatos, 1999). One of the special charac-teristics of nanostructured materials is the need of working (and manufacturing) at atomic and molecular rather than micro or macroscopic levels. This is one of the reasons why nanotechnology must be an interdisciplinary field. Concepts of quantum theory, which are used now by scientists for describing and explaining some properties of micro-structured materials such as color in organometallic complexes, will represent the "day to day" tools for nanoengineers. These concepts will be at the heart of the development of manufacturing techniques needed for bringing nanostructured materials to the market place.

The manipulation and control of a limited number of atoms require a new set of concepts and techniques that are not exclusive of a particular scientific field. Cox (1998) pointed out that variables such as the numbers of atoms (N) are becoming extremely important parameters for defining "small systems". Research has shown that basic properties of elements such as the ionization potential and the

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6 see Interdisciplinary Nanoscience http://nanotech.about.com

electronic affinity (Taylor et al 1992; Rademan et al 1987; Rohlfing et al, 1984), magnetic moment, polarizability, geometric structure and chemical reactivity can change dramatically when the number of atoms in a cluster varies. Similarly, biologically inspired models may offer innovative answers to problems in synthesis and assembly.

Much of the present multidisciplinary of the science and technology of nanostructuring is associated to special characteristics of nanostructures that combine identical small size, complex patterns of organization, very large surface areas to volume and strong lateral interactions. These characteristics are not only common in many nanostructures studied by different scientific fields, but their organization may inspire new methods of synthesis and assembly of nanostructured materials. In electronics, for example, nanostructures represent the limiting extension of Moore' s law and classical devices to small devices, opening the possibilities of fundamentally different new processors and architectures. In molecular biology, nanostructures are the fundamental machines that drive the cells; they are the basic components of the mitochondrion, the chloroplast, the ribosome, and the replication and transcription complexes (Whitesides and Alivisatos, 1999). In chemistry, nano-structures involve the study of single molecules, molecular assembly lines, nanoscale reaction vessels, etc. In material science, the nanometer scale is the largest over which a crystal can be made essentially perfect. Nanomechanics is also a new discipline, it supports the improvement areas of microsystems (MEMS), micro-fabrication associated with the IC industry and packaging technologies. This field may contain the fabrication of microstructures from polymers, 3D UV lithography, laser mechanical micromaching, and hydrophilisation of plastic surfaces (wetting behavior).

2.2 Future trends

Nanoscience is one of the promising frontiers of science, it offers not only the most exciting prospects of technological innovation, but also leads the way to totally new and better products. Currently, established disciplines have started to make substantial contributions to the development of nanostructured materials; however, is expected that the integration of the existing scientific fields and the emergence of new disciplines will dramatically accelerate the development of nanomaterials.

Nano Education

The need for a multidisciplinary education in areas of material and physical sciences, biology and engineering is recognized as of critical importance for the advancement in the science and technology of nanostructuring. At present, although changes are rapidly occurring in universities, many elements of the traditional training and research culture that hinder multidisciplinary education and research still exist. It is of paramount importance to accelerate changes in curriculum development that promote vertical and horizontal integration of education and favor a true multidisciplinary training. Additionally, fundamental courses for understanding the behavior of nanostructures such as quantum mechanics should be extended to all scientific and engineering curriculums. Finally, it is necessary to dismantle those administrative procedures that discourage integration (and promote competition) between academic departments in physical, natural sciences and engineering.

BCP Engineering

Engineering at the nanoscale involves the use of atomically precise components to design and build nanoscale devices and materials. Simulation and fabrication of nanomachines, quantum computers and molecular electronics may soon become standard practice in the engineering community. Nanotechnology will create a new multidisciplinary field of engineering that will include biology (B), chemistry (C) and physics (P) engineering, or the so called "BCP Engineering" will combine skills and concepts of the three fundamental disciplines plus the ability to engineering processes of at nanoscale.

Advances in instrumentation and enabling technologies

The future of the science and technology of nanostructured materials will be increasingly affected by advances in instrumentation and enabling technologies. These areas are (and will be) providing the necessary "nanotools" for measuring, observing and manipulating nanostructures. They will be an essential part of the "construction kit" that will allow the synthesis and assembly of the nanomaterials of the future. It is expected that the trends in instrument diversification and other enabling technologies will continue to develop at a face pace. For example, scanning tunneling microscopes have experienced a number of innovations that allow to make measurements sufficiently insensitive of temperature and other environments with challenging conditions. Similarly, atomic force microscope that allow manipulation of *in vivo* substrates and determine structures are becoming extremely popular among biologists and nanobiologists (Frenken, 1998, p.289, 292).

3. Current State of Nanostructured Materials

3.1 Big Players

The field of nanostructured materials has seen the emergence of a number of key players in the academia, industry and also government labs. Appendix 1 lists the key players in the field of nanostructured materials by country and by type of institutions. Based on our database of US patents and scientific papers (See Appendix 2), it is possible to identify which countries, institutions and firms are responsible for the patents and papers in this field. The database include all patents pertaining to nanostructured materials or related technologies, including categories such as materials, tools and instrumentation, and devices granted by US Patent Office (USPTO)[7] between the 1st of January of 2000 and the 12 of June of 2001. The data shows the United States predominate in most of the areas of nanostructured materials. From a total of 356 patents, the US accounts for more than 65 percent of the patents, followed by France (6.2 %), Germany (5.9%) and Japan (5.9 %). The US also leads in materials, tools and instrumentation and devices with 67 %, 87% and 59% of the patents respectively. Japan's patent performance shows a relatively strength in devices as the WTEC report pointed out.

Classification of patents in nanostructured materials and related areas (according to the patent's assignee) shows the industry as the leader (responsible for 64% of the patents), followed by universities with 22% of the total of granted patents. Substantial differences, however, are observed between various countries. In the US, patents are well distributed among large firms, specialized SMEs, universities, individuals and government labs. Large American companies such as Allied Signal, IBM, Texas Instruments, Xerox Company, Eastman Kodak, Honeywell, Lucent Technologies, Amcol, 3M, Exxon and Motorola account for approximately 30% of the 234 American patents. Specialized SMEs such as NanoGram Corp., Micron Technology Inc., Cytec technology Corp, Claytec Inc., Hyperion Catalysis, Applied Materials Inc., BioCrystal Ltd., Hitco Carbon Composites and others share approximately 25% of the patents granted. Universities account for 55 patents or 23 % of the American patents. Universities such as University of California (11 patents), MIT (4 patents), Harvard University (4 patents), Penn State University (3 patents) and Kansas State University (3 patents) seem to be the bigger players at least in terms of patents output. Government laboratories and hospitals also account for a significant number of patents; the Airforce and the Navy registered a total of 10 patents.

These patterns of patenting are relatively different in other countries; the distribution is less uniform, having either firms or government a more prominent role. Canada is perhaps the obvious exception with universities showing a relatively high rate of patenting.

In France, large pharmaceutical and chemical companies such L'Oreal, Rhodia Chimie, Atochem and Rhone Poulenc accounted for almost 70% of the patents, while universities and government research centers received only one patent

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7 It is well known the bias of considering only the number of patents issued in one country (in this case USPTO) ; local firms have a much stronger tendency than foreigner firms to patent in the local market. However, here the interest is mainly illustrative and the USPTO data well serve this purpose.

respectively. Individuals and SMEs made up the rest of the 22 patents. In Germany, large firms such as Bayer, BASF, Hoescht, Celanese GmbH, Deutsche Telekom and Bosch GmbH accounted for more than one third of the 21 German patents in the US. Specialized Institutes both public and private, such as the Institut fur Neue Materials and the Max-Delbruck Centrum fur Molekular Medicine accounted for more than 20 percent of the patents. Similarly, in France, only one patent was granted to a university. SMEs specialized in the area of chemistry also seem to play an important role in the patenting activity in Germany. In Japan large electronic firms have been by far the main players. NEC, Sharp, Fujitsu, Toshiba, Matsushita, Ricoh, Sony and Futaba account for 15 out of 21 patents. MITI's agency for Industry, Science & Technology, non-electronic firms and individuals without assignee registered the remaining 6 patents. In Canada, universities accounted for 40 percent of the patents. A very different picture is shown in the patenting activity of Chinese Taipei and Korea, where Government institutes such as ITRI (Chinese Taipei) and the Electronics and Telecommunications Research Institute (Korea) accounted for more than 50% of the patents.

In the academia, big players are distributed all around the world in a number of centers of excellence of nanotechnology and nanostructured materials. Their performance in terms of papers' publication was determined from the SCI database from the period 1991-2000. Keywords such as: nanomaterials, nanoparticles, nanocrystals, nanostructures, nano-synthesis, nanotubes, quantum dots, nano-catalysis, nanocomposites were used for the identification of those papers related to nanostructured materials. As Table 2 summarizes, at country level, the trends of paper publication do not differ substantially from those shown in patenting activity. Again an overwhelming dominance of the US is observed, as it accounts for more than 40% of the published papers during the period of 1991-2000. Japan was second with almost 20 %, then China in the 3rd place with 14 % and Germany in the fourth place. In contrast to the patent data that was based only on the patents granted by the USPTO, the SCI database includes journals which are based not only in the US, reflecting better the international distribution of the academic output in the field of nanostructured materials.

3.2 Important Initiatives Worldwide

Due to the importance of nanomaterials as a basis for the development of nanotechnology, many developed and some developing economies have started to mobilize resources with the objective of supporting the science and technology of nanostructures. Policy initiatives and funding prospects are appearing in many official documents. Nanostructured materials are considered to be one of the key areas for development because of their tremendous potential and possibilities of practical applications.

Table 2. Papers in nanostructure Science &Technology by authors' nationality (1991-2000)

	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	1991-2000	% 1991-2000
Total	52	80	122	182	267	390	471	681	952	1,119	4,316	100%
United States	28	38	54	96	122	193	190	287	368	421	1,797	41.6%
Japan	7	8	16	29	45	63	75	101	145	165	654	15.2%
China	1	9	17	16	23	31	65	93	154	206	615	14.2%
Germany	5	11	19	19	29	54	70	105	128	133	573	13.3%
United Kingdom	6	5	10	10	13	18	23	27	49	62	223	5.2%
Canada	3	6	3	7	11	13	8	11	15	26	103	2.4%
South Korea	0	0	0	0	3	2	8	14	33	33	93	2.2%
Switzerland	2	1	0	0	6	5	15	19	16	22	86	2.0%
Sweden	0	1	1	4	6	6	8	10	19	21	76	1.8%
Chinese Taipei	0	0	1	1	4	3	8	9	10	18	54	1.3%
Australia	0	1	1	0	5	2	1	5	15	12	42	1.0%

Source: SCI database (authors calculations)

In the last years a number of large R&D projects for nanomaterials were launched. In United States, the former administration declared National Nanotechnology Initiative (NNI) in January 2000, and many government agencies such as DOE, DOC, NASA and NSF have been allocating an increasing proportion of their R&D budget to nanomaterials research.

In Canada, the National Research Council will invest $120 million in the National Institute for Nanotechnology (NIN) to be located at the University of Alberta in Edmonton. The NIN will be a key resource to integrate a Nano-Structures Network in Canada.

In Europe, many countries have been advancing in their own R&D agenda on nanomaterials and some efforts at EU level have been growing substantially. This is the case of the COST program on nanostructured materials (COST 523), which has come forward from the European Consortium for Nano Materials (ECNM), a network that had been coordinated by Switzerland since 1996, with strong input from the Netherlands. However, in spite of these efforts, Europe still lacks an integrated strategy and cooperation program to support the interdisciplinary research of nanomaterials in large scale.

At the national level, United Kingdom's EPSRC has been supporting the Advanced Magnetic Program, the research focus of which is on nanomagnetism. Additionally, the UK's Institute of Nanotechnology is undertaking a project in conjunction with the industry and researchers with the objective of identifying nanotechnologies that will affect UK's manufacturing sector over the 5 to 10 years; and nanomaterials is one of the areas being studied extensively. These initiatives are linked to UK's Foresight exercise that aims to provide a guide for industrially targeted R&D. In Germany, the German science ministry (BMBF) is supporting a major initiative of $50 million over the next five years. This initiative includes the formation of a network of 'centers of competence' in nanotechnology (ten Wolde, 1998, p.45-46). Areas such as ultra-thin coatings, lateral nanostructures, molecular architectures and nanostructures analysis have been selected. Besides, the Institute for New Materials (INM) is organizing annual seminars focused on the applications of nanomaterials. In France, the Center National de la Recherche Scientifique (CNRS) is coordinating some public research projects related to nanomaterials; including nanocomposites and nanoceramics, the fabrication of C_{60} and its derivatives, physical-chemical study of Si-based nanophase ceramic powders and magnetic nanostructures. CNRS is also responsible for the 'Ultimatech' program, which focuses on enabling technologies for the manufacture of nanostructures. Finally, Sweden and Finland also have programs and government research institutes engaged in the R&D of nanomaterials.

In Japan, the Ministry of Trade and Industry (MITI) has a long tradition of funding nanotechnology projects. Since the 1980s and early 1990s it has supported large projects such as the Yoshida Nano-Mechanisms Project and the Quantum Functional Device project. Recently two new projects focused on nanostructured materials have been launched. One focuses specifically on research of nanomaterials' and has a budget of US$50 million per year. The other project is targeted towards the development of basic technologies for the next generation of semiconductor devices, and a total of US $60 million per year has been allocated to this project (Lerwen Liu, 2001). Furthermore, Ministry of Education, Culture, Sports, Science and Technology (MEST) has launched a national program on nanomaterials to be executed by National Institute of Materials Science (NIMS). At the corporate level, early this year, Fujitsu Corp. announced that its Nanotechnology Research Center in Kawasaki would concentrate on R&D of nanomaterials. Mitsubishi Corporation, on the other hand, has raised US $100 million for the R&D of nanomaterials and IT applications. Part of the strategy followed by Japanese firms seems to be concentrated on long-term niche competition.

Other economies in Asia, particularly China and Chinese Taipei and Korea have also put a strong emphasis on nanomaterials research. The development of nanoparticles, nanopowders, nanometals, biomaterials, nanocomposites have appeared on the top their nano-research agenda. In China, the Chinese State Council is planning to launch a National Nanotechnology Initiative with several million of dollars in funding. This five years initiative, which is expected to start in the year 2001, will be managed by Ministry of Science and Technology.

In Chinese Taipei, both the National Science Council (NSC) and Ministry of Education (MOE) have been developing a 4-year program for nanomaterials research since 2000. According to the recent information provided by the Ministry of Economic Affairs (MOEA), the government is expected to launch a major investment of US$300 million in nanotechnology R&D for the next 4 to 5 years. The objective of this program is to assist ITRI in the development of nano-technology.

In Korea, the focus has been mainly on the application of nanostructured materials for the IT industry. The Korean Advanced Institute of Science and Technology (KAIST) has been undertaking research in nano materials for information storage purposes. The scaling up of some processes for the manufacture of nanostructured materials has also been one of the main research targets of this institute. The Electronics and Telecommunications Research Institute (ETRI), which is one of the main government research institutes, has concentrated its research on applications of nanostructured materials to networks technologies. LG-Communications, one of the most active private research centers, has also followed the same line of research. A major research cooperative venture of 76.6 billion Won (approximately US $60 million) for the development of nanotechnology-based optical materials, has been initiated by the government and private groups. This ten-year project (2001-2011) will receive 45% of the funding from the government, and the rest will be provided by private companies. The development of nanostructured materials for energy use (e.g. fuel cells), optical and textile applications, and medical equipment are considered key areas by the Korean government.

3.3 Trends and main issues

Basic Research

It is well known that nanotechnology is a cross-disciplinary field. Therefore, competencies and skills in the core scientific and technologic disciplines are essential for advances in nanotechnology. The relatively large amounts of funding that some countries such as the United States, Japan and Germany had allocated to basic nanoresearch in the late 1980s and early 1990s seem to have a direct effect on their current leading position (DTI, 2000). Even from an economic viewpoint, there seems to be a consensus that high performance and cost effective nano-technology derived products will depend heavily on breakthroughs in research carried out at basic level.

At this time, there is a strong need for further understanding of the phenomena that occur at nanoscale. For example, much basic research is needed to understand the roles that surface and interfaces play in nanomaterials. Properties such as the tunneling effect; mechanical and chemical interactions that take place at nanoscale; charge, separation and transport between nanostructures are areas of enormous potential for research that require a deep understanding of fundamental issues.

Theory, simulation and modeling

Research of nanoscale materials structures presents an immense theoretical challenge. The basis of these theoretical difficulties are due to the fact that atomistic nature of these small systems and inadequacy of the well-established approaches of solid state physics to be extended to understand the behavior of nanostructured materials.

An obstacle for the development of nanostructured materials is that the fundamental behaviors of nano-systems are not well understood. The units might be too small to be measured, or too complicated to be predicted by current theoretical and numerical methods. Because of basic understanding and highly accurate analyzing methods are critical to the successful manufacturing of nanoscale materials, many countries have already focused on the development of more powerful and sophisticated calculating tools, software, and modeling techniques.

Fundamental understanding of the theory and methods required to adequately describe the mesoscale regime, an issue that has not been accomplished sufficiently yet (Willian A., Goddard III, 1998). Major breakthroughs must be achieved if theory, simulation and modeling (TSM) are expected to succeed in the application to nanostructure systems:

1. Theory – a better fundamental understanding of the connection between material properties and structure at the nanoscale.
2. Computation method – new computing algorithm to carry out calculations of mesoscale behaviors
3. Powerful postprocessor – elegant ways to communicate mesoscale information in suitable graphical representations in which related elements for designing nanosystems can be clearly visualized.

For example, quantum chemical, molecular theory and simulation are required to provide basic insights and offer predictable algorithms for nano-structured materials properties such as electrical, magnetic, optical and thermal behavior. Some examples of ongoing research in the use of TSM are:

- (Scaling issues for molecular calculations on nanoparticles (Pacific Northwest lab.);
- Carbon nanotubes simulation (NASA Ames);
- Quantum dots simulation (University of Illinois, Urbana);
- Molecular simulation of DNA molecule dynamics (New York University); and
- Simulation of quantum confinement in silicon nanocrystals (University of Minnesota).

Industry perspective

A recent report by UK's Department of Trade and Industry (DTI) showed that the three main issues shaping the vision of large firms in relation to nanotechnology and nanomaterials were:

- "No-one buy nano (for being nano); only new and improved products and processes"

- "Industry presently doesn't connect nano to a solution to a problem they may have"
- " all electronics will work at the nanoscale in 10-15 years"

Most firms have recognized the potential of nanotechnology and nanostructured materials; however, they are looking carefully for the right opportunity to become involved in this field. Although, the possibilities of nanostructured materials and other possible applications of nanotechnologies seem endless, firms are facing the dilemmas of where to invest, asking what are the winning technologies, and having problems with identifying them?

Many firms have responded in different ways. In the US for example, a number of large firms are establishing collaborations with centers of excellence and investing money in university nano-research. Their interest not only lies in the possible technologies that eventually could come out from universities' labs but also in the possibility of accessing the right people at the right time. In the US, there seems to be an urgent need to be prepared for the nano revolution. The idea is that no-one want to be left off the bandwagon. In sectors such as pharma-ceuticals, some firms have opted for a relatively low risk approach, buying specialized services or firms and by letting others undertake the risk associated to nano research. The basic response (at least in large firms) seems to be invest money and encouraging others to create the basic elements that firms may need in the near future to *develop technologies*. Developing in-house has been the approach followed by few.

Small and medium size enterprises (SMEs), however, seem to have followed a different approach. Many of these SMEs are spin-off from university research and have been established to commercialized the technologies that they have developed. In the US, a dynamics that combines entrepreneurship and vigorous industry-university relationships has been particularly important in many successful new firms. SMEs have been also powerful drivers for providing direction for further research in universities, for obtaining a better control over discoveries and for ensuring increasing income for professors, departments and universities (DTI, 2001). Another distinctive characteristic of SMEs associated to nanotechnology and nanostructured materials is the integration into dynamics networks of universities, institutes of technology, government labs and large firms. Mainly in the US, these networks have been strongly supported at state level and have become important mechanisms for fostering commercialization and creation and development of SMEs. Initiatives such as the Small-Business-Innovation-Research (SBIR) program in the US have been extremely successful in funding spin-offs.

Academic perspective

So far, universities have been one of the major players in the field of nanostructuring materials. Many technologies are coming from universities and it is expected that this trend will continue. Universities in the US, Europe and Japan have concentrated their efforts through the creation of centers of excellence in specific fields. These centers of excellence have been attracting important funding, both from government and private sectors, to undertake cutting-edge research.

However, the message from the academia is clear in three instances:

- It is essential to establish a supporting infrastructure with a long term perspective;
- Training in nanotechnology must incorporate physical, natural and engineering sciences, emphasizing cross-disciplinary education;
- A long-term commitment that ensures continuity of work and the accumulation of the necessary equipment and facilities.

In other words, it is clear that the necessary expertise and resources are not available

"on the shelf", and building up capabilities takes time, commit-ment, and long term planning. The support for the academia in terms of advanced facilities, equipment and personnel is critical for the continuation of critical dis-coveries through fundamental research. This was explicitly recognized in the President Clinton's National Nanotechnology Initiative.

3.4 Challenges

The development of nanostructured materials is at the threshold of an unprecedented revolution. However, to capitalize on the opportunities of this revolution, the science and technology of nanostructured materials must overcome a series of challenges. These challenges are not only limited to the manufacturing of materials itself but also about developing enabling technologies that will allow scientists to manipulate, characterize and measure individual nanostructures.

Achieving stability and reproducibility

Stability is a fundamental requirement for may applications of nanostructured materials. Thus achieving chemical, structural and thermal stability of nanostructures are a major challenges for nano scientists and engineers. Luckily, many nanostructures with potential uses have demonstrated good metastability or can be stabilized using traditional methods. A promising way to improve stability may be through the bottom-up assembly of nano structured materials.[8] However, this is a very active area of research[9] and researchers must determine what level of stability or metastability is needed (Siegel, 1998, p12) and find out new conditions affecting stability and methods for stabilization nanostructures.

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8 www.hpcmo.hpc.mil/Htdocs/SUCCESS/Success97/CCM/hpcmater.html

9 see for example, Structural Stability in Nanocrystal ZnS J.Z. Jiang, L. Gerward , J.S. Olsen, D. Frost, R. Secco and J. Peyronneau and other papers in the Proceedings of the International Symposium on Metastable, Mechanically Alloyed and Nanocrystalline Materials, Dresden, Germany, Aug. 30-Sept. 3, 1999 (2000) pp. 15 - 20

Reproducibility is also regarded as one of the critical issues for manufacturability of nanostructured materials (Gell, 1998). High quality and reproducibility of nanostructured materials are achieved by establishing clean conditions such as ultra-high vacuum environments, computer control of the synthesis parameters, and in-situ analysis techniques such as Reflection High Energy Electron Diffraction (RHEED). Advances in precision engineering and controlled manipulation of nanoscale objects are critical to ensure the adequate reproducibility of nanostructured materials.

Scaling up and process development

As in many other experimental research in the development of nano-structured materials, what works in the lab does not necessarily work at the commercial scale. To make the production of nanostructured materials a reality that can bring benefits to the society substantial improvement in scaling up and process technologies is required. This is another major challenge for the technological development of nanostructured materials.

As we have mentioned at the beginning of this paper, a number of methods are already available commercially such as the high-energy ball milling process that is used to generate nanoparticles at a high-volume for the preparation of magnetic, structural, and catalytic materials. However, products of this process are polydispersed amorphous powders that need to be recrystalized and consolidated into nanostructured materials (Hu and Shaw, 1998, p.22).

Better product quality has been achieved by other methods, however, at very low production rates. For example gas-phase synthesis produces typically about 100 milligrams of different types of nanoparticles per hour in research laboratories. Using the same technique, higher yields of about 20 grams per hour of different high purity nanocrystals, have been tested at Ångstrom Laboratory at Uppsala University in Sweden. Recently, a production rate of 1 kg per hour has been achieved commercially. Economical scale for the production of nanoparticles from sol-gel processing is not available yet and issues concerning the cost of precursors and the recycling of solvent need to be addressed (Hu and Shaw, 1998, p.22). More success has been achieved in the production of industrial-scale quantities of nanophase WC/Co powders. Nanodyne, Inc. has commercialized a Spray Conversion Processing that is able to produce compositions covering the range of commercial interest from 3-30 wt% Co (Kear and Skandan, 1998).

Scaling up is also of vital importance for the commercial production of carbon nanotubes. Although macroscopic amounts of nanotubes can be fabricated at the present by various research groups around the world, the present fabrication methods are incompatible with the requirements of industrial scale production (Gorokin, et al. 1998, p.87). Part of the limitations in achieving higher rate of production are related to advances in precision engineering (Mendel 1998, p.37) and controlled manipulation of nanoscale objects (Gorokin, et al. 1998, p.87)

In summary, to continue the rapid progresses in nanostructured materials, a key challenge is to make the necessary advances in enabling technologies such as scanning probe technology, which can provide characterization capability to understand and analyze physical properties and chemical composition of nanomaterials. The stability of the nanostructured materials during synthesis and assembly as well as stability in response to changes in temperature and conditions in the environment in which these nanomaterials are expected to function, are other challenges to be considered. Additionally, it is extremely important to achieve stability in terms of time; it is not useful to have nanoparticles and nanostructured materials that do not endure for long periods of time. Precision manufacturing and process monitoring of nanomaterials' fabrication also need to be further researched. To produce at a commercial scale, reproducibility and scalability from labs to industries and quality control of the synthesis and consolidation of nano-sized building blocks must be enhanced.

4. Emerging Opportunities and Potential Applications for Nanostructured Materials

4.1 Existing Industries

Advances in the research of nanostructured materials provide many technological and/or marketing opportunities to the existing industries. The NNI presents the following examples:

Materials and Manufacturing. The capability to synthesize nanoscale components with accurately controlled size and arrangements, and to assemble them into bulk structures with consistent properties and functions will revolutionize the material manufacturing industry. Some major advantages of nanostructured materials are that they are lighter, stronger and more manipulative through lower failure rates.

Nanoelectronics, Optoelectronics and Computer Technology. In the current manufacturing techniques, the limit of line-width for microelectronic devices is approximately 0.07µ (70 nanometer). According to the SIA (Semiconductor Industry Association) technological roadmap, the line-width is expected to reduce to 0.01µ (10 nanometer) in 2010. This is just slightly below the upper limit of line-width for nanostructured devices. Below this range, all chips should be designed and manufactured based on new principles and technologies. In order to overcome this bottleneck for information industry, theories and technologies in the nanoscale must be studied in depth. The processing speed of nanoelectronic computer will increase a million times than that of the existing microelectronic computer. On the other hand, nanostructured materials with giant magnetoresistance property are also beneficial to the area of magnetic information storage, a market worth $34 billion dollars in 1998. U.S government will invest over $10 billions to build a single fabrication plant for 70 nm nanometer microelectronics.

Medicine, Life Sciences and Pharmaceuticals A major focus of research in this field is to develop and deploy nanoparticles for delivering drugs, gene therapies, and other therapeutics. Drugs with nanoparticles will be delivered efficiently and directly to the site of action in the human body. Furthermore, intelligent nanostructured drugs can detect and attack cancer cells and a wide range of diseases and it will become possible to cure damaged tissues and organs.

Environment and Energy Saving. Progresses in nanostructured materials development provide lots of emerging opportunities for both environment and energy industries. Some nanoscale materials targeted for these two industries have been produced. For instance: (a) the ordered mesoporous material MCM-41 produced by oil industry with pore size of around 10~100 nm, is widely used for the removal of ultrafine contaminants, (b) nanoscale particles of clays and polymers are new materials used to replace carbon black in tires, (c) the sunlight-to-electricity conversion efficiency of solar cells using particle-based thin-film photovoltaic technologies have surpassed 11%.

Aeronautics and Civil Aerospace. One of the big challenges fore the design and manufacturing of advanced aircrafts and spacecrafts is reduction in weight, and power consumption of payloads. Nanotechnology provides solutions to the challenges. Some nanostructured materials are lightweight, strong, and thermally stable materials and can be used for airplanes, rockets, and space shuttles, etc. A key research project for NASA is to develop smart nanostructured materials with high strength-to-mass ratio. Both aircraft and spacecraft structures made by these materials are ultralight and ultrastrong. These nanostructured materials are also useful for building up large systems, such as: telescopes, antennas, and solar cells, so the weight will be reduced compared with existing systems.

Military and Defense Industry. Nanostructured materials are not only extremely practical for industries in general, but possible applications in the defense industry is also enormous. Except for high performance nanocomputers and " smart" military aircrafts as mentioned above, through applications of nanostructured materials' technology, desirable properties, such as anti-corrosion and invisibility of the weaponry (ships, submarines, bombers, etc) can be significantly enhanced. At this time, the research priorities for U.S Department of Defense in the field nanostructured materials are as follows: formation and properties of high surface area materials, nanocrystal networks and aerogels; large-scale manufacturing of high quality clusters, nanotubes, dendrimers, etc.

4.2 Potential Applications

Based on the ability to manipulate matter at the atomic and molecular scale, nanostructured materials bear important potential applications in areas such as energy engineering (fuel cell, batteries and solar cells.), environmental technology (material recycling, waste disposal and clean-up), as well as in information technology (high density memories, efficient processors, etc.) and medicare. It also provides opportunities in developing new diagnostic and analytical techniques. Before discussing the huge potential of nanostructured materials in various applications, it is important to mention their properties. Many nanostructured materials exhibit extraordinary mechanical, thermal, optical and magnetic properties. Table 3 shows some of the unique properties and potential applications.

Table 3. Nanostructured materials: properties and potential applications

Property	Application
Mechanical properties • High hardness and strength • Superplastic behavior of ceramics • Ductile ceramics	• Reinforcement fiber for high-strength composite • Pure and composite high-strength fiber
Thermal properties • Small heat capacity • Lower sintering temperature	• Heat-exchange materials • Combustion catalysts • Sintering accelerators
Optical properties • High and selective optical absorption of metal particles • Size small than wavelength	• Colors • Filters • Solar absorbers • Photographic material • Photovoltaic • Phototropic material • Light or heat absorbers
Electrical properties Small mean free path of electrons in a solid	• Special conductors
Magnetic properties • Single magnetic domain • Giant Magneto-Resistance	• Magnetic recoding • Highly sensitive sensors • Read/write devices • Anti-lock automobile devices

Source: COST 523 program

Other applications and emerging uses for nanostructures and materials are being investigated by research and development programs. Of particular relevance are the following:

- Nanostructured materials with giant magnetoreistance properties have been brought into commercial use with remarkable speed, and their acceptance suggests the importance of magnetic materials with nanometer-scale spin-flip mean free path of electrons.

- Their exist a range of ideas for high-density information storage, based on concepts such as nano-CDs and on nanostructured magnetic materials, including materials showing giant and tunneling magnetoresistive effects, holding great promise for providing future systems with ultrahigh density storage devices.
- New protective coatings, thin layers for optical filtering and thermal barriers, nanostructured polymers, and catalysts are already coming to market. Nanostructured coatings are showing good corrosion/ erosion resistance and could become as possible replacements for the environmentally troublesome chromium-based coatings.
- Aerogels-highly porous, sponge-like materials with three-dimensional filigree of nanostructures- have promise in catalysis and energy applications.

As ten Wolde (1998, Chapter 3) pointed out, the main advantages for future applications of nanostructured materials will come from two unique characteristics of nanostructures: the small particle size and the larger surface area. The first characteristic will induce quantum effects or will alter standard properties such as processing temperature. The later will cause the dependence of bulk properties on surface properties. Table 4 gives some examples of the relationship between these characteristics, the derived properties, and possible future applications.

Table 4. Properties and future applications related to particle size and large surface area of nanoparticles.

	Property	Future application
Particle size	Single magnetic domain	Magnetic recording
	Smaller than wavelength of light	Colored glass
	Superfine agglomeration	Molecular filters
	Uniform mixture of components	New materials and coating
	Hindered propagation of lattice	Strong and hard metals
	Imperfections	Ductile ceramics at elevated
	Enhanced diffusional creep	temperature
Large surface area	Specific	Catalysis, sensors
	Small heat capacity	Heat-exchange materials
	Dye-sensitized	Solar cell

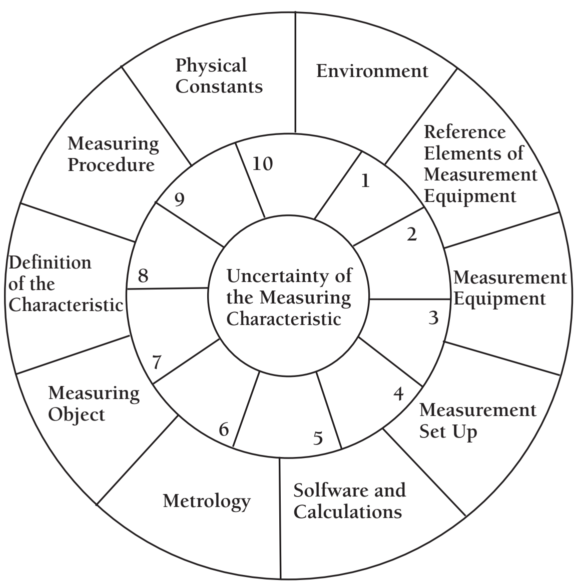
Source: ten Wolde (1998, Chapter 3)

Appendix 3 outlines a comprehensive list of possible future applications of nanostructured materials.

5. Nanomeasurement and Standards

The establishment of standards and metrology system is a key element in the development of an industry. Nanometrology will be an enabling tool for the development of nanotechnology; however, the challenges for developing an useful and universally-recognized standards' system for nanostructures are many, as it should account for the complexities of these products and technologies, as well as the multidisciplinary nature of this field. For example, determining appropriate units of measurement and physical constants are formidable tasks. Additionally, uncertainty in the measurement system at nano scale becomes more critical.

Fig. 3 Factors influencing uncertainty in setting up a standard system.



Source: David Whitehouse (2000), Tools of nanotechnology and nanometrology. In *Handbook of Nanostructured Materials and Nanotechnology*, Hari Singh Nalwa (Editor). Academic Press. London

Figure 3 summarizes the factors affecting uncertainty. The influence of these factors may be significant as highly sophisticated measurement equipment, software programs and calibration methods need to be developed. Murday et al. (1999, p.38) pointed out that locating and maintaining a specific position with nanometer accuracy and precision are still difficult; and this is one of the crucial issues affecting the commercialization of nano-devices. Another important issue is the need for uniform-size particles for the standardization and calibration of nanoscale measuring instruments. The US Department of Energy has organized a workshop to deal with this problem, and a number of specific goals were set for the next 5-10 years. These included: the development of particle size calibration standards for 3 nm, 10 nm and 30 nm size pariticles; improvements in nanomeasurements methods for nano-sized particles; and quantification of uncertainty in transmission electron microscopes.

Standards are fundament in the establishment of nano-based industries. They will be of critical importance for transforming fundamental nanotechnology discoveries into new technologies, products and services that will ultimately affect the economy and people's daily lives. However, standards are useful when they are accepted internationally. In the case of nanostructured materials, the standards system will play a decisive role in deciding product standards for materials, manufacturing procedures and calibration techniques.

For example, The US National Institute for Standards and Technology (NIST) is conducting R & D for developing measurement and standards in support of the National Nanotechnology Initiative. The focus of research includes:

- **New atomic scale measurements for length, mass, chemical composition, and other properties;**
- New nanoscale manufacturing technologies to be used by industry in assembling new devices at the atom or molecule level;
- **New standard methods, data, and materials** to transfer NIST nano-technology to industry and to assure the quality of the new nano-based commercial products. (see **http://www.nist.gov/nanotech/**).

Finally, the race for developing standards in nanostructured materials has already started; whoever is able to develop standards that can be adopted universally will lead the industry. The comprehensive list of NIST Laboratories focused on R&D of nanotechnology and nanostructured materials shows that the US is moving fast. A consistent support from the government as well as a close communication and cooperation amongst industry, government laboratories, academia and the international community are essential for ensuring that the standardization system is developing in the right direction.

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7. Appendices

Appendix 1[10] : "Big players" – Academic, Government and Industry research in nanostructured materials and related areas in some APEC member economies-Academic and research activities

[10] Due to the limited sources of information available, this list cover only partially the institutions involved in nanostructured materials research in APEC.

AUSTRALIA

University of New South Wales:

Synthesis of nanoparticles for membranes and catalysts

University of Melbourne/the Advanced Mineral Products Research Center:

Use of nanoparticles in processing minerals for special products.

CANADA

University of Toronto/Department of Metallurgy and Material Science:

Research on interfaces in nanocrystalline materials.

Queen's University/Department of Materials and Metallurgical Engineering:

Research on electrodeposited nanocrystalline metallic ocatings.

CHINA

Links to academic institutions are available at: http://www.casnano.ac.cn/gb/frdlink/index.html

CHINESE TAIPEI

National Taiwan University(NTU):

Synthesis and application of mesoporous molecular sieves, investigation of AlGaN/GaN quantum structures, optoelectrical properties of nanostructured III-V nitrides, quantum lasers.

National Tsing-Hua University(NTHU)/Materials Science Center:

Growth of self-organized semiconductor nanostructures by MBE, preparation of nanoparticles by vapor condensation, high-energy ball milling and semiconduct functional materials an nanophase materials for biological sensor applications.

HONG KONG, CHINA

City University of Hong Kong/Departments of Physics and Materials Science:

- Preparation and Properties of nanocomposites Materials
- Synthesis, characterization and application Nanoscale Materials
- Atomistic simulation for assembling functional nanostructured materials

Hong Kong University of Science and Technology/Institute of Nano Science and Technology (INST):

ZnO nanocrystallites, new types of electrorheological (ER) nanoparticles, carbon nanotubes and world-class fundamental research in the area of nanostructured materials.

JAPAN

Kyoto University/Graduate School of Energy Science:

Synthesis of nanocrystalline materials by mechanical alloying and study on immiscible systems such as Ag-Cu and Cu-Fe.

Nagoya University/Department of Crystalline Materials Science:

Nanoparticles by mechanical milling – Trigonal selenium, Li and graphite by ball milling.

Osaka University/Institute of Scientific and Industrial Research:

Ceramic-based nanocomposites prepared by sintering method and special emphasis placed on understanding the relationships between nanostructure of materials and their mechanical properties.

Tohoku University/Institute for Materials Research(IMR):

- Nanocrystalline (nc) Fe-based soft magnetic materials and amorphous, quasi-crystalline and nc materials.
- Metallic nanocluster assemblies and work on fullerenes and carbon nanotubes (e.g. chemical reaction studies of C_{60} on Si, polymerization of C_{60} and C_{84} by argon ion laser irradiation, and production of SWNT)
- Exploiting optoelectronic materials

The University of Tokyo/Department of Chemical Engineering:

- Nanoparticles focused on the synthesis and optical properties of nano-composites
- Fundamental studies of quantum confinement effects of heterostructured nanoparticles and nanoparticle structures.
- Study on superplasticity in nanostructured materials.

NEW ZEALAND

Canterbury University/Nanostructure Engineering, Science and Technology(NEST):

Research on nano-engineered materials, low cost nanofabrication, Si/SiN nanostructures and structure of nano-scale particles.

SINGAPORE

National University of Singapore/Institute of Materials Research & Engineering:

Developing methodologies of nanocomposite preparation, nanoscale characterisation and toughening of such materials

USA

University of Notre Dame/Center for Nanoscience and Technology:

Nano-based cellular architectures for information processing by Computation with quantum-dot cellular automata(QCA), optical and high-speed nano-based materials.

University of Massachusetts, Amherst, MA

Self-assembly diblock co-polymers for making functional nanostructures

Cornell Nanobiotechnology Center(NBTC), Ithaca, NY

Molecular templates- concerned with assembly of controlled arrays of molecules

Cornell Nanofabrication Facility(CNF):

Experimental and theoretical investigations of ultra-small transistor structures.

Cornell Center for Materials Research:

- Polymer nanocomposites and metal-ceramic composites: design, synthesis, and modeling
- Self-assembly systems: semiconductor patterning and deposition via self-assembled structures integrated.

University of Michigan/Center for Biologic Nanotechnology:

Biologic applications of nanomaterials, nanomaterials for drug and gene delivery.

University of Illinois at Chicago/Department of Mechanical Engineering:
    Processing and synthesis of advanced materials and their characterization.
University of Arizona/Department of Physics:
    Self-assembled structures are used as templates or masks for the synthesis of mesoscopic materials and molecular devices.
Rice Univeristy:
Manufacture of buckytubes and single wall nanotubes
Columbia University/Materials Research Science and Engineering Center (MRSEC)
    Focuses on new ways to chemically synthesize nanoparticles, self organization of these particles into useful films, and the electrical, optical, and other properties of these films and other aggregates.
North Carolina State University/Department of Chemistry:
    Research on using nanometer scale clusters and structures to fabricate single-electron tunneling devices, and making nanometer scale hollow spheres of polymers.
University of Wisconsin Madison/Department of Physics:
    Nanowires and magnetic nanostructures

Industries

AUSTRALIA

Advanced Powerder Technologies Pty Ltd.
    Use of MechanoChemical Process(MCP) to produce nanopowers

CANADA

Energenius, Inc.:
    Molecular exciter, nanophotonics, nanoelectronics, and nanofabrication.
BigBangwidth:
    Nanomachining of all-optical grids for fiber-optic telecommunication networks.

CHINA

http://www.nanotech.com.cn

JAPAN

Toshiba Research and Development Center:
    Advanced GMR, epitaxy of ferroelectric materials and production of spherical nanoparticles made by thermal plasma.
ULVAC Japan, Ltd./Vacuum Metallurgical Company(VMC):
    Generation of ultrafine-particles(UFP) such as metallic, organic, ferromagnetic and coated UFPs for various applications.
NEC/Electron Devices Laboratory:
    Si, Ge, C clusters and nanofabrication by lithography using e-beam
Hitachi Central Research Laboratory:
    Single-electron transistors, polysilicon transistor, ladder-shaped memory cell array as well as quantum dots and quantum wires.

Nissan Chemical Industries:

Production of colloidal dispersions of oxide nanoparticles, organic dispersions of silica, alumina dispersed in water, etc.

KOREA

Sukgyung AT Co

- Ceramic powders for multi layer ceramic condensers (MLCC used for electronic products including mobile handsets
- LG-electronics
- Electronic Applications

USA

Nanophase Technologies Corporation:

Use of its patented physical vapor synthesis process to make nanocrystalline materials such as TiO_2, In_2O_3, SnO_2...etc.

Packard Bioscience, Meridian, CT:

Drug discovery, genomics, proteomics and biochip analysis.

NanoPowders Industries(NPI):

Production of alloy powders such as Ag/Pd, Ag/Cu, Ag/Al

NanoGram Corp., Fremont, CA:

Fabrication for nanopowders and development on nanomaterial-based applications with its industrial partners.

Nanomaterials Research Corp.:

Production of nonagglomerated, free-flowing and uniform nanopowders in a variety of complex compositions.

Government Agencies

AUSTRALIA

Commonwealth Scientific and Industrial Research Organization(CSIRO):

Biosensors, interface materials, solid state devices, optics, and thin films.

CANADA

National Research Council(NRC):

Investigation on applications of semiconductor nanostructure for quantum computers and quantum cryptography, nanofabrication, biochip technology and bimetallic nanocatalysts.

Department of National Defense (DND):

Studies on hydrogen storage in carbon nanostructures, including the development of new fabrication process of carbon nanotubes.

Natural Resources Canada(NRCan):

Development of a novel method of nanoprocessing for increasing energy storage in battery materials, study on electrochemical hydrogen storage in carbon nanotubes, and use of energetic metal nanopowders for chemical energy storage.

CHINA

The Chinese Academy of Sciences:

Studies on nanotubes, nanoceramics and nanocomposites, zeolites, porous materials, C_{60} fullerenes, one dimension nano-functional materials.

More information is available at http://www.casnano.ac.cn/

CHINESE TAIPEI

National Science Council(NSC):

Funding supporting research on

- Fundamental studies in nanostructured systems including mesoscopic physics and chemistry, supermolecular chemistry, and theoretical calculation, simulation and prediction of properties of nanostructures.
- Fabrication of nanomaterials: high surface are materials, biological and non-biological interfacial materials, self-reparing and self-replicating materials...etc.
- Microcopy and manipulations of nanomaterials: high resolution microscopy, theoretical basis of probes.

Industrial Technology Research Institute(ITRI)

Coatings, fabrication of nanoparticles and molecular simulations, development of nanoscale Nylon6/Clay, PET/Clay and PP/Clay nanocomposites and kneading dispersion processing techniques.

Academia Sinica:

Surface physical and chemical at atomic level, manipulation on atoms, growth of thin film and crystals, structural and electronic properties of Fe, Co, Ni-based magnetic nanoparicles.

JAPAN

Okazaki National Research Institutes(ONRI)/Institute for Molecular Science(IMS):

- Understanding the properties of molecules and molecular assemblies, and the design and synthesis of new materials.
- Production of metallofullerenes. e.g. C_{82} containing Sc, Y, and La inside the cage structure.

Joint Research Center for Atom Technology(JRCAT):

Nanostructure formation and control of surfaces and interfaces(especially in semiconductor and related materials), theoretical simulation, and observation and manipulation of atoms and clusters.

National Institute for Advanced Interdisciplinary Research(NAIR)/Cluster Science Group:

Cluster science including clusters in liquid or solution, clusters stabilized on surfaces and in a nanocage such as zeolites.

National Industrial Research Institute of Nagaya(NIRIN):

Advanced materials research on ceramics, metals, and composites as well as cluster engineering and synthesis of ceramics, nanoporous materials for absorbing oil and identified particulates and ceramic materials with polymers.

National Research Institute for Metals(NRIM):
Particles assemblage by electrostatic force and studies on quantum magnetic properties.
Osaka National Research Institute(ONRI):
Work on nanosized gold catalysts and nanoscale gold colloid dispersed in glasses for optical applications.
Institute of Physical and Chemical Research(RIKEN):
Activities on quantum wire growth, Si nanostructure formation and GaN dot formation

SOUTH KOREA

The Electronics and Telecommunications Research Institute(ETRI):
Semiconductor quantum nanostructures, self-assembled nanosize dots, single-electron transistors and quantum wires.
The Korean Advanced Institute for Science and Technology (KAIST):
Mass-production technologies for nanopowders, new compositional technology. bar-shape nano-materials.

USA

NSF/Center for Quantized Electronic Structures(QUEST) in University of California at Santa Barara:
Quantum structures' magnetic, electronic and optical properties and possible applications.
DOE/Sandia National Laboratory:
Incorporating nanoscience into application for defense and energy like functional mesoporous materials integrated into micromachined deviced on small-sized chip for on-chip analysis of chemical warfare agents.
DOE/Lawrence Berkeley National Laboratory(LBNL):
- Synthesizing nanocrystals of semiconductors and metals of controlled size.
- Arrays of nanocrystals of defined spatial geometry are fabricated by attaching the crystals to strands of DNA of defined base sequence.
- Developing biomolecular materials: Enzymes are engineered, carbohydrates and related biomolecules are designed to control surface properties.

DOC(Department of Commerce):
Nanoscale manipulation for synthesis and fabrication of measurement systems and standards.
DOD(Department of Defense):
Research on new properties in nanostructured materials (quantum and interface effects), biomimetics, failure mechanism initiated at nanometer scales and bioengineering.
DOE(Department of Energy):
Specific classes of nanomaterials with implication for energy production such as supported catalysts and zeolites and buckytubes.

NIH(National Institutes of Health):

- Development of nanotubes, nanoparticles and nanospheres as drug delivery system scaffolds.
- Design of DNA lattices and their applications
- Understanding the principles of self-assembly at different dimensional level and component material interfaces.

NSF(National Science Foundation):

Promoting discovery on synthesis, processing, assembly, modeling and simulation at nanoscale; creation of materials by design; functional engineering at nanoscale.

DARPA(Defense Advanced Research Projects Agency):

Materials - for the generation of new properties.

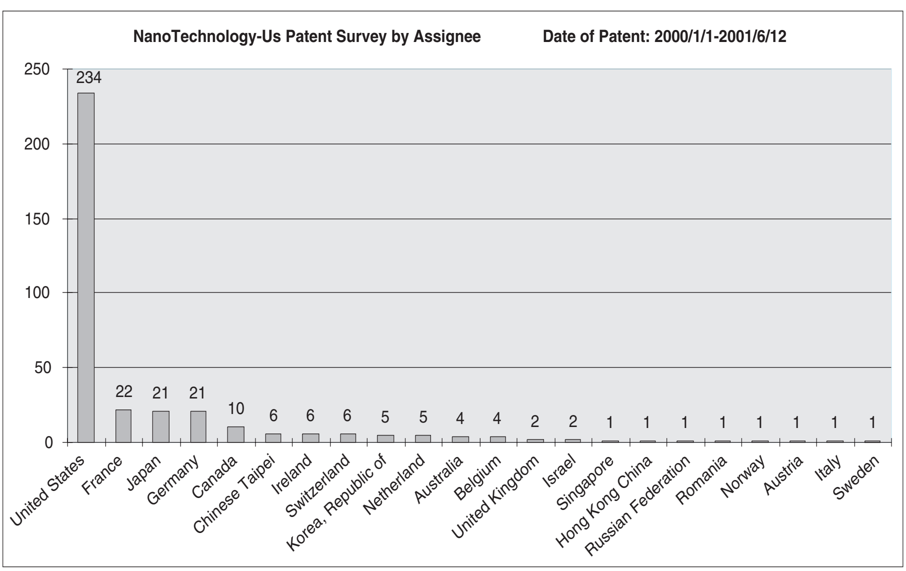
NSF/Division of Materials Research(DMR):

Nanostructured materials of synthesis, fabrication, processing, structure analysis, characterization, properties, and applications. Also, theory, modeling and simulation work related to clusters, self-assembly, artificially-structured materials and nanoproperties of materials.

Office of Naval Research(ONR):

Synthesis and processing of nanoscale powders including processing of bulk non-oxide ceramics from nanopowder precursors and thermal spray processing of nanomaterials.

Appendix 2: Patents Granted by the USPTO in Nanostructured Materials and related areas.



Patents Granted by the USPTO in Nanostructured Materials and related areas by type assignee and country.

Economy	(01) Industry-I	(02) Government-G	(03) Academy-A	(04) Individuals	(05) I & A	(06) G & A	(07) I & G	Total
United States	146	12	57	15	1	2	1	234
Japan	16	1		2		1	1	21
Canada	3		4	3				10
Chinese Taipei	3	3						6
Korea, Republic of	1	4						5
Australia	3	1						4
Singapore					1			1
Hong Kong China			1					1
France	16		2	3		1		22
Germany	15		5	1				21
Ireland	6							6
Switzerland	4		2					6
Netherlands	5							5
Belgium	4							4
United Kingdom	2							2
Israel	1		1					2
Russian Federation				1				1
Romania				1				1
Norway	1							1
Austria	1							1
Italy	1							1
Sweden	1							1

Patents Granted by the USPTO in Nanostructured Materials and related areas by area and country.

US Patent Survey by Nano Classification

Economy	(2) Materials	(3) Tools & Instrumentation	(4) Devices	Total
United States	189	7	38	234
Japan	15		6	21
Canada	8		2	10
Chinese Taipei	4		2	6
Korea, Republic of	2		3	5
Australia	1		3	4
Hong Kong China	1			1
Singapore	1			1
France	21		1	22
Germany	17	1	3	21
Switzerland	5		1	6
Ireland	5		1	6
Netherlands	3		2	5
Belgium	4			4
Israel	2			2
United Kingdom	2			2
Norway	1			1
Romania	1			1
Italy			1	1
Sweden	1			1
Austria			1	1
Russian Federation	1			1

Date of Patent : 2000/1/1—2001/6/12

Appendix 3: Future Applications of Nanostructured Materials

Area	Future applications
Energy technologies	- new types of solar, such as the Grätzel cells - window layers in solar cells from nanostructured semi-condcutors - high energy density (rechargeable) batteries - smart windows based on the photochrome effect or electrical orientation - better insulation materials - nanostructured rocketfuel ignitors for longer-lasting satellites - on-line repairable heat-exchangers in nuclear power plants - magnetic refrigerators from superparamagnetic materials - elimination of pollutants in power generation equipment
Automobile industry	- corrosion protection of an automobile's coach-work, stainless steel - elimination of pollutants in catalytic converters - electrical or hybrid cars using batteries based on nanostructured materials - smart windows - automobiles with greater fuel efficiency using nanostructured spark plugs and heat-resistant coatings for engine cylinders - scratch-resistant top-coats of hybrid materials - intrinsically simple couplings for automobile fabrication - automobile engine performance sensor
Optics	- graded refractive index (GRIN) optics: special plastic lenses - scratch-resistant plastic reading aids, lenses, visors, head lights and car windows - anti-fogging coatings for spectacles and car windows - cheap colored glass - optical filters
Electronics: materials for the next-generation computer chips	- single-electron tunneling transistors using nanoparticles as quantum dots - efficient electrical contacts for semiconductor devices - electrically conducting nanoceramics - conducting electrodes for photoconductors and solar cells - capacitive materials for, e.g., dynamic random access memories (DRAM) - magnetic memories based on materials with a high coercivity - magnetorestrictive materials, important for shielding components and devices - soft magnetic alloys such as Finemet - resistors and varistors (voltage-dependent resistors)

Area	Future applications
Electronics: materials for the next-generation computer chips	- high-temperature superconductors using nanoparticles for flux pinning - liquid magnetic O-rings to seal off computer disk drives - 'nanophosphors'for affordable high-definition television and flat panel displays - electroluminescent nanocrystalline silicon, opening the way for optoelectronic chips and possibly a new type of color television
Optoelectronics	- efficient light-emitting diodes based on quantum dots with a voltage-controlled, tunable output color - plastic lasers using nanoparticles as an active scattering medium - optical switches and fibers based on nonlinear behavior - transparent conducting layers - three-dimensional optical memories
High-sensitivity sensors	- gas sensors for Nox, Sox, CO, CO2, CH4 and aromatic hydrocarbons - UV sensors and robust optical sensors based on nanostructured silicon carbide (SiC) - smoke detectors - ice detectors on aircraft wings
Catalysis	- photocatalytic air and water purifiers - better activity, selectivity and lifetime in chemical transformations and fuel cells - precursors for a new type of catalyst (Cortex-catalysts) - stereoselective catalysis using chiral modifiers on the surface of metal nanoparticles
Medical	- longer-lasting medical implan'ts of biocompatible nanostructured ceramics and carbides - coatings for medical applications
	- tougher and harder cutting tools, especially based on nanocrystalline carbides - high performance parts for the aerospace and the building industry - gas-tight and dense metals - fire protection coatings - 20-nm-thin foil for food packaging - thermoelectric materials (used for thermocouples) - ceramic membranes for energy-efficient separation methods (for uranium, milk, malt beer etc.)

Area	Future applications
Various other applications	- ‘self-lubricating’ coatings based on diamond-like nanocomposites, to be used on sliding parts in the automotive, chemical, pharmaceutical, or biomedical industry - easy-to-clean surfaces, for instrance anti-graffiti coatings for trains, glass walls and brick walls - strong plasitc floors - binder for natural fibers and core sand - ferrofluids for mechanical vibration damping in stepper motors, magnetic muscles, dirt absorbers in waste separation facilities - molecular filters - fast-burning metal powders for the military

5.5 Nanotechnology Issues for Developing Economies (Philippines)

Dr. Fabian M. Dayrit and Dr Erwin P. Enriquez
Ateneo de Manila University, Philippines

The events following the September 11, 2001, terrorist attacks on the United States have jolted the community of nations into a reassessment of its development plans. Its effects will most likely be felt in the following ways: 1. All nations may suffer significant economic slowdowns beyond that already forecast prior to the terrorist attacks. While this is expected to be bad for developed economies, it will most likely be worse for developing economies. 2. The heightened need for security will funnel more resources into intelligence and military applications, and away from the development needs of society. The already large global spending on weapons will likely increase, and divert financial, institutional, and human resources from other social needs.

Given this mood of uncertainty, it is encouraging that the APEC sought to reaffirm its commitment to regional and global cooperation. To quote from the Joint Statement of Thirteenth APEC Ministerial (October 18, 2001):

"*In the face of the less favorable global and regional economic environment, Ministers affirmed their confidence in the medium and long-term prospects of growth in the APEC region and agreed to strengthen cooperation to tackle the short-term economic difficulties. In this connection, Ministers reaffirmed the importance of promoting dialogue and cooperation with a view to achieving sustainable and common development.*"

The challenge that confronts us all, particularly in the developing world, is: How can we develop nanotechnology so that it can contribute to "*sustainable and common development*" even in this post-September 11 scenario? Two important questions which are hanging at this time are: What will the S&T budgets and allocations look like? How will international cooperation in S&T be affected?

The three major scientific and technological developments which are predicted to radically influence economic and social development in the early 21st century are information and communications technology (ICT), molecular biology and biotechnology (MBB), and nanotechnology. The current and future impact of IT and MBB are already well recognized, and these have dominated investments in the technology sector.

In comparison, nanotechnology seems to be a more esoteric area whose impact is still many years away. Because nanotechnology is the newcomer, it faces the usual birth pains and expected comparisons with its very successful older siblings, biotechnology and ICT. In developing economies, securing support for the development of nanotechnology in competition with the more established fields can therefore become difficult.

This paper therefore seeks to answer the following questions and issues regarding the development of nanotechnology in developing economies:

1. *How can developing economies get involved in nanotechnology? What areas should be developed?*
2. *How can developing economies put together a viable R&D program in nanotechnology?*

1. How can developing economies get involved in nanotechnology? What areas should be developed?

Nanotechnology refers to the design and synthesis of materials and devices at the molecular and atomic level. Before the advent of nanotechnology, materials scientists could control the fabrication of materials down to the micron level (10^{-6} m). Meanwhile, chemists and molecular biologists were able to develop methods for controlling synthesis of molecules of moderate size, such as dendrimers, supramolecular complexes, peptides and nucleic acids. Nanotechnology brings together these separate fields into one.

Nanotechnology represents the logical development of science and engineering. Because it offers so many novel and important properties, it is certain to be one of the critical technologies of the future. Indeed, it is certain to have significant impact on ICT and MBB.

Just as microelectronics replaced the vacuum tube, nanotechnology will in time replace microelectronics. However, it is likely that nanotechnology will eventually occupy a more dominant role precisely because it encompasses more fields and is more widely applicable.

Because nanotechnology will likely have a significant impact in so many areas, it is imperative that developing economies embark on a nanotechnology S&T program to develop key capabilities and niche areas. However, because nanotechnology encompasses so many areas, and because of the high cost of equipment and human resource development, the choice and strategy should be carefully considered. Because the competition for resources pits basic needs vs R&D, it is clear that the nanotechnology development strategy needs to be carefully planned. Following are some criteria that should be considered when deciding on the recommendation of niche areas for a particular developing country:

- Strategic importance of the technology in terms of its S&T characteristics.
- Strategic importance of the technology to industry and agriculture, society, environment, and national security. These areas should address the concerns of poverty and competitiveness.
- Presence of a strategic advantage or natural strength.
- Current and potential capabilities of the S&T community, whether resident locally or overseas, and the ability to harness foreign capabilities.

Because nanotechnology interfaces with so many fields, there is a long list of possibilities, and it is indeed difficult for a S&T planning agency from a developing country to decide which direction to choose.

Based on the assumption that most developing economies have significant interests in agriculture, public health, environment, and water, the following research areas are recommended for development:

1. **Biosensors**
   - ✓ Strategic importance – Biosensors can be harnessed to improve agricultural productivity, public health, water quality and the environment. Thus, this technology addresses the priority goals of many governments of poverty alleviation, competitiveness and improvement of the well being of the poor.
   - ✓ Competitive advantage – At the heart of the biosensor is biological compound, for example, an enzyme, DNA, carbohydrate fragment or natural product (secondary metabolite). Many economies can turn to their rich biological resources to obtain such materials.
2. **Optoelectronic devices**
   - ✓ Strategic importance – It is likely that future developments in ICT and microelectronics (soon to be replaced by "nano-electronics") will be based on optoelectronic phenomena. The possible range of applications includes all current uses of microelectronics, and possibly more. Optoelectronics can also be merged with biosensors.
   - ✓ Competitive advantage – The capabilities of many developing economies in optoelectronics are limited and need to be expanded.
3. **Pharmaceuticals**
   - ✓ Strategic importance - – The high cost of drugs remains one of the challenges of health care. Notwithstanding the growing importance of combinatorial chemistry in drug discovery, many complex natural products will likely remain beyond the capabilities of this technology. However, there is a need to develop more efficient and cost-effective extraction and purification technologies. Improved purification processes may be built on the principle of molecular recognition and molecular imprinting. Part of this effort must include the development of high throughput biological assay methodologies.
   - ✓ Competitive advantage – Many economies have unique biodiversity (terrestrial and marine) which remain to be tapped.
4. **Water purification technologies**
   - ✓ Strategic importance – The need for clean water, especially in rural areas, will increase in the future. Water purification

technologies suitable for household and industrial use will meet this anticipated need. This is an essential adjunct to public health.

- ✓ Competitive advantage – Many economies have unique bio-diversity (terrestrial and marine) which remain to be tapped.

5. **Conducting polymers and composites**
   - ✓ Strategic importance – Polymer science shall continue to be an important field of development because it enables us to design and fabricate materials according to specific requirements, and which should include environmental considerations.
   - ✓ Competitive advantage – The capabilities of many developing economies in polymer science are limited and need to be expanded.

2. How can developing economies put together a viable R&D program in nanotechnology?

Nanotechnology is the convergence of the sciences and, as mentioned above, represents the logical evolution of S&T. It is made up of many of the same basic tools of S&T, with the added ingredients of close interdisciplinarity and targeted product development.

In putting together the nanotechnology program, We wish to stress two important philosophies: First, researchers and existing institutions should be asked to refocus and/or retrain and that they will be supported if they do so. Second, cooperation and interdisciplinarity among institutions (which are often competitors) and among the different disciplines (which normally do not interact) must be strongly encouraged. These may require a "reengineering" of institutions.

What strategy can we adopt in putting together a viable R&D program in nanotechnology? The nanotechnology initiative can be grouped into four inter-related objectives or phases:

<u>Objective 1: Education and development of capabilities in theoretical foundations</u>. This can be viewed as the preparatory stage to enable students and future researchers to understand the theories and principles of nanotechnology. The following activities are suggested:

- Development of introductory materials at the high school level.
- Development of appropriate courses and degree programs both at the undergraduate and graduate level.
- Support for research and training on theoretical aspects of nanotechnology. This can include mathematical and physico-chemical modeling studies, as well as advanced training into quantum theories.

Objective 1 should be commenced immediately and be sustained indefinitely because this provides the basic theory and preparation needed for students to enter the field. The infrastructure requirements are not expected to be so large as the main requirements will be computers, technical literature, and support for scholarships and fellowships.

Objective 2: Development of capabilities in physico-chemical analyses. Chemico-physical analyses are basic capabilities that must be developed. These enable a country to characterize a product or material, whether this be for trade purposes, quality assurance, or reverse engineering of a product or device. The following types of analyses should be considered:

- Solid structure determination.
- Surface analysis.

Because of the high cost of instruments usually needed for physico-chemical analyses, Objective 2 requires the development of reliable and accessible instrumentation centers.

Objective 3: R&D in nanotechnology devices and techniques. Nanotechnology R&D should have the primary objective of producing prototypes. The choice of application should consider the local needs and priorities. Ancillary targets should include patents and related outputs. Potential industry partners may be invited at this stage.

Objective 4: Development of capabilities in device fabrication; product development. This step takes the technology beyond the laboratory to the pilot production and product development. Local and international partnerships may be sought as needed.

Ending comments:

In conceiving this conference, APEC demonstrated its economic and scientific foresight. Despite the events of September 11, it is our hope that the goals of "*sustainable and common development* "will not change.

The Economy Papers

6.1 Australia

6.2 Canada

6.3 Chinese Taipei

6.4 Japan

Nanotechnology in Japan
Tetsuya Yamazaki
Science and Technology Foresight Center
National Institute of Science and Technology Policy
Ministry of Education, Culture, Sports, Science and Technology, Japan

1. Background and Definition of Nanotechnology

From 1970's, LSI design rule have been shrunk by x0.7 and integration quadrupled every 3 years. Today, minimum line width in ULSI reaches around 130-150nm in production, and 20 nm in R&D.

The technology of today's LSI is called "Top down", that means processes cutting something to small to make functional device. Since the limitation of the present silicon process is foreseen within 10 – 20 years, because of limitation from lithography resolution and transistor physical limitation. So novel paradigm has been researched in these 20 years.

The concept of "bottom-up" came from the talk given by Richard Feynman in 1959. That means processes manipulating atom or molecule to build up some functional devices. This is the origin of "Nanotechnology". A bottom-up technology seems very attractive, but it seems tremendously difficult to be robust or highly reliability in terms of the integrated circuits.

Today, the definition of nanotechnology contains very wide technology areas and seems to be confused. It seems to contain at least these five technology areas,

1) Conventional "top-down" technologies under 100nm scale, containing semiconductor technologies, quantum devices, and many information and communication technologies.
2) "Bottom-up" technologies manipulating atoms or molecules directly, containing biotechnology.
3) Material technology that materials have nano scale structure and novel functions, like carbon nanotube and nano metal particle.
4) Micro machine or MEMS(Micro Electronics Machine Systems) and LoC(Labo on Chip), that has μm or up to mm scale.
5) Basic science and technology for example, quantum theory, molecular simulation technology and measurement technology for nm scale.

In this paper, I would like to talk about "Nanotechnology" containing these 5 technology areas in Japan.

2. Nanotechnology in the Government Part

In Japan, the Atom Technology Project, "Research and Development of Ultimate Manipulation of Atoms and Molecules", was the start of a government's funded project for nanotechnology (in means of the bottom-up technology). This project is funded by the Ministry of Trade and Industry, and started in 1992 to 2002. Objectives of this project are, "Identification and Manipulation of Atoms and Molecules", "Formation and Control of Nano-structures in Surfaces and Interfaces", "Spin Electronics" and "Theoretical Analysis of Atomic and Molecular Dynamic Processes".

After this, many projects or funds have been established in nanothnology area by ministries or agencies. But ministries or agencies had decided their R&D policies each other, so it was sometimes poor in strategy.

In 1995, the Science and Technology Basic Low had been established to make strategic R&D plan. According to this low, the Council for Science and Technology Policy (CSTP) was established and it made recommendation for the Science and Technology Basic Plan (1st period, 1995 to 2001). This plan requested to increase budgets related to science and technology, especially in basic science area, and to increase number of post-doctor to be up R&D power. But it was still poor in strategy. For example, the plan didn't decide what facility takes leadership in making S&T policy.

In Jan. 2001, CSTP was renewed and moved under Cabinet Office. And CSTP made a recommendation for the Science and Technology Basic Plan (2nd period, 2001 to 2006). In this new plan, CSTP requested to spent 200B$ totally in S&T area in this five years, and decided four important areas to allocate resources of budgets and researchers. Important areas are Life science, Information technology, Nanotechnology and Materials and Environmental S&T. And in each important area, project team under CSTP discussed about strategy and resource allocation for budget and researchers.

Under this condition, total budget for R&D related nanotechnology in FY2001 is up to 430M$, which increases three times from 1997 budget. Detail of budget is,

1) 250M$ budget for MEXT (Ministry of Education, Culture, Sports, Science and Technology, large part of budget is for basic and application research in universities,
2) 165M$ budget for METI (Ministry of Economy, Trade and Industry), large part of budget is for research projects in semi-conductor and electronics technology area and material technology area,
3) Small amount for the Ministry of Agriculture, Forestry and Fisheries, and the Ministry of Public Management, Home Affairs, Posts and Telecommunications, use for biotechnology and telecommunication technology area.

Inside of technology areas, priorities are on the semiconductor technology and nanodevice technology area, but it seems too small budget for the bio-nanotechnology area and the basic science area.

3. Nanotechnology in the Industry Part

In the industry part, semiconductor industry is also the main player. Many projects collaborated with industry and universities, and partly or fully budgeted by government, are running now. Main projects are listed in table 1.

Table 1. Project in Industry Part

STARC □ Semiconductor Technology Academic Research Center □ 1995- ; collaborate with university
Selete □ Semiconductor Leading Edge Technologies, Inc □ 1996-2006 □ 300mm Wafer line
Asuka □ Advanced Semiconductors through Collaborative Achievement □ 2001-2008 □ 70nm SoC
Mirai □ Millennium Research for Advanced Information Technology □ 2001-2008; 50nm or less LSI
ASUKA and ASRC in AIST; 50-70nm basic research collaboration with Association of Super-Advanced Electronics Technologies ASET and University

(1)ASRC: Advanced Semiconductor Research Center:
(2))AIST: National Institute of Advanced Industrial Science and Technology

In 1990's, Japanese semiconductor industry had lost its competitiveness versus U.S., Korea and Chinese Taipei. So nanotechnology is thought as an important way to get back its competitiveness.

In the other hand, nanomaterials are also important technology in Japan. Carbon nanotube or nanoparticles are very useful as a catalyst or combined materials those add novel or superior characteristics to conventional materials. Many companies and universities had started their research plan, and some of them will go to production stage in next 5 or 10years. FED and a fuel cell using carbon nanotubes, and a glass coated with nano particles which keep clear itself are hopeful candidates.

4. Issues and Foresight in Nanotechnology

Nanotechnology is very attractive for its novel functions or superior characteristics, but there are also tremendous difficulties lying to realize them. Those problems are like this,

1) Productivity: In the bottom-up scenario, it is expected that a complex chemistry or self-organization method to make a functional block. Using biotechnology may be one solution for this problem. But there is still large gap to make up complex system like system LSI. And some quantum devices only work in very low

temperature, so it is difficult to use these devices in mass-production area.

2) Reliability: Today's semiconductor technologies have huge amount of engineering techniques and knowledge to keep reliability. It is expected to need 10 years or more that nanodevices will reach same level.

3) Cost: Today's semiconductor factory needs huge machine cost, and it still increase by generations. In the case of nanotechnology, dose it need same cost? It may be case by case, but low productivity and complex process means high cost. So balance between cost and function is very important.

4) Interface between nanotechnology and conventional technology: Nanodevices in the scale of atoms or molecule, have very low level signals like current of single electron, so it expected huge difficulty to detect and amplifier these signals to effect in conventional systems or outer world. And these small signals are easily lost in environmental noises. So it becomes very important to make functional interface or detection system to integrate in small chip or high density system, but it seems there are not enough effort or resource in this area.

NISTEP (National Institute of Science and Technology Policy) have been researching in foresight for development of science and technology each 4 or 5 years. The 7th foresight was done from 2000 to 2001. The result of this foresight is published in July 2001. Table 2 shows results of important issues in nanotechnology area. These results show that it will need more than 10 years to realize most of nanotechnologies.

5. Conclusion

It seems huge difficulty to realize nanotechnolory especially bottom-up scenario. But most attractive points like novel functions or superior characteristics are also exist same area.

So it seems there is enough worth to make effort hardly in nano-technology.

But it will be important to keep balance between cost and function, and also important to harmonize the functional blocks consist of the nanotechnologies with the conventional technologies like semiconductor devices.

Table 2. Foresight for Nanotechnology Issues

1) Nano processing, Nano measurement

2010	Length, displacement and surface roughness measurement to the Å (0.1nm) order, and measurement to the femto-second order become possible
2013	Development of semiconductor microprocessing and measuring technology for 1nm resolution for manufacturing 10nm rule LSI
2015	Development of technologies that can freely control the super-molecular structure of organic polymers (higher order functional structure formed between molecules) utilizing self-organization functions
2016	Development of three-dimensional cumulative processing technology of nanometer scale
2020	Practical use of single electron memory device

2) Nano material

2013	Development of technology for manufacturing nano-tubes with structutres as designed
2015	Practical use of functional organic and inorganic composite materials with constituent parts of the order of sub-nm to several 10nm
2015	Practical use of technology enabling the mass production of LSI with minimum pattern of 10nm
2016	Development of X-ray microscopes capable of resolution of 10nm or less
2018	Practical use of memory material that provides specific nano-scale structure and characteristics through self organization

3) Next generation information communication

2015	Development of a magnetic recording hard disc of 1TB per square inch recording density
2015	Practical use of VLSI with more than 256Gb per chip
2105	Practical use of LSI operating at more than 50GHz clock
2018	Development of devices that utilize switching functions of a single molecule/atom
2019	Practical use of TOPS (tera-operations per second) level microprocessors
2023	Development of logic LSIs and memory LSIs in which the basic switching element is a single molecule

4) Nano bio/Medical treatment

2013	Widespread use of single-responsive missile drugs capable of efficiently reaching targeted parts such as tumor cells
2015	Practical use of single atom/ molecule manipulation techniques as methods for devise fabrication and gene manipulation
2017	Low-invasive surgical techniques using micromachines or robots account for the majority of surgical operations
2021	Development of diagnostic and medical treatment micromachines capable of traveling on their own inside organisms (body cavity organs)

6.5 New Zealand

Nanotechnology in New Zealand
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Introduction

Like many other nations, New Zealand has recognised the potential for revolutionary and economically important discoveries from basic research on nanostructured systems and devices. Considerable effort has gone into investigating the role nanotechnology can play in the future of a small nation such as New Zealand, and targeted research investments have recently begun at a small scale. In parallel with this policy development and direction setting, a number of research groups have initiated bold and ambitious research programmes of their own and these are beginning to see successful outcomes. This Economy Paper will outline the current status of nanotechnology research in New Zealand and will highlight the important role it is expected to play in the nation's economic evolution.

Investment in Nanotechnology

Investment in nanotechnology-related research has primarily been government funded, using the general-purpose funding mechanisms. For nanotechnology research these mechanisms are the Marsden Fund (MF)[1] for basic research, together with the Public Good Science Fund (PGSF) and New Economy Research Fund (NERF)[2] for research with more potential for economic benefit.

Historically there has been some investment in the background area of microelectronics, with the establishment of a research facility at a Crown Research Institute (CRI) – formerly part of the Department of Scientific and Industrial Research (DSIR) – in the 1980s. This was established even though New Zealand didn't (and still doesn't) have any microelectronics manufacturing industry. This facility successfully prototyped a number of different microelectronic circuits and sensors, but commercial uptake has been relatively limited. In addition, there is a broad base of research strength in biological and chemical sciences in New Zealand, and many well-established groups can put valid claims to having been involved in nanotechnology research for many years.

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1 Investment in the Marsden Fund currently runs at $NZ27.8M ($US11.7M) per annum and is spread over the full range of scientific research, including social science and medicine.

2 PGSF and NERF investment is around $NZ300M ($US125M) per annum.

Specific nanotechnology-branded investment began in the mid 1990s, mainly with MF support. For example, in 1996 a project was initiated at the University of Canterbury with a single principal investigator, a postdoctoral fellow and a PhD student to investigate a low cost optical nanolithography technique[3], with significant success. This led to the development of a Nanostructure Engineering, Science and Technology (NEST) group, which has expanded considerably and now runs a more extensive programme[4] supported by one MF grant and two NERF grants. The overall investment in this group's activities has been approximately $NZ3M ($US1.3M) over the past 5 years, and the activities have expanded to include researchers from three other Universities and two CRIs.

Other nanotechnology-related work - predominantly chemistry-based – has been ramping up since the mid 1990s as well. For example, since the MF was initiated in 1994 there have been a total of 11 nanotechnology programmes funded (including the NEST programmes above), with a total investment of $NZ4.1M ($US1.7M). Investment details from the PGSF and NERF for this period are not available, but the amount would be similar, giving a total government investment of around $NZ10M ($NZ4.2M). This is very small in international terms, and needs to be increased significantly if New Zealand is to play a credible role in this important area.

The researchers themselves have provided the direction for most of New Zealand's investment in nanotechnology, however in late 2000 a small, targeted investment was initiated by the Foundation for Research Science and Technology (FRST), one of the government's science investment agent. A modest amount of $NZ300,000 ($US125,000) per annum has been invested initially, which has been divided between the NEST-based physical sciences nanotechnology programme and a newly-established network of chemistry-based researchers. One important result of this targeted investment is the establishment of a New Zealand nanotechnology workshop series, which will be used to bring the diverse group of researchers together on an annual basis.

Nanotechnology is a particularly equipment intensive field of research, and there has not yet been any coordinated plan to equip New Zealand laboratories with the necessary tools. It is worthy of note that the current funding mechanisms for research in New Zealand make it particularly difficult to purchase any significant capital equipment. Some research can be carried out, however, using traditional research equipment from the physical, chemical, biological and engineering sciences. In the case of the Canterbury NEST group, equipment has often been purchased on the second-hand market, or donated by other research institutes. In some cases new equipment has been purchased from University funds, and the total investment in equipment and laboratory space has been under $NZ1M ($US0.4M). Infrastructure investment in other institutes would be of a similar magnitude. Whilst

3 For a review of this work see Alkaisi, M.M., Blaikie, R.J. and McNab, S.J. *Nanolithography in the Evanescent Near Field*, Adv. Mater. **13**, 877-887 (2001).

4 For details of the NEST group's research activities see www.elec.canterbury.ac.nz/research /nest/

this approach does not give ready access to the most state-of-the-art tools, it has been a reasonable approach for ramping up activity slowly in a small economy where research funds are limited.

Number of Researchers Involved

The number of nanotechnology researchers in New Zealand is steadily growing. From a small start in the late 1990s the University of Canterbury NEST team now numbers 5 academic staff, 2 postdoctoral fellows, 5 support staff and approximately 12 postgraduate students. The group leads a programme that involves 10 more PhD-level researchers and 6 research students at other Universities and CRIs, giving a total of 40 people. In addition, the other materials, chemical or biological science personnel that perform some form of nanotechnology research in New Zealand would be at least the same number. Whilst it is very difficult to perform a detailed head-count, the total number of researchers involved is around 100, in a population of only 3.8 million. Given the prospects for expanding economic and scientific developments from nanostructure science, this number would be expected to double every 18 months to two years in the short-term future.

Programme Areas

There are nanotechnology-based programmes in many of New Zealand's Universities and CRIs, although many reside within their traditional science fields. In geographical order, from North to South, a survey of research activities yields the following active programmes:

- ***University of Auckland***
  - Research Centre for Surface and Materials Science. This centre offers a number of powerful imaging and surface analysis techniques including X-ray photoelectron spectroscopy, Auger electron spectroscopy, electron microscopy, atomic force microscopy and energy dispersive x-ray analysis.
  - Department of Chemistry. Activities include Fullerene chemistry and the design/synthesis of elaborated porphyrin complexes.
- ***Massey University***
  - Nanotechnology Research Centre, Polymer Group and Porphyrin Group. These groups specialises in the synthesis of arrays of man-made porphyrins. They have developed a building block approach to array construction that will enable the construction of large arrays of porphyrins, which potentially could duplicate the properties of chlorophyll.
  - Scanning probe microscopy development. Hardware and software is being developed to drive a scanning probe microscope.

- ***Institute of Geological and Nuclear Sciences***
  - o Ion Beam Analysis and Synthesis. Research into modification and analysis of surfaces and interfaces by ion beams, including the formation of silicon nanowhiskers by ion implantation into silicon nitride. Analysis techniques include Rutherford backs-cattering, particle-induced x-ray emission, particle-induced gamma ray emission and nuclear reaction analysis.
- ***Industrial Research Limited***
  - o Applied Inorganic Chemistry Team. Research includes the development of novel and improved microporous, supermicro-porous, mesoporous and macroporous silicate catalyst and molecular sieve materials.
  - o Sensors and Electronics Team. A long history in the development of novel microelectronics-based sensors and systems. Current activities include the development of an integrated 'electronic nose' and the investigation of cell and molecular sorting using electromanipulation.
  - o Light Standards Group. Research includes the optical properties of superlattices and multi-layered materials, diffuse and scattering materials (including ceramic superconductors and cermets).
- ***Victoria University***
  - o School of Physical and Chemical Sciences. Research includes: the synthesis and study of carbon nanotubes, amorphous semi-conductor superlattices, conducting polymers and colossal magneto resistance materials for magnetic memories; the development and use of high performance nanostructured silica materials from waste geothermal water.
- ***University of Canterbury***
  - o Nanostructure Engineering, Science and Technology (NEST) group. Significant research activities include: development of low cost nanolithography techniques; investigation of etch-induced damage and optical emission effects in gallium nitride; micro- and nano-structured surfaces for improved optical films and improved light trapping in solar cells; atomic cluster structure determination and cluster-based device studies; micromachined devices for sub-mm wavelengths; near field optics experiments and simulations; and molecular beam epitaxy growth of novel electronic, optical and magnetic materials. On site research facilities include electron microscopy, atomic force microscopy, optical and electron beam lithography, reactive ion etching, dual-chamber molecular beam epitaxy, optical spectroscopy, atomic cluster source with in-situ analysis and deposition. This group organised a successful *Advanced Research Workshop on Semiconductor Nanostructures* (Queenstown, New Zealand, 3-5 Feb. 2001) for more

than 100 international experts in the field, and they have recently filed the first nanotechnology-related patent in New Zealand.[5]

  - Department of Chemical and Process Engineering. Nanotubes research is carried out, and it is to be noted that an early discovery of nanostructured carbon filamentary growth was made here in the 1970s.
  - Department of Chemistry. Design of new supramolecular structures, as well as research into the use of carbon nanofibre electrodes for electrochemistry.

- ***University of Otago***
  - Department of Physics. Nanoengineered thin film optical coatings have been developed using serial bi-deposition techniques, result-ing in the ability to engineer birefringent and chiral properties to a greater extent than is possible using naturally-occurring materials.
  - Department of Chemistry. Research includes molecular self assembly and the development of new electroluminescent organic compounds.
  - Department of Biochemistry. Self assembly has been studied in conjunction with efforts to image nucleic acids for a DNA sequencing based on direct molecular inspection.

Future Plans

Significant acceleration of the growth of nanotechnology research in New Zealand will require high-level input to ensure that the diversity of current activities is managed to produce a greater deal of coordination of activities. To this end there has not been a great deal of progress, apart from a modest investment ($NZ300,000 per annum) by the FRST in 2000. There is reluctance by New Zealand's scientific research funding agencies to identify special topics that are preferentially funded over others. Formation of research networks and clusters is encouraged, but it is left to the researchers to instigate this in general. This 'bottom up' approach does have the advantage that sensible partnerships are formed at an early stage. However, it does mean that nanotechnology must compete with many well-established research programmes (mainly in the biological and agricultural sciences in New Zealand) to secure sufficient funding.

One very significant recent development is the announcement of the establishment of a small number (three to six) of Centres of Research Excellence (CoREs) within New Zealand Universities[6] , with overall funding at the level of $NZ12M ($US5M) per annum, as well as a one-off $NZ20M ($US8.4M) equipment fund. This will provide a sufficient level of funding to enable a coordination of

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5 S. Brown and J. Schmelzer, *Nanoscale Electronic Devices & Fabrication Methods*, New Zealand Patent Application No. 513637. (Provisional Application filed 20 August 2001).

6 The Royal Society of New Zealand will administer the CoRE Fund, and information can be found on their web site at http://www.rsnz.govt.nz/funding/core/.

research efforts in a small number of areas. Nanotechnology is one area that could be established as a CoRE, and a number of groups have combined to put forward a strong proposal. At the time of writing the application process is still underway, and decisions are due in early 2002. The success of nanotechnology researchers in securing funding through this mechanism will be critical in the future development of the field in New Zealand.

Local Issues

Nanotechnology research in New Zealand has been difficult to establish. The country's economy has traditionally been centred on agricultural production, and the research base reflects this. The long-term decline in returns from agricultural production has resulted in static or declining investments in basic research, and the development of new research areas such as nanotechnology is clearly difficult in such an environment. In addition, the manufacturing and technology-based industries that New Zealand does have are not focussed on basic materials and devices, but rather are more concerned with systems and software; there has been no industry push for the development of a nanotechnology research effort, either.

However, for the development of new technology and new industries in New Zealand nanotechnology is very attractive. The field is new and exciting, and it is not clear which areas of research will result in new, high profit enterprises; there are possibilities for applications in fields from medicine to microelectronics, and research coming out of a laboratory in New Zealand has just as much chance of providing critical breakthroughs as that from elsewhere. In addition, the high value-to-volume ratio for nanotechnology products eliminates New Zealand's geographical isolation as a barrier to delivery of products to markets quickly and at low cost; the country is well serviced with communications infrastructure, and well linked to the rest of the world with daily air services. Finally, the environment for establishing start-up enterprises to exploit research gains is improving in New Zealand, and some venture capital funding is available. The recent slowdown in the world economy may hinder these positive developments, but it is critical that commercial opportunities be explored as aggressively as possible.

6.6 Philippines

Status of Nanotechnology in the Philippines
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Current status

Nanotechnology is still in the process of transition in the Philippines from an academic curiosity to an area of active research interest. The current research interests are mainly in the following niche areas:

- **University of the Philippines**:
  - National Institute of Physics: surface physics, microelectronics and semiconductors, photonics, liquid crystals
  - Institute of Chemistry: polymer chemistry, materials science, electrochemical and photochemical devices and catalysts
  - National Engineering Center: materials engineering, electronics engineering, robotics
- **Ateneo de Manila University**:
  - Department of Chemistry: polymers & biopolymers, surface chemistry
  - Physics: photonics, materials science
- **University of Santo Tomas**:
  - Research Center for the Natural Sciences: electrochemical sensors, biosensors
- **De La Salle University**:
  - Department of Chemistry: polymer science, dendrimers
- **Department of Science and Technology**:
  - Metals Industry Research & Development Center: surface characterization
  - Industrial Technology Development Institute: metrology, polymer science

  Currently, the specific areas of application include:
  - Microelectronics and semiconductors
  - Environmental – detection and clean-up
  - Materials – polymers and surface coatings, biodegradable materials
  - Medical – enzyme biosensors, liposomes

Plans

Because nanotechnology is such an interdisciplinary field, there is a need to bridge the curricular and cultural gap between the sciences and engineering.

Nanotechnology must be able to merge the theoretical interests of the sciences, with the practical bent of engineering, and finally with the economic and commercial requirements of business and industry.

Some specific measures to be undertaken:

1. Creation of a nanotechnology development committee which will include representation from academe, R&D institutes, government policy makers, and industry.
2. Upgrade the curricula:
   (a) Introduce nanotechnology topics in basic courses in the science and engineering curricula;
   (b) Integrate nanotechnology into advanced courses of the various disciplines;
   (c) Introduce nanotechnology in science courses for non-science majors (e.g., business and economics).

6.7 Singapore

Singapore's Nanoscience Initiative "The next small thing"
National Science and Technology Board

1. Brief History

1.1 The 1960s : A Time of Turbulence and Economic Uncertainty

In the 1960s, Singapore was considered a third world country with a GNP per capita of less than US$320. We had poor infrastructure and insufficient capital. Our economy was supported by low-end commerce with little or no direct foreign investment. Industries were few and only for domestic consumption. Labour unrest was also common due to massive unemployment brought on by the British troop withdrawal.

In the midst of such social turbulence, creating employment through intensive industrialisation was Singapore's prime objective.

Virtually unknown as a lucrative investment location on the global map, it was challenging for Singapore to attract foreign investment through creating an environment conducive to industrial development.

The Jurong Industrial Estate was originally a wasteland along the west coast of the island. Jurong, as it is commonly referred as was set aside for Singapore's first industrial estate. The successful transformation of Jurong in the 1960s from what was a swamp has come to stand as a pioneering success of Singapore's industrialisation programme.

The next step was to attract labour-intensive industries. To generate employment, companies were welcomed to set up in the Jurong Industrial Estate. Singapore's industrialisation programme began with factories producing garments, textiles, toys, wood products and hair wigs. At the same time, some relatively capital and technology-intensive projects began operation such as Shell Eastern Petroleum and the National Iron and Steel Mills.

1.2 Search for a Global Market

The separation of Singapore from Malaya in 1965 meant the loss of a hinterland and a large domestic market. There was therefore a need to accelerate the programme of export-oriented industrial development, by attracting export-oriented industries for the global market.

It was during this period that the government though the Economic Development Board (EDB) set up its operations overseas with its first overseas centres in Hong Kong and New York to attract investments into Singapore.

Today, more than 6,000 international companies have invested in Singapore and are engaged in a myriad of activities, from R&D to manufacturing to traded services to regional headquarters. These companies have found Singapore an excellent pro-business location and partner for success. Singapore will continue to reinvent itself and add value to businesses here as it develops into vibrant and robust knowledge-based economy.

With the world as its arena, Singapore's open economic policies, willingness to learn and its ability to adapt to global trends have enabled it to progress, to remain competitive. Singapore's GDP growth was 9.9 percent in 2000. Please see annex B for the economic sectors and development trend.

1.3 2001 and beyond

Singapore is one of the world's most competitive economies largely resulting from sound fundamental policies. Singapore operates as an open market economy with a global network and perspective. It has a highly efficient, flexible and qualified workforce. Internally, the tripartite co-operation among workers, labour unions and government ensures a common understanding to overcome national problems. This in turn allows for domestic stability and peace, with the low rate of labour strikes over the past 33 years as testimony.

Most importantly, the Singapore government promotes a pro-business environment that has encouraged MNCs and local companies to invest and expand in Singapore. The role of the government — its foresight and strategic planning - is crucial in anticipating problems and implementing effective solutions.

In the new millennium, Singapore's economic challenge is to build a Knowledge-Based Economy. In this new economy, knowledge, creativity and innovation are key determinants of long-term competitiveness. The development of a highly educated and flexible workforce is therefore very important. Singapore is actively cultivating its human capital by developing strong industries with a high level of innovation and technology, and an employment profile of skilled knowledge workers.

The EDB, the lead governmental agency in industry promotion has charted several strategies to realise its vision for the 21st century of ensuring that Singapore remains a relevant and competitive centre for goods, services and information. They are:

a) To deepen Singapore's technology base and broaden its applications to meet specific developmental needs of industries.
b) To strengthen knowledge-based manufacturing and services clusters with higher value-added activities.
c) To achieve sustainable growth through diversification among the three major clusters: electronics, chemicals and engineering.
d) To build up local enterprises into world-class companies by supporting core competency development such as brand management and encouraging strategic partnership between local enterprise and MNCs.

e) To encourage companies to engage and develop capabilities in new knowledge-driven activities.

f) To aggressively promote innovation development and expansion of innovation infrastructure.

g) To develop a flexible workforce by encouraging companies to set up and upgrade training programmes in core skills such as IT, and promoting continuing education and training.

h) To continue to attract the best foreign talent to augment our local pool.

2. Deepen Technology Base

The International Institute of Management Development (IMD) conducted its annual survey in 2000 to measure different countries' abilities to attract business activities. Singapore registered as the second most attractive location for investment in manufacturing activities. It is regarded as the third most attractive location for setting up services and management activities but only amongst the top ten countries chosen for their attractiveness for research and development activities.

Location Attractiveness Rankings – Global

Ranking Country	Country	Manufacturing Ranking	Research & Development Ranking	Services & Management Ranking
1	USA	1	1	1
2	SINGAPORE	2	8	3
3	FINLAND	4	2	2
4	NETHERLANDS	3	5	4
5	SWITZERLAND	7	3	5
6	LUXEMBOURG	-	18	8
7	IRELAND	5	13	10
8	GERMANY	13	4	14
9	SWEDEN	8	7	13
10	ICELAND	-	11	12

(Source: Yearbook of Competitiveness 2000)

As the country continues in the promotion of foreign direct investment (FDI), it is cognisant that efforts to deepen its technology base need to be concurrently pursued.

Singapore's National Science and Technology Board (NSTB) recently launched its Science & Technology 2005 (S&T2005) plan. The strategic intent of this S&T2005 Plan is to identify and build world-class science and technology capabilities to strengthen and seed growth sectors which are globally competitive in the new economy.

NSTB's Scientific and technological capability development programmes include the funding of the public sector research institutes and centres (RI/Cs), non-defense government agencies, universities and polytechnics as well as strategic national programmes and projects.

The strategies of S&T2005 are:

a) **Support R&D to develop our capabilities in niche areas**.
Technology capability development in the existing and new industry clusters will continue to be supported and strengthened. In addition to life sciences, other areas which are of importance are infocomms, chemicals, microelectronics, precision engineering & data storage technologies. See Annex C for a list of institutes funded by the NSTB in strengthening R&D capability in niche areas

b) **Establish the processes & institutions to manage public sector research**. These are:
   i. Research councils to manage competitively funded research by the RI/Cs, IHLs as well as non-defense government agencies, and
   ii. Foresight and technology scanning mechanisms to identify strategic national projects.

c) **Continued support for frontier research in RI/Cs and IHLs to allow new ideas to emerge**.
Existing university and polytechnic research grant programmes will be strengthened by:
   i. Competitive funding of projects ;
   ii. Institutionalising local and international peer review for selection of projects; and -

S&T2005 plan also call for strategies to;

a) stimulate private sector research,
b) foster a system to provide a steady flow of R&D results to the industry via a comprehensive technology transfer system and,
c) increase the proportion of research scientists and engineers with postgraduate research qualifications.

3. Singapore Nanoscience Initiative

In Singapore, nanoscience and engineering has developed in open competition with other existing disciplines. This has stimulated early-stage development of ideas and built skills for the new and emerging discipline, much of the research has been distributed among the various public sector research agencies.

NSTB's Science and Engineering Research Council (SERC) established a Nanoscience Initiative Panel (NIP) to identify and define programs that harnesses Singapore's research and economic capabilities, provide focus to strategic programs, cooperation among researchers, catalyse the best ideas, encourage research teams and build infrastructure to undertake R&D in nanoscience an engineering.

3.1 Current Status

To seed early stage capabilities development, Singapore has spent more than US$35 million in the last three years. The focus of the research activities has been in the areas of:

- Nanomaterials
- Nanometrology
- Nanomagnetics
- Nanocharacterisation

Presently, there are over 100 researchers working in the areas supported for nanoscience and engineering.

3.2 Actions

The Council has identified several technology fields in the discipline, the research areas and opportunities where more effort may be brought to bear.

The fields listed are;

a. Electronics
b. Magnetics
c. Catalysis
d. Medical
e. Metrology

With opportunities identified, the Singapore Nanoscience Initiative is currently working to propose actions in line with the overall strategies put forth in S&T2005 to build capabilities and to train manpower in nanotechnologies.

ANNEX A – Economic Data

Main Indicators of the Singapore Economy, Annual Data

(in S$Singapore Dollars)

National Income	1996	1997	1998	1999	2000
GDP At Current Prices ($m)	128,201	140,228	137,464	142,111	159,042
GDP At 1990 Market Prices ($m)	110,699	120,140	120,207	127,250	139,840
GDP At 1990 Market Prices (Change In %)					
Total	7.6	8.5	0.1	5.9	9.9
Goods Producing Industries	7.4	7.5	0.6	7.1	10.1
- Manufacturing	2.9	4.5	-0.6	13.6	15.2
- Construction	23.1	16.1	3.0	-8.8	-4.6
Services Producing Industries	8.1	9.6	-1.0	4.5	8.9
- Wholesale & Retail Trade	6.1	6.4	-4.1	7.1	15.2
- Hotels & Restaurants	6.0	6.5	-7.5	4.0	8.2
- Transport & Communications	8.2	8.8	6.4	7.1	9.0
- Financial Services	7.3	18.6	-8.6	0.8	4.1
- Business Services	9.4	8.3	1.1	1.5	6.6
Per Capita GNP ($)	35,482	39,494	37,226	38,832	42,212
Per Capita GDP ($)	34,928	36,963	35,040	35,958	39,585

(Source: Singapore Department of Statistics)

External Trade	1996		1997		1998		1999		2000	
Trade at Current Prices ($m) (%change)		(%)		(%)		(%)		(%)		(%)
Total	361,455	5.1	382,218	5.7	353,627	-7.5	382,431	8.1	470,001	22.9
Imports	185,183	5.0	196,605	6.2	169,863	-13.6	188,142	10.8	232,175	23.4
Exports	176,272	5.2	185,613	5.3	183,763	-1.0	194,290	5.7	237,826	22.4
Domestic Exports	103,589	5.2	107,535	3.8	105,918	-1.5	116,325	9.8	135,938	16.9
Oil	16,551	20.6	15,911	-3.9	13,473	-15.3	15,143	12.4	22,867	51.0
Non-Oil	87,038	2.7	91,624	5.3	92,445	0.9	101,182	9.5	113,071	11.8
Re-exports	72,683	5.3	78,077	7.4	77,846	-0.3	77,965	0.2	101,888	30.7

(Source: Trade Development Board)

	1996	1997	1998	1999	2000
Investment Commitment in Manufacturing[1] ($m)	8,085.1	8,488.4	7,829.5	8,037.4	9,208.9

([1] Including servicing, engineering and R&D. Source: Economic Development Board)

Labour Market	1996	1997	1998	1999	2000
Labour Force ('000) (As At June)	1,802	1,876	1,932	1,976	2,192
Employed Persons ('000) (As At June)	1,748	1,830	1,870	1,886	2,095
Unemployment Rate (%) (Average)	2.0	1.8	3.2	3.5	3.1
Employment Creation (Number)	102,600	120,300	-23,400	39,900	108,500
Productivity[2] (%Change)	1.3	2.3	-2.7	6.3	5.6

(Source: Ministry of Manpower) ([2] Source: Singapore Department of Statistics)

Tourism	1996	1997	1998	1999	2000
Visitor Arrivals ('000)	7,292	7,198	6,242	6,958	7,691
Visitor Arrivals (Change In %)	2.2	-1.3	-13.3	11.5	10.5
Consumer Price Index (CPI)					
CPI (Nov 97–Oct 98=100)	98.0	100.0	99.7	99.8	101.1
CPI (Change In %)	1.4	2.0	-0.3	0.0	1.3

(Source: Singapore Department of Statistics)

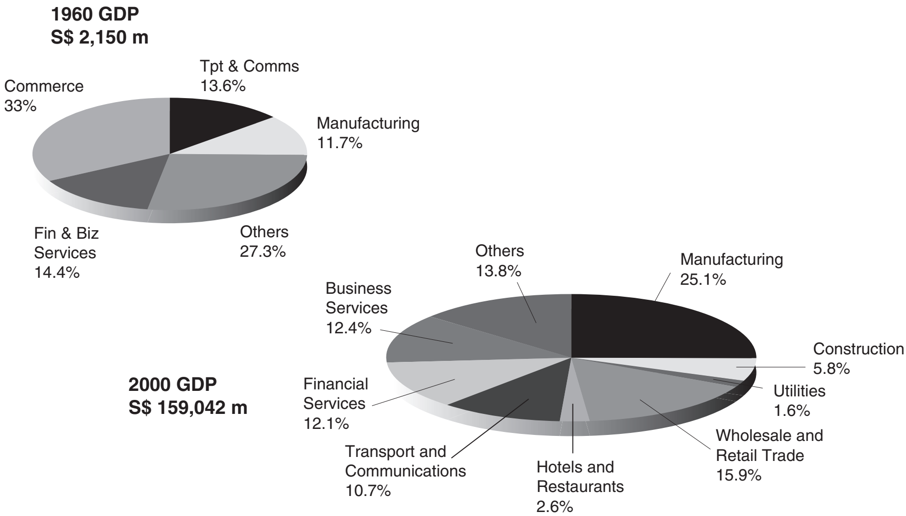
Balance of Payments[1]	1996	1997	1998	1999	2000
Current Account Balance ($m)	18,080	26,618	34,031	36,866	37,576
Capital & Financial A/C Balance ($m)	-6,999	-16,555	-36,884	-31,308	-19,932
Overall Balance ($m)	10,407	11,856	4,981	7,321	11,835
Foreign Reserves[2]					
Total Official Foreign Reserve ($m)	107,751	119,617	124,584	128,457	139,260
Exchange Rate[2]					
S$ Per US$ (Average)	1.4101	1.4848	1.6736	1.6949	1.7239
S$ Per US$ (End of Period)	1.3998	1.6755	1.6605	1.6660	1.7315

(Source: [1]Singapore Department of Statistics & [2]Monetary Authority of Singapore)

People	
Total Population:	3.89 million
Resident Population (citizens & permanent residents):	3.22 million
Population growth (1997-1998):	1.7%
Population density:	5,900 persons per sq. km
Population by race:	Chinese (76.9%); Malays (14%); Indians (7.7%); Others (1.4%)
Population by age:	0-14 (22.3%); 15-64 (70.4%), 65 and over (7.3%)
Main languages:	English (language of administration), Chinese (Mandarin), Malay (National language) & Tamil.
Religions:	Buddhism (31.9%), Taoism (21.9%); Islam (14.9%); Christianity (12.9%); Hinduism (3.3%);
Other religions (0.6%);	No religion (14.5%) [1995 Household Survey.]

Education	
General literacy rate:	93.5%
Literacy in 2 or more languages:	47.5% [1990 Census of population]
Tertiary education:	2 universities (National University of Singapore and Nanyang Technological University); 4 polytechnics. (Working adults can enroll in the Open University Degree Programme offered by the Singapore Institute of Management.)

ANNEX B - Economic Overview

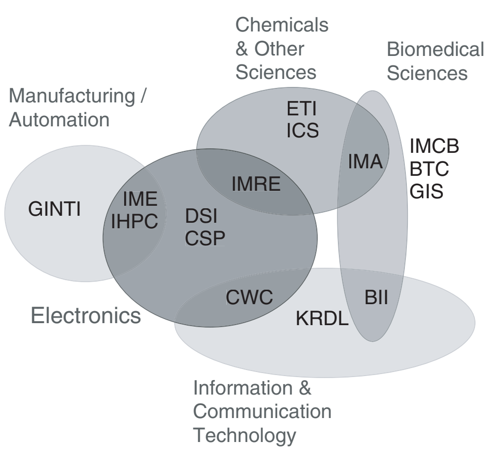


Source: The Economic Development Board, Singapore (EDB)

Annex C - Strengthen R&D Capabilities in Niche Areas

Research Institutes & Centres

15 RICs to support industry clusters



GINTIC	- Gintic Institute of Manufacturing Tech.
IME	- Institute of Microelectronics
IHPC	- Institute of High Performance Computing
DSI	- Data Storage Institute
CSP	- Centre for Signal Processing
CWC	- Centre for Wireless Communications
KRDL	- Kent Ridge Digital Labs
IMA	- Institute of Molecular Agrobiology
ICS	- Institute for Chemical Sciences
ETI	- Environmental Technology Institute
IMRE	- Institute of Material Research & Engineering
IMCB	- Institute of Molecular and Cell Biology
RTC	- Bioprocessing Technology Centre
GIS	- Genome Institute of Singapore
BII	- Bioinformatics Institute

6.8 Thailand

Nanotechnology Status in Thailand
S. Panyakeow[1] and P. Aungkavattana[2]
[1] The Semiconductor Device Research Laboratory (SDRL)
Department of Electrical Engineering, Faculty of Engineering
Chulalongkorn University
[2] National Metal and Materials Technology Center (MTEC)
National Science and Technology Development Agency (NSTDA)
Ministry of Science, Technology and Environment Bangkok, Thailand

1. Introduction

"Nanotechnology has given us the tools...to play with the ultimate toy box of nature - atoms and molecules. Everything is made from it..The possibilities to create new things appear limitless."

- Horst Stormer
Lucent Technologies and Columbia university,
Physics Nobel Prize Winner

From the above saying, "nanotechnology" seems to cover all means of making molecules and atoms do what we want. The knowledge in nanoscience increases worldwide as materials and devices are changed to nanometer scale in production. It is not only another step toward minimization, but a qualitatively new scale—the new behavior which is dominated by control of matter as its building blocks: molecule-by-molecule, atom-by-atom, and nanostructure-by- nanostructure. Today, nanotechnology has drawn the attentions of scientists, engineers and economists all over the world because of the potential society implications. This article aims to say briefly on the state of nanotechnology in Thailand for APEC Experts' Meeting on Nanotechnology on November 4-7, 2001, Ottawa, Canada.

2. Investment in Nanotechnology in Thailand

Thailand currently spends 0.2% of its Gross Domestic Product on research and development. This is one-tenth the percentage that other technologically-advanced Asian countries and Western countries spend for R&D. MTEC (National Metal and Materials Technology Center), NSTDA should play a leading role in increasing this percentage in an appropriate way, through both government and private sector support.

The development of Thai economy has reached the stage that manufacturing is playing a significant role. By its nature, manufacturing invariably needs the support of a myriad of materials and related technologies at various levels. The need to develop strong technological capability in materials technology is therefore imperative if the competitiveness in manufacturing industry is to be maintained and enhanced. Rapidly changing technologies and development-related problems such as environmental and quality of life issues also need the support of advanced materials and processes, particularly environmental-friendly processes, to be sustainable and acceptable.

The major research group in the area of nanoscale science and engineering in Thailand are the followings:

1) The Semiconductor device Research Laboratory (SDRL)
Department of electrical Engineering, Faculty of Engineering
Chulalongkorn University, Bangkok, Thailand

Researchers

1. Prof. Dr. Somsak Panyakeow
2. Assoc. Prof. Dr. Montri Sawatslingkan
3. Assoc. Prof. Dr. Banyong Thoprasertpong
4. Assoc. Prof. Dr. Chumpol Antrasane
5. Assist. Prof. Dr. Somchai Ratanathampan
6. Dr. Songpol Kanjanachuchai
7. Dr. Suwat Sopitpan

Summary

The research team at SDRL, Chulalongkorn University, Bangkok started its activity on silicon planar technology in 1975, then extended its research to thin film silicon by Chemical Vapor Deposition 9CVD) technique, and III-V compound semiconductor by liquid phase epitaxy (LPE) in 1985. The installation of molecular beam epitaxy (MBE) machine for quantum devices and nanoelectronics took place in 1992. With extensive experience in solar cells and laser engineering, SDRL has focussed its research activities in nanostructures, aiming for various optoelectronic applications. Quantum dots (QDs) for long wavelength applications are also the focus of current research activities. These nano-scale devices are under development for efficient, high speed lasers, detectors, optical switches, optical memory, and single electron transistors.

Funding Agency:

National Metal and Materials Technology Center (MTEC), NSTDA
Thailand Research Fund (TRF)

Technical Collaborations:

Max Planck Institute in Stuttgart, Germany
Tokyo Institute of Technology, Japan

Annual Budget in 2001
10 million Baht ($US 0.25 million)

2) **Department of Physics, Department of Chemistry, Faculty of Science, Mahidol University, Bangkok, Thailand**

Researchers:
1) Assist. Prof. Dr. Teerakiat Kerdchareon
2) Dr. Yutthana Tantirungrotechai
3) Assist. Prof. Dr. Vudhichai Parasuk

Summary:
The geometrical and electronic structure of nanotubes and their applications as charge storage and transport devices.

Funding Agency
Mahidol university
Shell Centenary Educational Fund

3) **The Petroleum and Petrochemical College, Chulalongkorn University**

Researcher
Dr. Boonyarach Kitiyanan

Summary
- Laser vaporization of carbon nanotubes.
- Exploring new formulation of catalysts: Co, Fe, Ni, W, Mo
- Exploring other catalyst without using support: sol-gel, aerogel or design new catalysts without using support
- Systematic study for other carbon sources : e.g. CH4, C2H4, or natural gas
- Purification of carbon nanotubes
- Collaboration for application of carbon nanotubes (e.g. composite materials research)

Funding Agency
National Metal and Materials Technology Center (MTEC)
The Petroleum and Petrochemical college, Chulalongkorn university, Bangkok, Thailand

4) **Plastic Engineering Group**
Plastic Product Development (PPD) and Plastics for Agriculture Program,
National Metal and Materials Technology Center (MTEC), NSTDA

Researchers

1) Dr. Wannee Chinsirikul
2) Dr. Asira Feungfuchart
3) Mr. Pitipong Somboonwiwat
4) Dr. Worravut Pattaropong
5) Mr Atomo Yukimune
6) Mr Chitsakon Pakjamsai

Summary:

Development of novel polymer-inorganic nanocomposites materials, including polymer-clay and polymer-ceramic composites, have been carried out for applications in both agriculture and industrial field. Adding clay to plastics could improve their qualities for specialized uses (e.g. permeability and flammability). Adding small amounts of natural clay to some plastic composites changes the physical properties of the plastics, making them less permeable to liquids and gases. Current polymer-ceramic composite research at MTEC has been directed towards developing packaging films used for extending shelf life of fresh produce and films with high barrier performances.

5) **Ceramic Technology Program**
National Metal and Materials Technology Center (MTEC), NSTDA

Researchers

1) Dr Sitthisuntorn Supothina
2) Dr Pavadee Aungkavattana
3) Dr Paisan Setasuwan

Summary:

- Nanocrystalline SnO_2 for gas sensing application
  By Sitthisuntorn Supothina

The recognition of the gas-sensing capability of a semiconducting oxide dates back to the 1950's when it was observed that the adsorption of reducing gas on zinc oxide (ZnO) brought about a change in the electrical conductivity of the oxide. The practical significance of this was quickly realized leading to patents for gas-sensors. Over the past 3 decades gas/vapor sensor technology has mushroomed, with the applications multiplying. As early as 1968 sensors were marketed to monitor leakage of town gas and liquid petroleum gas (LPG). Nowadays, applications are extended to air pollution monitoring, gas leak detection and process controls. The sensors are commonly in the form of lightly sintered powder compacts or films since both offer high surface-to-volume ratios, favoring sensitivity. Because tin oxide (SnO_2) offers high sensitivity at conveniently low operating temperatures, attention has been concentrated on this material. So far, the tin oxide sensor is the most widely used solid state device for gas-alarms on domestic and industrial premises.

Although the general principle of the detection mechanism is appreciated, there are many problems associated with developing a satisfactory materials' design approach. These problems are concerned with achieving selectivity and sensitivity. The sensors' selectivity and sensitivity are found to be dependent on the microstructure, method of preparation and to the addition of dopants. Recently, emphasis is being given to work on the nano-structure scale to exploit the unique properties. As far as gas-sensing application is concerned, nanosized materials provide the advantages that the surface-to-volume ratio is much greater than for coarse materials, and the sensor tends to exhibit increasing sensitivity with decreasing the grain size.

The focus of this research is to fabricate SnO_2-based materials containing nanosized crystallites, and to exploit gas-sensing behavior of such structure to butane which is one of the two major compositions of liquid petroleum gas (LPG). We pay attention to this gas because of its widespread use in Thailand. In the near future, work will be extended to cover producing nanosized powders for screen-printing technique. Screen-printing technology is a simple and automated technique that allows the production of low-cost, small feature sensors with good reproducibility. The targeted gases will include toxic gas such as carbon monoxide (CO) and volatile organic compounds such as alcohol.

The method for preparation of SnO_2 nanocrystallites was modified from the Ph.D. work of the author. The original method, so called "biomimetics", was inspired by unique microstructures and resulting properties of biomaterials. Biominerals, such as teeth, bone, shell, etc., exhibit control of structure over a wide range of scales, from atomic to macroscopic level. Since the starting reagents for material synthesis are all liquid, homogeneity of the precursor solution at the molecular level can be obtained, and additional constituents or dopants can be readily added to the based materials. Furthermore, by-products from aqueous media are usually environmentally benign. The microstructure of SnO_2 prepared by this approach, as shown in a transmission electron microscope (TEM) image, contains nanosized grains, ~5 – 10 nm in size.

- Synthesis of ferroelectric thin films by sol-gel methods
  By Pavadee Aungkavattana

Sol-gel processing technology have been widely used to prepared nano particles of ceramic and thin films. It is proposed in this study that lead zirconate titanate (PZT) ferroelectric ceramic powders and thin films of various compositions are prepared via this chemical route. Ferroelectric ceramics have unique properties which render them useful in applications including microelectronic and optical devices, non-volatile Random Access Memories (RAMs), Dynamic Random Access Memory (DRAMs), integrated capacitors on Si, non-linear optical elements, and pyroelectric detectors. The primary objective of this study are to establish the sol-gel technology at MTEC via the preparation and characterization of ferroelectric ceramics and to explore the potential of this technology in the preparation of materials and processes of significance to the multilayer technology programme at MTEC.

3. Local Issues for Nanotechnology in Thailand

Nanotechnology can be a tool for a developing country like Thailand to innovate some appropriate devices for future development. Newly proposed QDs solar cells are one of the nanostructure devices suitable for a sun-rich country like Thailand.

Carbon nanotube is currently a hot research topic. With strained nano-layers of semiconductors, III-V compound semiconductor nanotubes can be made possible by selective etching techniques. These nanotubes may have various applications as sensors, especially in medical and biotechnology. Thailand is an agricultural country producing foods for the world population. Therefore, an innovative idea making use of nanostructures for biotechnology, agro-industry and medical applications is another local issues in Thailand which we may explore.

4. Future Perspectives

Nanotechnology in Thailand must be fully supported by responsible R&D agencies like Thailand Research Fund (TRF), National Science and Technology Development Agency (NSTDA), National Metal and Materials Technology Center (MTEC), etc. More qualified manpower on nanotechnology must be created to a critical mass for future development. In order to jump over the present barrier, a national policy to promote nanotechnology must be set up, and more publicity to local communities nationwide must be conducted in an easy-to-understand way.

6.9 United States

National Nanotechnology Investment in the FY 2002 Budget Request by the President
(From: AAAS Report on R&D in FY 2002, Washington, D.C., May 2001)
M.C. Roco, NSF
Chair, National Science and Technology Council's subcommittee
on Nanoscale Science, Engineering and Technology (NSET)

Introduction

The emerging fields of nanoscale science, engineering, and technology – the ability to work at the molecular level, atom by atom, to create large structures with fundamentally new properties and functions - are leading to unprecedented understanding and control over the basic building blocks and properties of all natural and man-made things. The FY 2002 funding request for nanoscale science, engineering and technology (noted in brief - nanotechnology) research and development (R&D) in eight federal departments and agencies is summarized in Table 1. The total nanotechnology budget request is approximately $518.9 million ($485 million reported on April 9 plus $33.9 million in associated programs), 23% over $422 million approved by Congress for FY 2001. This investment is known as the

Table 1. Summary of Federal nanotechnology investment in FY 2002 Budget Request (in million of dollars)

Department/Agency	FY 2000 NNI Budget	FY 2001 NNI Budget	FY 2002 Budget Request
Department of Defense*	70	110	133.0
Department of Energy	58	93	97.0
Department of Justice	-	-	1.4
Environmental Protection Agency	-	-	5.0
National Aeronautics and Space Admin.	5	20	46.0
National Institutes of Health	32	39	45.0
National Institute of Standards and Techn.	8	10	17.5
National Science Foundation	97	150	174.0
Total**	**270**	**422**	**518.9**

(*) FY 2002 entry for DOD is subject to change as a result of the Defense Strategy Review now underway.

(**) Figures are not available for four departments that participate in the federal nanotechnology investment starting with January 2001: Department of State (DOS), Department of Transportation (DOT), Department of Treasury (DOTreas), and US Department of Agriculture (USDA).

National Nanotechnology Initiative (NNI). The National Science and Technology Council (NSTC) Subcommittee on Nanoscale Science, Engineering, and Technology (NSET) will coordinate the Federal government's multi-agency nanoscale R&D programs, including planning, budgeting, implementing, developing interagency collaboration, and reviewing the NNI to ensure an efficient investment with broad impact. The R&D strategy is balanced across five kind of activities: fundamental research, Grand Challenges, centers and networks of excellence, research infrastructure, as well as ethical, legal and social implications and workforce programs (see NNI at http://nano.gov).

Department of Defense (DOD)

The FY 2002 request is $133 million, $23 million over the enacted FY 2001 budget. This represents a projection from estimated FY 2001 budget and is subject to change as a result of the Defense Strategy Review now underway in DOD. The request will continue support for the nanoscale science and technology R&D base of $70 million in Air Force, Army and Navy, and $30 million for the Office of Strategic Defense (OSD). In addition, this budget will include basic research funds for the university / DOD laboratory collaborative research programs at Air Force (by $10M), Army (by $10M), and Navy (by $13 million). DOD's priorities are aligned with its Basic Research Plan, the OSD guidance for basic research; and with its Joint Vision 2010, the Chairman of the Joint Chiefs' conceptual template for achieving new levels of warfighting effectiveness. These documents forecast dynamic change in the nature of potential adversaries and emphasize the increasingly critical nature of technological advances.

The FY 2002 funding will largely be utilized to augment programs in the three NNI R&D Grand Challenges with prime DOD interest – nano-electronics, optoelectronics, and magnetics; nanostructured materials "by design"; and bio-nanosensor devices. The distribution of DOD augmented funds between these three challenges will be determined in collaboration with other NSET agencies: DOE and NASA in nanoelectronics; NSF and DOE in nanomaterials; and NSF, NIH, DOE and NASA in nanobiotechnology, as well as a function of the quality of proposals received. With its $10 million augmentation, the Army Research Laboratory (ARL) programs will catalyze the recently created ARL Nanoscience and Technology Center (NSTC). The ARL NSTC coordinates active 6.1 nanoscience and 6.2 nanotechnology research teams in the Sensors and Electron Devices Directorate, the Weapons and Materials Research Directorate, the Computation and Information Science Directorate, and the Army Research Office. With its $10 million augmentation, the Air Force Research Laboratory will extend its programs in nanostructured materials, nanofabrication technologies, sensor components, and simulation of nanomaterials. With its $13 million augmentation the Navy plans to expand its collaborative University - Naval

Research Laboratory program addressing interconnection and interaction between disparate nanostructures in complex systems. Funding for research, equipment, student fellowships have been requested. DOD participation in NNI is coordinated by the Research Director in the Office of Director, Defense Research and Engineering (DDR&E). The DOD nanotechnology budgets and programs are identified at http://nano.gov or http://www.nanosra.nrl.navy.mil .

Department of Energy (DOE)

The FY 2002 Request of $97 million is an increase of $4 million over FY 2001 for the Basic Engineering Sciences (BES) project related to the establishment of user centers for nanoscale science, engineering, and technology research. The funds will allow designated projects for four centers to proceed from conceptual design into definitive design. The base funding from FY 2001 of $93 million includes about $36 million for university and national laboratories R&D, and $10.5 million in the Office of Defense Programs, the same as in FY 2001. The amount is an estimate of the fraction of the work supported at Sandia, Los Alamos, and Livermore National Laboratories. The funding covers approximately $34 million for fundamental research, $29 million for NNI Grand Challenges, $15 million for centers, $15 million for research infrastructure. A R&D program solicitation of approximately $18 million for university research and $18 million for DOE laboratories is planned. The DOE nanotechnology budgets and programs are identified at http://nano.gov or http://www.sc.doe.gov/production/bes/BES_FY02budget.pdf).

Department of Justice (DOJ)

The FY 2002 DOJ budget for nanotechnology R&D is $1.4 million. Major interests are in forensic research, sensors, DNA sequencing, high performance computing, and data base management. The National Institute of Justice (NIJ) is the research agency of the U.S. Department of Justice. NIJ investment of $1 million will continue the DNA R&D as well as the demonstration of chip based or micro device technologies to analyze DNA in forensic applications. Nanotechnology products will be a significant part of the device under development that will eventually be integrated into the current crime laboratory processes and protocols to analyze forensic DNA samples. NIJ investment of $0.4 million for the Chemical and Biological Defense Program will include developing a wearable, low-cost device to provide warning of exposure to unanticipated chemical and biological hazards in sufficient time for its wearer to take effective protective measures. The current approach relies on an enzymatic reaction. It is based on vapor exposure of an immobilized enzyme surface. Nanotechnology will be used to address limitations of the enzymatic approach.

Environmental Protection Agency (EPA)

The FY 2002 research request is approximately $5 million. The goal is improved characterization of environmental problems, significantly reduced environmental impacts from çcleaneré manufacturing approaches, and reduced material and energy use. The potential impacts of nanoparticles from different applications on human health and the environment must also be evaluated. Major nanotechnology related interests are in aerosols, colloids, clean air and water, measurement and remediation of nanoparticles in air, water, and soil. The Office of Research and Development (ORD) manages EPA's nanotechnology research, and the National Center for Environmental Research (NCER) manages the external grant solicitation. In addition, NCER has supported a limited number of nanotechnology-based projects through its Small Business Innovation Research (SBIR) Program. In house research currently includes the National Exposure Research Laboratory and the National Risk Management Research Laboratory, and may expand to other ORD laboratories in the future.

National Aeronautics and Space Administration (NASA)

The FY 2002 request is $46 million, $24 million over FY 2001. The breakdown is approximately as follows: $11 million for materials (lead by the Langley Laboratory); $15 million for electronics and computing (Ames Laboratory); $10 million for sensors and components (including Jet Propulsion Laboratory with $3million); and $10 million for Basic Nanoscience. NASA's investment in nanoscience and nanotechnology is composed from contributions of several laboratories (mainly Ames, Langley and JPL) and externally supported research. Major themes and new programs in FY 2002 include: (a) Manufacturing techniques of single walled carbon nanotubes for structural reinforcement; electronic, magnetic, lubricating, and optical devices; chemical sensors and biosensors; (b) Tools to develop autonomous devices that articulate, sense, communicate, and function as a network, extending human presence beyond the normal senses; and (c) Robotics using nanoelectronics, biological sensors and artificial neural systems. Due to NASA's relatively modest budget, the Agency will focus primarily on NASA-unique needs, that is: low power devices, high strength materials that perform with exceptional autonomy in the hostile space environment. NASA looks to NSF-sponsored work for wide-ranging contributions in fundamental research, and emphasizes work in direct support of the Grand Challenge areas the agency selects for focus, some of them in collaboration with DOD (aerospace structural materials, radiation tolerant devices, high resolution imagery), NIH (non-invasive human health monitoring via identification and detection of molecular signatures, and biosensors) and DOE (lab-on-a-chip, and environmental monitoring). A major focus at NASA is to advance and exploit the zone of convergence between nanotechnology, biotechnology and information technology for space exploration. The Agency will spend up to $1M per year towards an understanding of the societal and ethical implications of nanotechnology, with a focus in the area of monitoring of human health. Opportunities will be sought with university research centers to arrange for student and postdoctoral fellows, including opportunities to work for periods of time at NASA Centers. It is the Agencies intent to extend international space mission collaborations into the arena of nanotechnology.

National Institutes of Health (NIH)

The FY 2002 request is approximately $45 million, an increase of $6 million above the approved level for FY 2001. NIH will issue several nanotechnology related R&D program announcements, that are subsets of the NIH FY 2002 Research Initiatives, of which more relevant are: (a) The Genetic Medicine Initiative includes large-scale sequencing to assist in interpreting the human sequence, and identifying and characterizing genes that are responsible for variations in diseases. An increased investment in nanotechnology research is planned to develop novel, revolutionary instruments that can be used to collect DNA sequence variation and gene expression data from individual patients, initially to identify genes involved in causing diseases, and later to diagnose exactly which form of the disease the patient has, to guide therapy that will actually treat that patient's disease; (b) The Initiative in Clinical Research to bridge basic discoveries to tomorrow's new treatments, including nanotechnology advances for development of sensors for disease signatures and diagnosis of diseases. Major themes and new programs in FY 2001 include: biomaterials, clinical diagnostic sensors, genomics sensors, nanoparticles and nanospheres for drug and gene delivery, Multidisciplinary training, Study social, ethical and legal aspects. The National Institute of Biomedical Imaging and Bioengineering (NIBIB) is in formative stages at NIH and is expected to be operating by FY2002. The NIH Bioengineering Consortium (BECON) will coordinate research programs through NIBIB, including nanotechnology research.

National Institute of Standards and Technology (NIST)

The FY 2002 request is $17.5 million, $7.5 million increase over the enacted FY 2001 budget. The funds will be distributed across the NIST Laboratories. NIST will develop the critical enabling infrastructural measurement, standards, and data for nanomagnetics, nanocharacterization, and new information technologies that will replace semiconductor electronics in the future. Nanomagnetics research will provide measurement and standards for current and near-term applications of nanotechnology in the semiconductor, communications, and health care industries. Nanocharacterization research will produce standards and tools for visualization and characterization at the nanoscale, which are in high demand by a broad base of U.S. industries. Research will be conducted to provide fundamental measurements needed for future generations of information technology hardware that will be needed to replace semiconductor electronics technology in a decade or so. In order to leverage internal efforts, NIST will develop stronger strategic alliances and collaborations with universities, businesses, and other government agencies that possess leading expertise in nanotechnology. NIST plans to extend the FY 2001 investment for nanotechnology funding to these external organizations to conduct much of the specific work required to meet the goals of this initiative and avoid developing costly, complex in-house capabilities that may only be used once. As an agency of the U.S. Department of Commerce, NIST works to help facilitate international trade by working with international standards organizations and national metrology institutes. Key issues in the future for international trade, with respect to nanotechnology, will be traceability of measurements and çharmonizationé of international standards.

National Science Foundation (NSF)

The FY 2002 request for the Nanoscale Science and Engineering is approximately $174 million, $24 million increase over FY 2001. All research directorates participate as it is shown in Table 2.

Table 2. NSF FY 2002 request (in millions of dollars)

Directorate	FY 2001 Current Plan	FY 2002 Request
Biological Sciences	2.33	2.33
Computer and Information Science and Engineering	2.20	6.20
Engineering	55.27	70.30
Geosciences	6.80	6.80
Mathematical and Physical Sciences	83.08	88.08
Total, Nanoscale Science and Engineering	**$149.68**	**$173.71**

FY 2002 investment will expand a wide range of research and education activities in nanoscale science and technology, in order to develop and strengthen critical fields and to establish the physical science and engineering infrastructure and prepare the workforce. Support will be focused on interdisciplinary research and education teams, nanoscale science and engineering centers, exploratory research and education and training. NSF five programmatic focus areas are: (a) Fundamental research and education ($107.72 million) with special emphasis on biosystems at the nanoscale ($19.0 million); nanoscale structures, novel phenomena and quantum control (36.72 million); device and system architecture ($25.50 million); Nanoscale processes in the environment ($9.50 million); multi-scale, multi-phenomena theory, modeling and simulation at the nanoscale ($17.0 million); (b) Grand Challenges ($7.90 million) will fund interdisciplinary activities to focus on major long-term challenges: nanostructured materials 'by design,' nanoscale electronics, optoelectronics and magnetics, nanoscale-based manufacturing, catalysts, chemical manufacturing, environment and healthcare; (c) Centers and networks of excellence ($29.39 million) will provide support for four new research and education centers, a multidisciplinary, multi-sectoral network for modeling and simulation at the nanoscale, and nanofabrication experimentation and user facilities to come on line in FY 2002; (d) Research Infrastructure ($19.90 million) for instrumentation and facilities for improved measurements, processing and manipulation at nanoscale, and equipment and software for modeling and simulation; (e) Societal and educational implications of science and technology advances ($8.80 million) for student assistantships, fellowships and traineeships, curriculum development on nanoscience and engineering and development of new teaching tools. The impact of nanotechnology on society will be analyzed from legal, ethical, social, and economic perspectives. Collaborative activities are planned with DOD in the area of nanostructured materials and modeling, with DOE in the areas of user facilities and sustainable development, with NASA in nanobiotechnology and nanodevices, with NIH in bioengineering and bionanodevices, with NIST in instrumentation development, and with other agencies. The Nanoscale Science and Engineering (NSE) Group including representatives from all directorates coordinates the NNI activities at NSF. The NSF nanoscale science and engineering budgets and programs are identified at http://nano.gov or http://www.nsf.gov/nano .

CollaborativeActivities in FY 2002

The NSTC' subcommittee on Nanoscale Science, Engineering and Technology (NSET) will coordinate joint activities that create synergies between the individual agencies in a variety of topics and modalities of collaboration. The coordination will: identify of the most promising research directions, funding of complementary/synergistic fields of research that are critical for the advancement of the nanoscience and engineering field, develop a balanced infrastructure (portfolio of programs, development of new specific tools, instrumentation, simulation infrastructure, standards for nanoscale), correlate funding activities for centers and networks of excellence, cost share high cost R&D activities, develop a broad workforce trained in the many aspects necessary to nanotechnology, study of the diverse, complex implications on society such as effect of nanomaterial manufacturing on environment and effect of nanodevices on health, and avoid of unnecessary duplication of efforts. The coordination also will address NNI management issues.

Examples of major collaborative NNI activities crossing the eight agencies with FY2002 budget request listed in Table 1 are shown in Table 3. DOS is contributing to international aspects on all topics. DOT, DOTreas and DOA also participate in their areas of interest.

Table 3. Examples of proposed NNI interagency collaborative activities

Agency	DOD	DOE	DOJ	EPA	NASA	NIH	NIST	NSF
Fundamental research	x	x			x	x		x
Nanostructured materials	x	x		x	x	x	x	x
Molecular electronics	x				x		x	x
Spin electronics	x				x			x
Lab-on-a-chip (nanocomponents)	x	x	x		x	x	x	x
Biosensors, bioinformatics			x		x	x		x
Bioengineering	x	x				x		x
Quantum computing	x	x			x		x	x
Measurements and standards for tools	x	x		x		x	x	x
Nanoscale theory, modeling, simulation	x	x			x			x
Environmental monitoring		x		x	x			x
Nanorobotics		x			x			x
Unmanned missions	x				x			
International collaboration	x	x	x	x	x	x	x	x
Nanofabrication user facilities		x		x	x	x	x	x

Scenario-Based Futures

Scenario creation is a way of envisaging what the future might hold for a particular economy, industry sector or organisation. Rather than using projections from past trends, scenario creation attempts to develop stories about possible and plausible futures. It follows a systematic sequence of steps. First, the key STEEP drivers - social, technological, economic, environmental and political – are identified. The next step is the 'scenario logic' or pattern of interactions that determines how the key drivers could contribute to future directions in each scenario. The key drivers are separated into predetermined elements, e.g. demographics, and critical uncertainties, e.g. public opinion or economic crises. This analysis is then used to create scenarios for a period 10-20 years in the future. These are internally consistent stories which present distinctly different possible futures – the actual outcome may be a blend of elements from more than one scenario. From these scenarios it is possible to draw out policy issues and make strategic decisions.

In the Ottawa meeting the Experts identified a large number of drivers using the STEEP approach. Their findings can be summarised as in Table 1.

Table 1. Key Drivers for the Development of Nanotechnology Identified by Experts in Ottawa

Society	
	Ageing population
	Enhanced quality of life
	More effective health care
Technology	
	Scientific breakthroughs
	Need for miniaturisation in production
	Demands of information and communication technology industry
Economies	
	Novel / unique products to stimulate industry development
	Investment in high technology
	Rise of knowledge society
Environment	
	Clean and leaner production processes
	Improved air and water quality
	New energy sources
Policies	
	National security issues
	Changing patterns of S&T expenditure
	Public perception of technological change

The Experts then speculated on possible, even improbable, events which could occur to change the pattern of development of nanotechnology. Again they identified a large number of uncertainties which have been summarised as in Table 2.

Table 2. Critical Uncertainties for the Development of Nanotechnology Identified by Experts in Ottawa

Technical Uncertainties	
	Nanotechnology fails to deliver
	Inability to solve standards issues
	Breakthroughs in current technical paradigms – devices and materials
Environmental / Economic Uncertainties	
	Major financial crisis
	Kyoto Protocol ratified by all economies
	Major disruption of energy supplies
Political / Societal Uncertainties	
	Lack of public acceptance of nanotechnology
	Nanotechnology facilitates major advances in bio-health
	Terrorism and national security
Global Uncertainties	
	World War III
	Widespread epidemic

Using these inputs and bearing in mind the technological opportunities identified in the Position Papers of Section 5 and the issues identified in Section 4, the Experts constructed three scenarios for 2015.

Scenario 1: Nano-paradox-Things are more the same today than they ever have been.

Headline # 1 - Sept. 23, 2009 Canadian researcher introduces quantum computer prototype – computer stocks dip!

Headline #2 - June 10, 2010 Kyoto targets projected to be reached ahead of schedule. New environmental technologies lead the way!

Headline #3 - Feb. 14, 2012 US Government report on how insurance companies may use genetic information leak. Nano-wireless genetic ingestible chips identified as source of the information.

Introduction

Setting the stage – A five year old child wanders into the study with a plaque found in a box in the attic with his grandfather's name on it. The plaque states "For distinguished achievement in nanoscale metrology – American Physical Society 2004. Child asks granddad "What is nanoscale?" Answer It was a new way of thinking that evolved in the 1990's that involved atomic scale measurements, smaller than you can imagine, but very significant in their application. Many of the things that you take for granted today here in 2015 have some connection to nanoscale development. But we no longer use the term 'nano'. While we believed it had great potential, there were some big problems that occurred almost a decade ago that caused us to drop the reference to 'nano' although the technical legacy remains. These problems involved genetics, privacy, and problems of access and benefit from the capabilities of our research.

However, the legacy is embedded in many technology achievements including our ability to improve the environment and attain the Kyoto protocols ahead of schedule. Your future will continue to depend on these technologies but you must always be cognizant of the down sides.

The Early Period - 2002 - 2006

The period 2002 to 2006 was characterized by continued uncertainty and significant global tension and economic stagnancy, as the war on terrorism dragged on with no clear conclusion. Meanwhile, the interest in global environmental improvements and greenhouse gas controls was re-ignited by the US. This was a result of the continued threat of oil supply cut-off by unstable Middle East governments but, perhaps more importantly; new energy security emerged from Canadian and Russian sources. As part of its global strategy against terrorism, the US decided to seek release from its OPEC ties and to consolidate its global alliances with Kyoto as a convenient vehicle for future economic growth fuelled by the R&D promise of nano and energy technologies.

During this period, significant nano research progress was made, characterized by a molecular computer prototype and the application of nano scale knowledge to enable ULSI platforms to become faster and smaller as the silicon limit was approached. As well, the rapid penetration of wireless and large bandwidth accelerated this process.

The Developmental Period - 2006 - 2009

This was a period of rapid adjustment to the industrial base and significant growth in the R&D system. All industries were forces to seek more efficient modes of delivery and embrace new energy technologies and greenhouse gas conversion or mitigation mechanisms. The R&D system was able to generate new projects related to fuel cells, renewables, and next generation high-performance vehicles. However, there was a downside. Repeated bio-food and GMO scares began to harden public attitudes toward technology. Anti-growth alliances succeeded in grouping nano technology projects with bio-technology, Nano-technology breakthroughs began to emerge e.g. hydrogen storage infrastructure (nano-facilitated cartridges), fuel cells; new catalysts for CO2 conversion; NEMS for bio-diagnostic systems, tissue engineering organ replacement clinical trials (several of which failed with high-profile consequences). In 2008, rapid genetic profiling using DNA chips tested by insurance companies with federal R&D support, but this information was leaked and became a public scandal. By 2009, the public mood was anxious about the new and uncertain applications of nano-technology, which reinforced concerns about the many constraints on personal life and the lack of significant economic growth dating back to 2001.

The Consolidation Period - 2010 - 2012

This period represented a consolidation of increased technical capability and an intensification of concerns over the applications of nano derived technologies. In 2009, a major advance in a disruptive technology, quantum computing, appeared as a first generation prototype with implied changes for future computing platforms. Concurrently, there were positive introductions of other nano-derived technologies, which were now becoming rapidly embedded, in new products to obscure the nano connection because of its worsening public image. In 2010, two major events affected the nano situation. First, the Kyoto protocol targets were surprisingly projected to be attainable given the rapid market penetration of advanced fuel cells, solar films and energy storage systems, as well as greenhouse gas catalytic conversion. Second, public anger over privacy concerns and genetic profiling boiled over in the form of a scandal involving nano privacy with government and major industries being caught in collusion over the use of privileged information. A government report on the use of genetic information by insurance companies and constraints of peoples' ability to obtain health insurance deepened public cynicism and activism against nano R&D linked to bio-information. Activist groups began to initiate class action lawsuits and seek government bans on nano-related R&D.

The Ubiquitous Period - 2013 - 2015

During this period, nano-applications were becoming quietly familiar if not readily visible to most sophisticated consumers in advanced industrial economies. However, the benefits and the costs were not uniformly distributed across APEC economies or within them. In 2015, APEC convened a virtual forum on nano-technology retrospective. In the context of a strong recognition of benefits but with some regrets and also relief, this group concluded that the term nanotechnology almost was now almost out of use – it had gone underground. The group recognized that while great progress had been made, and significant impacts had occurred in the energy infrastructure and in bio diagnostic applications, the rate of penetration/acceptance of nano-technology had been overestimated and the barriers to public acceptance had been underestimated. The paradox between the lingering negative effects of public litigation and the validated but obscure economic impacts of the embedded nano-technology applications continued to confuse even the most techo faithful of the public. An additional key concern was the documented evidence of a growing gap in access, use and affordability over technologies that were originally derived from nano research, in particular nano biological and nano computation. Specifically, social science studies and health system statistics had revealed significant gap between income groups in their access and use of a) genetic/viral profiles for health protection, b) quantum computing for large organizational infrastructure and c) access to self-diagnostic "lab in a pill" wireless interface tied to Artificial Intelligence Medic and Personal Professional Health Advisors.

Conclusion

At 2015, the results of the nanotechnology progression and acceptance pathways indicate clear technical success in significant niche areas but widespread adoption and acceptance of the full potential has been clouded by uncertainty. The paradox continues. The public has become so accustomed to nano originated or derived technologies that it almost cannot live without them. But public anger lingers over the privacy and genetic indiscretions. Nano is scarcely visible. It had to be rebranded and integrated with other technology labels to progress and be accepted. At 2015, the uncertainty principle still rules.

Scenario 2: Green Energy Triggers Collapse in Energy Markets

Invention of nanotechnology based energy system triggers collapse in fossil fuel markets, leading to major political unrest within energy producing states, and a re-emergence of global terrorism

2015

Energy options for the average consumer, whether this was the industrial consumer or the householder have changed from twenty years ago. Today, green energy options are universally available and they offer a substantial cost advantage over old-fashioned fossil fuel systems. I remember the time when we had to pay electricity from an electrical utility that had a monopoly on supply, that transportation was powered by the internal combustion engine, and that portable electrical and electronic devices could run for no more than a few hours before they would run out of energy.

Today things have radically changed. Now, most energy for houses and small businesses is provided by hydrogen or natural gas powered co-generation systems that produce heat and electricity. No one today would dream of buying a car powered by an internal combustion engine – they all use hydrogen powered fuel cell systems. And more changes are predicted to come. Hydrogen today is produced from fossil fuel or hydro electricity. The efficiency of photovoltaics is being improved dramatically and combining this technology with advanced hydrogen storage systems will virtually eliminate the use of fossil fuels in some countries.

The change in energy markets has not been without problems. The first impact was the rapid decline in demand for fossil fuels. Our new energy systems are significantly more efficient than old technology. This has led to a drop in global fossil fuel demand by approximately 50%. Energy producing states that had been able to sustain an oil price at $15 per barrel were caught by surprise in 2014 by the drop in demand. Disputes between OPEC countries and the reluctance of a few states to reduce production triggered a collapse in the price in 2015 to $5 per barrel. Low cost producers such as Saudi Arabia saw its foreign exchange inflows drop substantially, but for higher priced producers it rapidly became apparent that they must stop producing. New Zealand and Argentina were very hard hit. These two countries had brought on stream major off shore reserves in 2010 but production costs were at $10 per barrel and each national government had borrowed heavily to finance the production capacity. As well, a number of developing countries with high production costs also suffered a financial crisis.

The energy crash of April 2015 was as bad as the 20th century depression – at least 15 oil producing countries were effectively bankrupt and two of the world's major energy companies were also forced into receivership. Not soon after, civil unrest and localized border disputes caused major restrictions on civil liberties in these states, fuelling ethnic unrest and a significant rise in regional terrorism.

History of the Energy Revolution

In 2005 the recession that had been triggered by the al Queda attacks was over. The war on terrorism by the NATO alliance had effectively eliminated the forces that opposed them, new security measures had been put in place, and consumer confidence was largely restored. Increased consumption and investment had brought about strong economic growth. However, it had also driven up oil prices to the $25 per barrel level and this became a new driver for research investment in alternative energy. The first breakthrough came in nanotechnology based hydrogen storage systems – it appeared that portable storage of hydrogen at a cost equivalent to gasoline would be possible within five years. This breakthrough provided the stimulus that the fuel cell industry needed – and many companies now started research in production technologies of advanced catalysts and polymer systems.

Between 2007 and 2010 wide scale demonstration projects were held in developed countries of new hydrogen storage systems and fuel cell powered electricity production. Costs were still above conventional energy and reliability was a problem – but with the level of investment in R&D it was clear that the cost differential could be overcome.

2012 was the breakthrough year. Independently Hitachi and Siemens released domestic co-generation systems and Renault and General Motors fuel cell powered cars. What was remarkable about these new products was that they were priced below the cost of conventional vehicles, used 50% less fuel, and carried five-year warranties. They all ran on hydrogen that could be produced through reformer technology or through a local distribution network. The effect on demand for the systems was dramatic. Major cities around the world began the investment to convert their natural gas pipelines to hydrogen. By 2015, demand for conventional energy systems had collapsed and with it the energy market.

Scenario 3: Nanotech Wins the War!

"Nanotech leads to Bush re-election"

Associated Press, February 2005

It was a dark stormy night at the White House in February 2005. President Bush uttered: "That Clinton was right with his **nanotechnology** initiative!". Bush owed his re-election to some extent to research breakthroughs initiated under his predecessor.

Bio-terrorism has been at the forefront of everybody's mind since October 2001, when the first anthrax threats first occurred. Other viral attack waves had been launched every few months.

Nanotechnology research centers had started to emerge. After the 2001 attacks, the emphasis had shifted throughout 2002 and 2003 on research on rapid diagnostic tools and cures.

The breakthrough:

- Bio-Vada: Early prototypes of bio-chips able to sequence viruses showed great promise. Working prototypes had been manufactured with the characteristics: single molecule detection, virus identification, LED display.

Instability in the Middle East has increased ever since the famous fall 2001 events. Muslim states have started to tighten the oil production as a reaction to the increasing western pressures.

As a result, significant state and private sector research efforts had been diverted to the development of new energy sources. Nanotechnology research centers received the mandate to speed up development of fuel cells and solar cells.

"Bay of Pigs in the Gulf"

Associated Press, February 2010

2007: meeting of OPEC leaders results in drastic oil export reduction. Anti-US sentiment as a response to the botched attempt to assassinate Bin Laden in the Saudi Royal Palace where he was suspected to hide for the last few months.

Result: World-wide energy crisis.

Energy research hasn't produced the breakthroughs yet and the western states move in the Middle East to turn on the taps. Forces led by the American and British forces invaded Saudi Arabia, Yemen in May 2008. The Pakistan government is overthrown by the military, which sides with the Middle East states.

In 2009, Iraq started to use chemical and germ warfare. As a result of these new threats, during the war, the research on nanotechnology shifts more intensively to:

- in vivo and in vetro stem cells growth for tissue regeneration
- templates for drug delivery systems
- nano-facilitators for hydrogen fuel storage
- energy conversion based on nanostructured catalyst
- improving solar cells efficiency and reducing production cost and exploring biomemitic alternatives

"New victories for wartime breakthroughs"

Associated Press, July 2015

The breakthroughs that turned the war around are generating new victories: commercialization of the technologies is leading to a surge in stock markets.

It all started in 2012, as the war drew to a close. Breakthroughs in fuel and solar cell technology have led to dramatic reductions in the need for oil in the western states. The stakes being much lower lead to incentives to find a workable peace.

Commercialization of the research on solar cells and fuel cells has followed swiftly. Industry evolved to adopt the new technology. The infrastructure is modified to give emphasis on energy requirement at the consumer level.

Portable energy sources and wireless technology is widely available. Resources-poor but sun-rich regions have now access to large amounts of cheap energy.

Outcomes in wartime research health-related research:

- Bio-chips can send diagnostic results by wireless technology
- Implantable biochips deliver some targeted drugs in real time

Despite starting from different combinations of key drivers and uncertainties, the three scenarios present similar futures where intensive R&D in nanotechnology enables significant advances in health care, e.g. biodiagnostic and drug delivery systems and in energy systems, e.g. solar cells and fuel cells based on hydrogen to be achieved in 5-10 years. Commercialisation is envisaged in 12-15 years. These developments are in general agreement with the Position Papers (Section 5) and the views expressed by the Experts in a preliminary brainstorming session (see Table 3).

Table 3. ***Estimated timing of the realisation of some Technological Opportunities in Nanotechnology, Identified at Experts' Meeting in Ottawa***

In 3 years	
Category 1	
	Selective bio nano-sensors
	Specific drug delivery systems
Category 2	
	Nano-electronics based on miniaturised silicon devices
	Novel devices based on magnetic spin electronics
Category 3	
	Nanostructured materials as industrial catalysts
	Self-cleaning surfaces based on nanomaterials
In 10 years	
Category 1	
	Advanced medical diagnostics
	Targeted human cells for organ repair
Category 2	
	Single electron devices
	Optical computing
Category 3	
	Portable fuel cell and advanced battery
	Artificial photosynthesis

In two of the scenarios, nanotechnology is accepted strongly by society, albeit as a solution to problems posed by external forces such as bioterrorism and oil shortages. In the other, nanotechnology is rejected by society because of a more general backlash against science and technology although nanotechnology products continue to be used. These alternative views of the future support the need to address social and ethical concerns of nanotechnology at an early stage.

Policy Implications for Future of Nanotechnology in the APEC Region

This study has identified a set of issues critical to the future of nanotechnology and policymakers in APEC economies must take account of these in considering the strategic management of their S&T resources, both people and facilities. Based on these issues, the following policy responses are recommended:

- ***Broader recognition of nanotechnology in APEC economies as a new technology arising from a fusion of physics, chemistry, mathematics, biology and engineering.***

A good example of a response is the educational outreach program being supported by the US National Science Foundation. This is designed to reach the general public through exhibits in museums and to reach middle and high school students through special designed learning modules. Opportunities are provided to interact with research scientists in nanotechnology.

A critical area is the introduction of nanotechnology into courses for technicians and for managers in industry to alert them to the changing paradigm of manufacturing.

- ***Identification and Assembly of Resources for R&D in Nanotechnology as a National Program***

Such programs already exist in the larger developed APEC economies but other economies need to move rapidly to ensure that they are not left behind in the exploitation of nanotechnology. Given the very large capital investments needed in facilities for research in physical and chemical aspects of nanotechnology, it is possible that small, and less developed, economies may see the biological route to nanotechnology development as more applicable to their economies.

- ***Increased Multidisciplinarity in Universities to Ensure Development of a Nanotechnology Workforce***

Academic disciplines such as physics, chemistry, biology and engineering have been separated by culture, management and terminology. New approaches to course design and to the setting-up of interdisciplinary research centres are needed. These must interact with industry to exploit research results.

- ***Adequate Funding to Ensure that Economies can Develop and Foster Expertise in Nanotechnology***

Large developed APEC economies have earmarked large sums for R&D in nanotechnology. Small, and less developed, economies must make adequate provision for funding to create and maintain a critical mass of expertise in the nanotechnology area.

- ***Developing a Network of APEC Resources in Nanotechnology***

This is particularly important for the smaller, and less developed, economies to ensure that their researchers gain rapid access to development in nanotechnology throughout the APEC region. A network also offers the opportunity for researchers from different economies to collaborate on projects of mutual interest and to identify possibilities for future development.

- ***Identification of Opportunity Areas in Technology***

Foresight techniques offer a tool to assist in tackling this challenge and APEC economies need to start prospective dialogues among officials, academics, researchers, industrialists and the community on the possibilities of nanotechnology in their different contexts.

- ***Changing of Mindsets of Industry Leaders and Investors in APEC Economies***

To take advantage of opportunities offered by nanotechnology there needs to be radical changes in management approaches and company strategies. Most industry leaders and investors are unaware of the potential for change and economies must develop awareness programs aimed at industry leaders and investors. Management courses must include discussion of emerging technologies including nanotechnology. Researchers can assist by offering their services to help industries solve their problems by application of nanotechnology.

- ***Establishment of Standards and a Nanometrology System***

National and international standards bodies must recognise the importance of establishment of a universally – recognised system for nanotechnology. Measurements and calibration at nanometer levels will require completely new approaches to those currently employed. However, without a nanometrology system, commercialisation will be inhibited.

- ***Implications for Small and Less Developed Economies***

As noted above, small and less developed, economies face a series of critical decisions in defining the role of nanotechnology in their futures. The formation of an advisory group of researchers with multidisciplinary skills is perhaps the most immediate way to assist decision-makers by provision of advice on nanotechnology.

- ***Ethical and Moral Concerns Arising from Nanotechnology***

The ethical and moral problems that have arisen in the development and commercialisation of biotechnology can be envisaged to arise with nanotechnology. It is important for APEC economies to encourage debates between researchers, social scientists and community representatives at an early stage to define issues unique to their economies eg in agriculture, environment and health care.

While individual economies must tackle these key policy areas within their own systems, there is a role for APEC, through Ministerial and Working Group meetings, to:

- Give leadership in ensuring that experience with these different issues is shared;
- Facilitate the development of nanometrology databases;
- Support multi-economy and multidisciplinary programs on nano-technology;
- Stimulate the move to a new paradigm in manufacturing based on nanotechnology;

- Encourage economies to address the institutional barriers to the equal participation of women in APEC's S&T workforce, since it is clear that woman are under-represented within the field of nanotechnology research as in so many other branches of science and technology.
- Support the concept of sharing facilities and specialised equipment to enable less-developed economies to gain expertise in nanotechnology.

The choices that APEC economies make in the next few years will influence profoundly their future economic growth and the development of nanotechnology in the APEC region.

Conclusion

Nanotechnology represents the beginning of a revolution in our ability to manipulate materials for the good of humanity. As with all new technologies there are benefits and threats. The challenge for policymakers is to recognise these at an early stage through techniques such as the foresight approach and to put in place appropriate policy measures. The outcomes of the study reinforce the value of scenario creation as a tool for aiding strategic planning. The choices that APEC economies make in the next few years will influence profoundly their economic growth and the well-being of their citizens.

Appendix 1: List of Contributors

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