行政院所屬各機關出國人員報告書

(出國類別：考察訪問)

參加渥太華專家會議(APEC Experts Meeting on Nanotechnology)並參訪科技政策研究機構

服務機關： 行政院國家科學委員會
科學技術資料中心

出國人姓名職稱： 孟憲鈺　中心主任

出國地點： 美、加

出國日期： 民國 90 年 11 月 4 日至 90 年 11 月 13 日

報告日期： 民國 91 年 1 月 28 日

行政院研考會/省(市) 研考會編號欄

系統識別號:C09006213

公務出國報告提要

頁數: 5　含附件: 是

報告名稱:

參加渥太華專家會議(APEC Experts Meeting on Nanotechnology)並參訪科技政策研究機構

主辦機關:

行政院國家科學委員會科學技術資料中心

聯絡人／電話:

交流合作組／

出國人員:

孟憲鈺　行政院國家科學委員會科學技術資料中心　　簡任

出國類別: 其他

出國地區: 加拿大

出國期間: 民國 90 年 11 月 04 日 -民國 90 年 11 月 13 日

報告日期: 民國 91 年 01 月 28 日

分類號/目: G0／綜合（各類工程）　G0／綜合（各類工程）

關鍵詞: 奈米技術,加拿大

內容摘要: 此行目的主要乃赴加拿大渥太華參加APEC(亞太經濟合作會議) Center for Technology Foresight (CTF)主辦的奈米技術專家會議(APEC Experts Meeting on Nanotechnology)，順道訪問美國藍德政策研究所(RAND － Science and Technology Policy Institute)及美國奈米技術相關公司，以便掌握更先進的奈米技術，以利我國奈米技術計畫及前瞻計畫之進行。奈米技術(Nanotechnology)已是21世紀最重要的技術，世界各國無不全力發展此一耀眼的明星技術。根據近期的研究調查，全世界在2002年對相關奈米技術的產品會成長到US$40 Billion。今年(90年)四月在越南河內舉辦的第二 屆APEC ISTWG會議中已通過CTF所提的 NANOTECHNOLOGY the technology for the 21st century ，並受到各個經濟會員體的支持。經CTF會議中指派四個經濟會員體分別提出4篇position papers，加拿大負責nanophotonics、澳大利亞負責nanobiodevices、日本負責nanoelectronics以及中華台北負責nanostructured materials。顯見我國在此領域仍佔有重要的地位。該篇position paper（附件一）於科資中心的研究小組努力下已竣完成，且經國內專家牟中原教授及工研院材料所劉仲明所長審核過，該篇paper發表後，受到與會學者一致的認同及讚許，對中華台北表示佩服之意。會後所攜回之資料，亦值得有興趣的學者研讀。

本文電子檔已上傳至出國報告資訊網

摘要

此行目的主要乃赴加拿大渥太華參加APEC(亞太經濟合作會議) Center for Technology Foresight (CTF)主辦的奈米技術專家會議(APEC Experts Meeting on Nanotechnology)，順道訪問美國藍德政策研究所(RAND – Science and Technology Policy Institute)及美國奈米技術相關公司，以便掌握更先進的奈米技術，以利我國奈米技術計畫及前瞻計畫之進行。

奈米技術(Nanotechnology)已是21世紀最重要的技術，世界各國無不全力發展此一耀眼的明星技術。根據近期的研究調查，全世界在2002年對相關奈米技術的產品會成長到US$40 Billion。今年(90年)四月在越南河內舉辦的第二十屆APEC ISTWG會議中已通過CTF所提的"NANOTECHNOLOGY the technology for the 21st century"，並受到各個經濟會員體的支持。經CTF會議中指派四個經濟會員體分別提出4篇position papers，加拿大負責nanophotonics、澳大利亞負責nanobiodevices、日本負責nanoelectronics以及中華台北負責nanostructured materials。顯見我國在此領域仍佔有重要的地位。該篇position paper（附件一）於科資中心的研究小組努力下已竣完成，且經國內專家年中原教授及工研院材料所劉仲明所長審核過，該篇paper發表後，受到與會學者一致的認同及讚許，對中華台北表示佩服之意。會後所攜回之資料，亦值得有興趣的學者研讀。

重要活動日程

日期	拜訪機構	備註
11/4(日)	起程，當日抵達渥太華	路程
11/5(一) – 11/7(三)	參加APEC Experts Meeting on Nanotechnology, 並發表論文	開會
11/8(四)	由渥太華飛往洛杉磯	路程
11/9(五)	參訪美國藍德政策研究所(RAND – Science and Technology Policy Institute)	參訪
11/10(六)	拜訪駐洛杉磯科學組	拜會科學組
11/11(日)	整理資料	
11/12(一)	參訪參訪美國Advanced Bionics Corporation，下午搭機返台	參訪、回程
11/13(二)	抵台北	

目次

伍、 附件

1. APEC Nanotechnology Position Paper -Nanostructured Materials: The Materials for the 21st Century
2. APEC Nanotechnology Position Paper - Nano-Photonics
3. APEC Nanotechnology Position Paper - Nanobiosystems
4. APEC Nanotechnology Position Paper - Nanoelectronics

Participants' Program for APEC Experts' Meeting on Nanotechnology

4-7 November 2001 at the Delta Hotel, Ottawa

Hosted by the National Research Council of Canada

****

Sunday 4 November 19.00-20.30 Welcome Reception at the Delta Hotel, Champlain Room

Mon 5 Nov	**Victoria Room, Delta Hotel**
9 00am	Welcoming speech
9 10am	Introduction to APEC CTF
9 20am	Introduction to project and roles of participants
9 30am	Presentations of Experts on Nanotechnology in their Economies
11 00am	*- Break -*
11.30am	Continuation of Presentations
12 30pm	*- Lunch –**Champlain Room, Delta Hotel***
2 00pm	Presentation and discussion of Position Papers 1 and 2
2 40pm	Presentation and discussion of Position Papers 3 and 4
3 20pm	*- Break -*
3 50pm	Presentation and discussion of Issues Paper
4.20pm	Identification of Technological Opportunities
5 10pm	Presentation of Paper on 'Issues for Developing Economies'
5 30pm	*- Close -*

Tues 6 Nov	**Victoria Room, Delta Hotel**
8 30am	Identification of Key Issues by Experts
9 30am	Introduction to Foresight
9 50am	Introduction to Scenarios
10 10am	Identification of Key Drivers
11 00am	*- Break -*
11 30am	Identification and Ranking of Uncertainties
12 30pm	*- Lunch –**Champlain Room, Delta Hotel***
2 00pm	Assignment of Scenario Logics, and small groups
2 15pm	Scenario Creation (small groups) *(including break)*
4 30pm	Group Reports and discussion
5 30pm	*- Close -*
7.30pm	**Participants Banquet, Champlain Room, Delta Hotel**

Wed 7 Nov	**Victoria Room, Delta Hotel**
8 30am	Scenario Refinement (small groups), and Group reports
10 00am	Identification of Outcomes and Actions
11 00am	*- Break -*
11 30am	Prioritisation of Actions
12 30pm	*- Lunch –**Champlain Room, Delta Hotel***
2 00pm	Further Discussions - Implications for developed economies - Implications for developing economies - Gender issues - Moral and ethical concerns
3 30pm	*- break -*
4 00pm	Briefing on follow up to the meeting and further stages in the project
4 20pm	Closing Remarks and Evaluation
4 30pm	*- Close -*

參加渥太華專家會議(APEC Experts Meeting on Nanotechnology)並參訪科技政策研究機構

一、參加會議經過

由 APEC Center for Technology Foresight (CTF)主辦，加拿大國家研究委員會(NRC)協辦的奈米技術專家會議(APEC Experts Meeting on Nanotechnology)於二OO一年十一月四日至七日在加拿大渥太華舉行。不同於一般的研討會，此次會議採取員額管控(close meeting)，約有十個 APEC 經濟會員體，三十餘名學者出席，出席者皆是各國在奈米技術領域中一時之選。此次中華台北由職與工研院材料所副所長　共同參與。

奈米技術(Nanotechnology)已是 21 世紀最重要的技術，世界各國無不全力發展此一耀眼的明星技術。根據近期的研究調查，全世界在 2002 年對相關奈米技術的產品會成長到 US$40 Billion。APEC(亞太經濟合作會議) Center for Technology Foresight (CTF)更已將奈米技術(Nanotechnology)列為該中心的重點研究主題之一。今年(90 年)四月在越南河內舉辦的第二十屆 APEC ISTWG 會議中已通過 CTF 所提的"NANOTECHNOLOGY the technology for the 21st century"，並受到各個經濟會員體的支持。

筆者自 2001 年起即被聘任為 CTF 之國際顧問團(International Advisory Board, IAB)的成員之一，有其榮幸可參與其中的討論。在 2001 年五月的 CTF 會議中，指派四個對奈米技術有較多研究的經濟會員體分別提出 4 篇相關奈米技術的 position papers，最後決定由加拿大負責 nanophotonics、澳大利亞負責 nanobiodevices、日本負責 nanoelectronics 以及中華台北負責 nanostructured materials。並預計今年(2001)八月底前完成 position paper 初稿，十一月於加拿大渥太華召開專家會議(experts meeting)，邀請專家針對所提出的四篇 position papers 作充分的討論。各個撰寫 position paper 的經濟會員體除了對自己負責的 paper 作 present 外，尚且就目前該國國內 nanoscience 及 nanotechnology 的發展概況作一說明。

由於多年來我國在科技領域的努力下，雖然正面臨產業升級與大陸市場的工衝擊，但由 CTF 對我們的重視下，顯見我國在奈米新興技術

領域中仍佔有重要的地位。該篇 position paper（附件）於科資中心的研究小組經過三個月努力下已竣完成，且經國內專家牟中原教授及工研院材料所劉仲明所長審核過，在此次專家會議中獲得好評。

二、與會心得

(1)此次的會議約有十個 APEC 經濟會員，三十餘名學者出席，出席者皆是各國在奈米技術領域中一時之選。會議中完全針對奈米技術，特別是由加拿大、澳大利亞、日本以及中華台北(nanophotonics 、nanobiodevices 、nanoelectronics 及 nanostructured materials)所提出的四篇 position papers 作更進一步的深入討論。(相關此四篇 position papers 之內容，請參考附件。）各國學者對我方提出的論文報告有非常高的評價。

(2)經各分組熱烈的討論後，各學者將奈米技術在三年內及十年內會影響的範圍羅列如下(Identification of Technological Opportunities)，可供國內有興趣的學者參考:

In 3 years:

Selective bio-nanosensors
Self cleaning surface treatment of nano material
Small and high capacity energy storage devices
First Q-bit device demonstrateo
Nanoparticles/catalysts
Control of crystalline architecture of materials
Nanoelectronics utilizing new physics(Quantum effect, spin, etc.)
Nanoelectronics i.e. MEMS
Thin-film technologyies
Nano structured materials as industrial catalysts
Drug delivery system. Efficient and specific drug delivery systems
Quantum dot biotags
Quantum dot lasers in production
Self organised growth of nanostructures
Photonic bandgap materials for IT
Biosensors using nanotechnology
DNA chip is hopeful
Electronic detection of single molecules
Electrical detection in biochips

In 10 years:

Portable fuel cell and advanced battery
Advanced thin film coatings for energy conservation
Electronics single charge transitors
Artificial photosynthesis
Molecular devices. Molecular switches
Identification of nanoelectronic architecture
Energy storage - H2 and ethanol
Quantum information technology
Single electron memory or trangister used ULS I
Integrated nanocircuits for electronics
Tuning of magnetic properties of materials
Highly efficient solar energy captors
Direct and sequencing in real time
Medical diagnostics; eg. For cancer, disease
Targetted human cells for organ repair
Integrated devices for real time protein expression analysis (perhaps implantable)
High resulution printer
Optical computing
NEMS using combination for top down and bottom up approaches
Manufacturing issues - large area, low cost

(3)奈米（nm），這個只有十億分之一米大小的單位，實現了元件微小化的理想，而奈米科技不僅是目前電子與資訊產業技術急於突破的關鍵技術，甚至對材料、光電、生化、醫療也將帶來前所未有的技術革命。美國柯林頓總統於前年初，宣布一項5億美元2001年的預算，投入奈米技術（Nano-technology），相較2000年經費，增加了83%。我國工研院也在四年前投入相關研發，涵蓋量測、電子、機械、材料、化工等技術投入。去年12月，行政院召集的科技顧問會議，所建議的五大科技項目中，奈米技術為其一，奈米技術被界定為具有次一工業革命的衝擊，包括奈米（百萬分之一釐米，稱為奈米） 材料，奈米電路電腦，生化醫療等，其應用可擴展至所有科技領域，最終影響國家安全，可見此一技術的重要性日趨增加。

(4)奈米科技是二十一世紀產業革命動力，國內半導體廠商目前也積極將ＩＣ推到奈米領域，盼藉由奈米技術，將半導體產業由代工升級到領先地位。此外，奈米新材料及量子理論的應用，可為聲、光、電磁與熱等領域之技術發展帶來新的前景；另外利用奈米技術研發生物晶片，將可取代生理檢查時繁雜的檢驗工作，病變的基因與細胞也可利用奈米技術修護，使其恢復正常與健康。這皆是先進國家競相投入奈米科技發展的原因，我國自然也不落人後。在微觀和巨觀間的介

觀性質是工業材料發展上獨特的機會與挑戰。奈米結構的操控技術更是介觀特性創造工業應用的關鍵所在，奈米材料技術將衝擊所有的高科技產業，而機會就是現在，我國絕不可錯失此良機。

(5)由於奈米給了所有物質新特性與新應用，因此，有人認為奈米科技將是產業升級的催化劑與觸媒。美國、日本及歐盟均已積極展開奈米 研究，每年各投入四億至五億美元進行研發。美國目前在奈米結構與自組裝技術、奈米粉體、奈米管、奈米電子元件及奈米生物技術上有顯著發展；德國則在奈米材料、奈米量測及奈米薄膜技術，日本在奈米電子元件、無機奈米材料領域上均已各具優勢。這些技術的發展勢必影響我國現在具競爭優勢的半導體、光電，及資訊等高科技產業的未來。

(6)筆者很欣慰我國對奈米技術的重要性已有相當的瞭解。國科會已通過六年奈米國家型科技計畫，而經濟部也已積極投入奈米研發，並在工研院成立奈米科技研發中心，成為國內首座奈米研發單位，選定奈米材料、奈米電子、奈米機械及奈米生技四大應用發展領域，以現有的高科技產業，如積體電路、顯示器、資訊儲存、通訊、電子構裝、能源等，或是基礎產業，如人纖、塑膠、染料、建材、造紙及金屬製品等為基礎，再結合新興的醫療及生技產業，使國內產業全面導入奈米技術，提昇產業競爭力。

三、參訪科技政策研究機構

綜由各方資訊，對於奈米技術的發展，美國仍是其中的翹楚。本中心正積極準備從事國內前瞻計畫(National Technology Foresight Program)，而奈米技術亦列為我國未來科技重點技術。然而此行正巧在紐約 911 事件之後，所有往來美國和加拿大地區都檢驗非常嚴格，因此訪問美國藍德政策研究所(RAND – Science and Technology Policy Institute)及美國 Advanced Bionics Corporation 奈米技術相關公司的路程中也受到許多延誤。

(1)美國藍德政策研究所(RAND – Science and Technology Policy Institute)

藍德科技政策研究所是由 NSF 以合約方式經營以支援白宮科技政策辦公室(Office of Science and Technology Policy, OSTP)及科技相關政府機構。此機構原於 1991 年國會立法，1992 年成立「關鍵技術研究

所」(Critical Technologies Institute, CTI)，1998 年 10 月由國會立法更名為「科技政策研究所」(Science and Technology Policy Institute，S&TPI)。

筆者曾於前年十月訪問過 RAND 位於華盛頓特區的辦公室，針對彼此未來的合作已有初步的共識。由於本中心正積極從事國內前瞻計畫(National Technology Foresight Program)，並且擬採用藍德科技政策研究所開發並且長期使用的「關鍵技術」(Critical Technologies)應用在前瞻計畫中。但由於 911 事件，原擬和筆者會談的相關業務負責人員，未能及時從歐洲趕回，而臨時取消合作事宜的會談，只就關鍵技術未來在我國前瞻計畫的應用交換意見，並參觀其組織。

(2)參訪美國 Advanced Bionics Corporation

Advanced Bionics Corporation(ABC)位於美國洛杉磯，是 1993 年由 MiniMed Inc. spin off 獨立出來的公司。目前該公司擁有約 250 名科學家及工程師。另外該公司在法國有一個約三十多人的分公司。經由駐外科學組的協助聯繫，得以參觀並了解其公司。

ABC 主要的產品是"CLARION Platinum Series"，應用奈米(nanotechnology)技術生產人體植入系統、生物模擬植入器，其結合生技及奈米技術之產品，為目前世界上已俱規模之生技奈米技術公司。藉由此次訪問，對未來了解奈米技術商品化之過程及產業建立之經驗，應可有很大的助益。

四、結語/建議

承　主委日前指示，科資中心應參加本會奈米技術計畫小組會議，提供各國的發展趨勢及相關計畫。此次科資中心很榮幸能代表中華台北應 CTF 的邀請撰寫其奈米技術(Nanotechnology)相關報告，並出席其舉辦的專家會議。因應產業競爭及國際的趨勢，未來幾年我國勢必加速提升我國的產業技術，而奈米技術正是我們應該努力的方向。加速奈米材料技術之發展為有效達成提升我國的產業技術，除充實人才、建設良好研發環境外，更需加強資源之整合運用，包含與學界、業界及其他專業研究機構之合作交流，以及積極推動國際合作技術引進的工作。

APEC TECHNOLOGY FORESIGHT CENTER NANOTECHNOLOGY PROJECT

Nanostructured Materials : The Materials for the 21st Century

Position Paper Prepared by Chinese Taipei
15-September 2001

Research Team

Prof. Dr. Hsien-Chun Meng
Dr. Antonio Balaguer
Dr. Yau Shyu
Dr. Feng-tai Hwang
Dr. Iris Yu-ling Luo
Ms. Chiu-yen Chen

STIC

Science and Technology Information Center
National Science Council
Chinese Taipei

STPRC #01-P-01

FOREWORD

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

Table of Contents

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, 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 ;

---

[1] Giga Pascal

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

- 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 21stcentury, 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.

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)

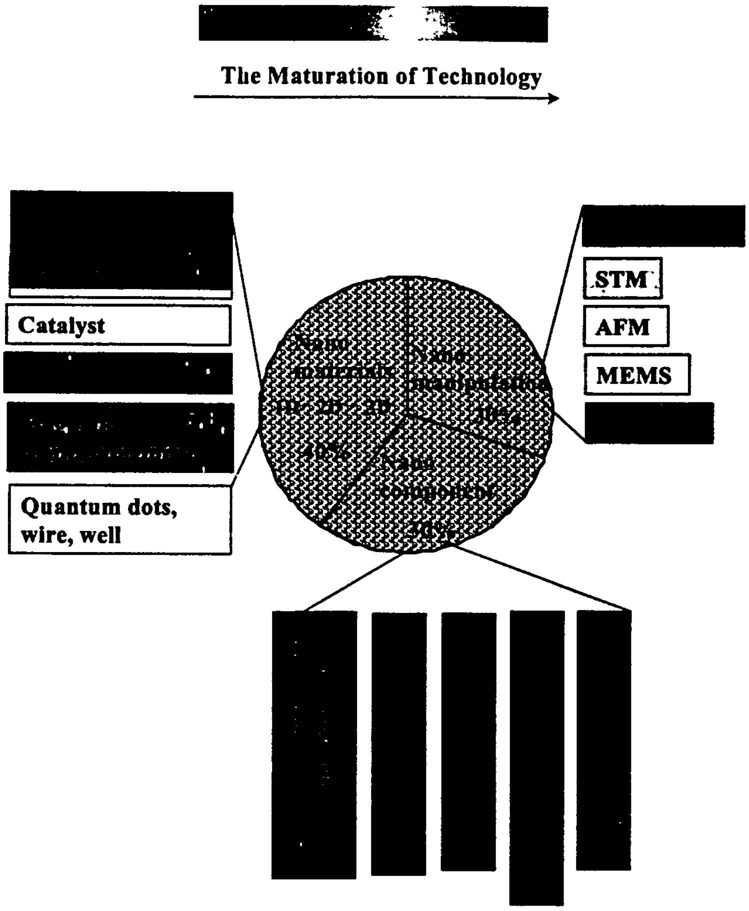
	Year 1996	Year 2001
Ceramics	5,912	8,811
Coatings	2,103	8,811
Pigments	568	1,137
Solar cells	454	795
Sunburn lotion	227	284
Polymer composites	-	1,023
Total	9,266	20,864

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.

---

[3] Richard W. Siegel (1998). Chap1. Nanostructure Science and Technology. A world wide study. WTEC, Loyola College, Maryland.

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



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

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 version4. Materials often

---

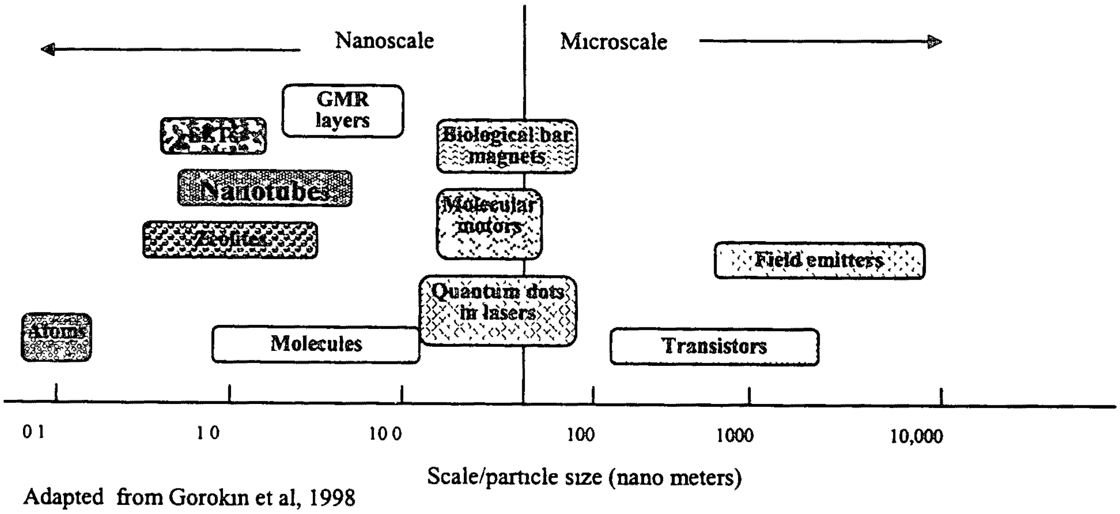
[4] http://www.cordis lu/growth/calls/top-3.32.htm

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.

Figure 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.

---

[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)

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 nanoscale. 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%;
- Increased hardness and strength—hardness values for nanocrystalline 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 nanostructured 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 "sculpted" 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 "ball-milling" 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, "bottom-up" 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 nanostructures. 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

---

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

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 characteristics 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 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, nanostructures 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), microfabrication 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 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

---

[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.

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.

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)

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.

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 nanotechnology.

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 nanotechnology 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 nanostructured 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 pharmaceuticals, 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, commitment, and long term planning. The support for the academia in terms of advanced facilities, equipment and personnel is critical for the continuation of critical discoveries through fundamental research. This was explicitly recognized in the President Clinton's National Nanotechnology Initiative.

3.3 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.

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 nanostructured 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

---

[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

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	• Reinforcement fiber for high-strength composite • Pure and composite high-strength fiber • Ductile ceramics
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.

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

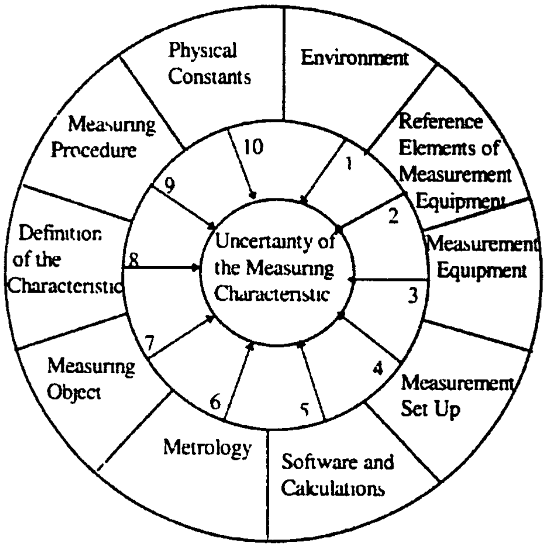
Source: ten Wolde (1998, Chapter 3)

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. 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

Figure 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 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 nanotechnology 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.

6. REFERENCES

Business Communication Company (2001) "Nanoparticle Industry Review", Business Communication Company, Inc, Norwark

Cox, D. M (1998) Chap 4 High surface area materials. In *Nanostructure Science and Technology -A world wide study*, Siegel, Hu and Rocco (Eds.) WTEC, Loyola College, Maryland.

Deparment of Trade and Industry, United Kingdom.(2001).'The International Technology Service Missions on Nanotechnology to Germany and the USA.'

European Consortium for Nano Materials – COST program (1997) "Memorandum of Understanding for the implementation of a European Concerted Research

Frenken, J.W.M (1998) Scanning Tunneling Microscopy. In *Nanotechnology Towards a Molecular Construction Kit.* Arthur Ten Wolde (Editor). Study center for Technology Trends, STT Netherlands, The Hague

Gell, M (1998) Nanostructured Coatings. *In R&D Status and Trends in Nanoparticles, Nanostructured Materials, and Nanodevices in the United States.* Siegel et al Editors.

Goddard III, W. A.(1998).Nanoscale Theory and Simulation: A Critical Driver for and a Critical Challenge to Commercial Nanotechnology. , In *Nanotechnology Research Directions: Vision for Nanotechnology R&D in the Next Decade.* National Science and Technology Council, Interagency Working Group on Nanoscience, Engineering and Technology (IWGN).

Gonsalves, K.E., S.P Rangarajan and J. Wang (2000). Chemical Synthesis of Nanostructured Materials, Metal Alloys and Semiconductors. In *Handbook of Nanostructured Materials and Nanotechnology,* Hari Singh Nalwa (Editor). Academic Press. London

Gorokin, H., P. Von Almen, K. R. Tsui and T. Zhu (1998) Chap 5 Functional Nano devices. In *Nanostructure Science and Technology -A world wide study,* Siegel, Hu and Rocco (Eds.) WTEC, Loyola College, Maryland.

Hu, E. L. and D. T. Shaw (1998) Chap 2 Synthesis and Aseembly. In *Nanostructure Science and Technology -A world wide study,* Siegel, Hu and Rocco (Eds.) WTEC, Loyola College, Maryland.

Jaworek, T., D. Deher, G. Wegner, R.H. Wieringa, and A.J. Schouten. (1998).' Electromechanical Properties of an Ultrathin layer of directionally aligned helical polypeptides. Science 279:57-60

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

Koch, C.C. (1989). Materials synthesis by mechanical alloying. *Annual Review of Mater.* Sci. 19:121-143

Liu, L. and M. Waga (2001).'Nanotechnology Initiatives in the Asia Pacific Region.' mstnews.3/01

Mendel, J. (1998) Chap 3, Dispersions and Coatings. In *Nanostructure Science and Technology -A world wide study,* Siegel, Hu and Rocco (Eds.) WTEC, Loyola College, Maryland.

Mertz J. L. and A Ellis (1999) Chap. 11, Infrastructure needs for R&D and Education. In *Nanotechnology Research Directions: Vision for Nanotechnology R&D in the Next Decade.* National Science and Technology Council, Interagency Working Group on

Nanoscience, Engineering and Technology (IWGN).

Murray, C.B, D.J. Norris and M.G. Bawendi (1993) *J. Am. Soc.* 115:8706
Murday, J., R. Celotta, D.Y. Pui, P. West (1999) Investigative Tools: Experimental Methods and Probes. In *Nanotechnology Research Directions: Vision for Nanotechnology R&D in the Next Decade.* National Science and Technology Council, Interagency Working Group on Nanoscience, Engineering and Technology (IWGN).

Rademan, K., B. Kaiser, U. Even and F. Hensel (1987) *Phys. Rev. Lett.* 70:3079

Roco M.C.et al. (2000) "National Nanotechnology Initiative: The Initiative and Its Implementation Plan", National Science and Technology Council Committee on Technology Subcommittec on Nanosclae Science, Engineering and Technology, Washington D.C.

Rohlfing, E.A., D.M. Cox and A. Kaldor (1984) *J. Chem. Phys.* 81:3846

Siegel, R. W. (1998). Chap1 Introduction and Overview. In *Nanostructure Science and Technology -A world wide study*, Siegel, Hu and Rocco (Eds.) WTEC, Loyola College, Maryland.

Taylor, K.J., C.L. Pettiette-H, O. Cheshnovsky and R.J. Smalley (1992). *J. Chem. Phys.* 96:3319

ten Wolde, A (1998) Introduction. In *Nanotechnology Towards a Molecular Construction Kit.* Arthur Ten Wolde (Editor). Study center for Technology Trends, STT Netherlands, The Hague

Whitehouse, D. (1999) Tools of nanotechnology and nanometrology. In *Handbook of Nanostructured Materials and Nanotechnology*, Hari Singh Nalwa (Editor). Academic Press. London

Whitesides G., P. Alivisatos (1999), Fundamental scientific issues for technology, chapter 1, In *Nanotechnology Research Directions. Vision for Nanotechnology R&D in the Next Decade.* National Science and Technology Council, Interagency Working Group on Nanoscience, Engineering and Technology (IWGN).

Wu, M.K, R. S. Windeler, T. Bors and S. K. Friedlander (1993) Controlled synthesis of nanosized particles by aerosol processes. *Aerosol Sci. Technol 19:527*

7. APPENDIXES

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

---

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

Academic and research activities

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 nanocomposites
- 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.

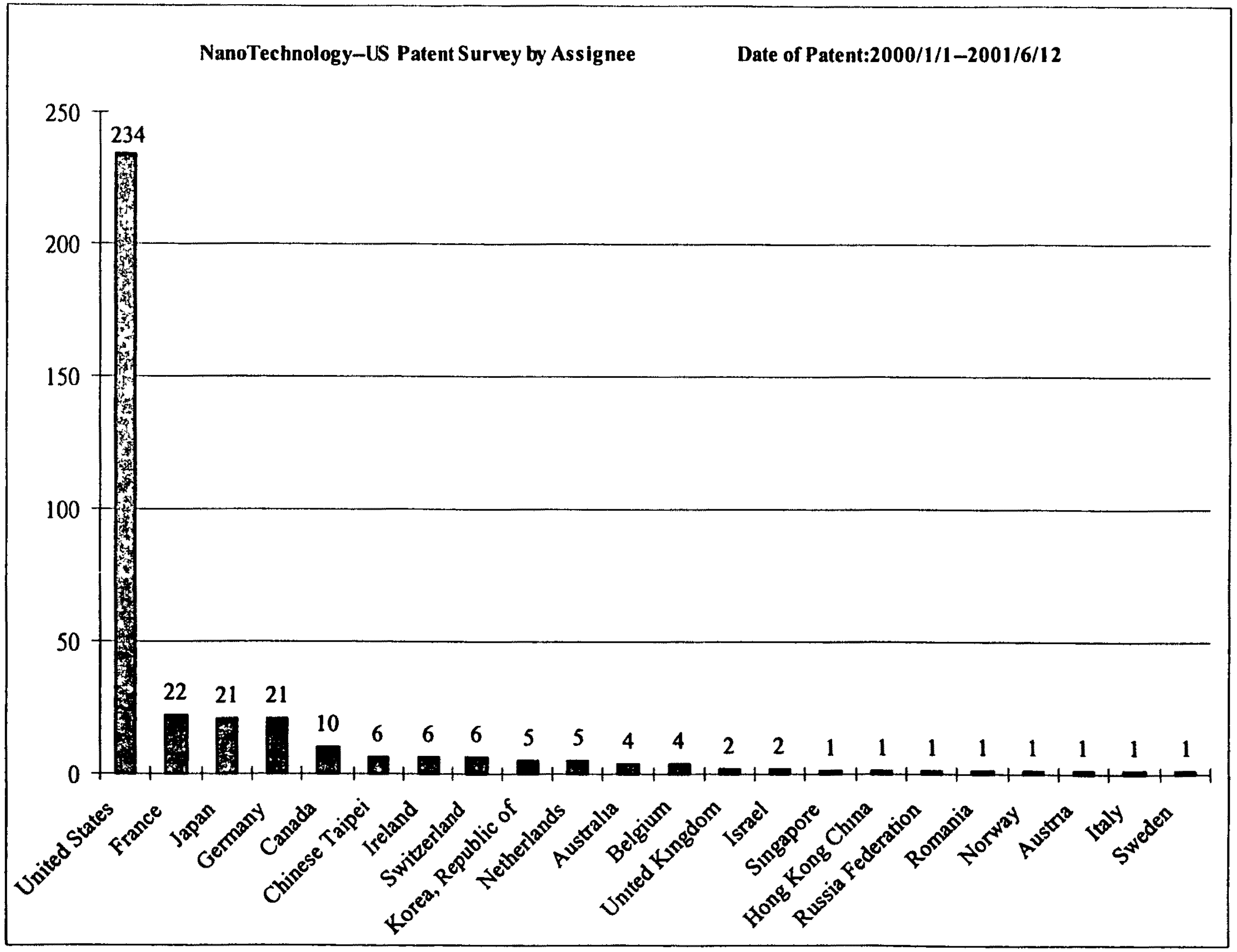
NSF/Division of Materials Research(DMR):

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: Patens Granted by the USPTO in Nanostructured Materials and related areas



Appendix 2: Patens 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
Russia Federation				1				1
Romania				1				1
Norway	1							1
Austria	1							1
Italy	1							1
Sweden	1							1

Appendix 2: Patens 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
Russia 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 Gratzel cells - window layers in solar cells from nanostructured semicondcutors - 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 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) - high-temperature superconductors using nanoparticles for flux pinning - liquid magnetic O-rings to seal off computer disk drives

Optoelectronics	- '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 - 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
Various other 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.) - '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

SCIENCE AND TECHNOLOGY INFORMATION CENTER
NATIONAL SCIENCE COUNCIL, CHINESE TAIPEI
Address: 16F, 106, Sec. 2, Ho-Ping E. Rd., Taipei, Taiwan
TEL: 886-2-27377621 FAX: 886-2-27377663
APEC-STPRC web site http://www.apec-stprc.org/

APEC Center for Technology Foresight
National Science and Technology Development Agency
73/1 Rama VI, Rajdhevee
Bangkok 10400, Thailand

Nano-Photonics

A Background Document
for the
APEC-wide Experts Meeting
on
Nanotechnology

Nov 5-7, 2001
Ottawa, Canada

Prepared by

National Research Council of Canada
August 2001

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

Table of Contents

Contributors

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.

John Alcock
Starlene Buchanan
Paul Corkum
Marie D'Iorio
Jan Dubowski
Peter Grant
Sadiq Hasnain
Pawel Hawrylak
Thomas Jackman
H-C Liu
David Lockwood
Richard Normandin
Alex Szabo
Rod Taylor
Dan Wayner
Robin Williams

Ottawa, Canada
August 2001

Chapter 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 nanotechnology 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 electromagnetic 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 'optoelectronics'. 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.

Chapter 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. Chapter 3 examines some recent developments and breakthroughs in research ('nano-science'), which will be the building blocks for nanotechnology in the future. Finally, Chapter 4 discusses the continuing need for advances in metrology and the challenges facing our educational and infrastructure systems.

Chapter 2

Today: Nano-Photonics in the Marketplace

This chapter 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, interchangeability 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 '70s, 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

Chapter 3

Tomorrow Today: Nano-photonics Science

This chapter 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 To-date 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 semiconductor 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* ($\chi^{(2)} \sim 100$ 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 simultaneously 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 nanocomposites 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, nanotechnology 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]

Chapter 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 the 10^{-15} level.

Chapter 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 Chapter 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 Chapter 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.

References

1 *'An Invitation to Enter a New Field of Physics: There's Plenty of Room at the Bottom'*, http://www.zyvex.com/nanotech/feynman.html

2 'National Nanotechnology Initiative The Initiative and its Implementation Plan' http.//www.nano.gov/

3 *'Nanostructure Science and Technology: A Worldwide Study'*, **http://itri.loyola.edu/nano/**

4 *'Nanotechnology Research Directions: IWGN Workshop Report'*, http.//itri.loyola.edu/nano/IWGN.Research.Directions/

5 *'Optical Fibre Communications: Conference & Exhibit'* www.osa.org/mtg_conf/OFC/)

6 *'Compound Semiconductors'* 7, p5 (2001)

7 B.D Terris, H J Mamin, D Rugar, W.R.Studenmud and G.S.Kino, Appl. Phys Lett 85, p388 (1994)

8 Y.Martin,S Rishton and H K.Wickramasinghe, Appl Phys. Lett.,71, p1 (1997)

9 F Zenhausern, Y Martin and H K. Wickramasinge, Science, 269, p1083 (1995).

10 M F.Garcia-Parajo, J -A.Veerman, B.G.de Grooth, J. Greve, N.F. van Hulst, Optical Memory and Neural Networks, 7, p283, (1998)

11 L.Novotny, R.X.Bian and X.S Xie, Physical Rev Lett, 79, p645 (1997).

12 Z-P Luo, Y-l Sun and K-N An, Appl. Phys Lett , 76, 1779 (2000).

13 M Labardi, S.Patane and M.Allegrini, Appl. Phys. Lett. 77, p621 (2000).

14 X.S Xie and R.C. Dunn, Science, 265, p361 (1994)

15 F Flack, N.Samarth, V Nikitin, P A Crowell, J.Shi, J.Levy and D.D.Awschalom, Physical Review B54, R17312 (1996)

16 J Michaells,C Hettich,J Mlynek and V Sandoghdar, Nature, 405, p325 (2000)

17 L.Pavesi, L Dal Negro, C Mazzoleni, G Franzo and F. Priolo, Nature, 408, p440 (2000)

18 M H. Huang, S Mao, H Feick, H. Yan, Y. Wu, H. Kind. E. Weber, R Russo and P. Yang, Science, 292, p1897 (2001)

19 I P Bilinsky, J G Fujimoto, J.N. Walpole and L.J. Missaggia, Appl. Phys. Lett., 74, p2411 (1999).

20 J.Lu, M Prabhu, J. Song, C Li, J. Xu, K. Ueda, A.A. Kaminski, H. Yagi and T. Yanagitani, Appl Phys B71, p469 (2000).

21 S Fafard, Z.R Wasilewski and M Spanner, Appl. Phys. Lett. 75, p1866 (1999).

22 N Carlsson, T Junno, L Montelius, M. -E. Pistol, L. Samuelson, W. Seifert, J. Cryst Growth 191, p347 (1998).

23 P J. Poole, J P McCaffrey, R L Williams, J. Lefebvre, D. Basnagge, J. Vac Sci. Technol B19 (2001)

24 V I Klimov, D W McBranch, C A. Leatherdale and M.G. Bawendi, Phys. Rev. B 60(19), p13740 (1999)

25 F -Y. Tsai and C P Lee, J Appl. Phys 84(5), p2624 (1998).

26 D Gammon, E S Snow, B V Shanobrook, D S Katzer and D. Park, Science 273, p87 (1996)

27 I N. Stranski, L von Krastanow, Sitzungsber K Preuss, Akad. Wiss., Phys. Math. Kl 146, p797 (1937)

28 Y Arakawa and H Sakaki, Appl. Phys Lett. 40, p939 (1982).

29 N N Ledentsov, V A Shchukin, M Grundmann, N. Kirstaedter, J. Bohrer, O. Schmidt, D. Bimberg, V.M Ustinov, A.Y Egorov, A.E Zhukov, P.S. Kop'ev, S.V. Zaitsev, N Y Gordeev, Z.I Alferov, A I Borovkov, A.O. Kosogov, S.S. Ruvimov, P Werner, U Gosele, J Heydenreich, Phys. Rev. B54, p8743 (1996).

30 K Eberl, A Kurtenbach, M Zundel, J.Y. Jin-Phillipp, F. Phillipp, A. Moritz, R. Wirth, A Hangleiter, J. Cryst Growth 175/176, p702 (1997).

31 K Hinzer, J Lapointe, Y Feng, A Delage, S. Fafard, A.J. Springthorp and E.M. Griswold, J Appl Phys 87(3), p1496 (2000)

32 H Saito, K Nishi, S Sugou, Appl Phys Lett. 78(3), p267 (2001).

33 H C Liu, M Gao, J McCaffrey, Z R Wasilewski, S. Fafard, Appl. Phys. Lett. 78, p79 (2001)

34 S Sauvage, P. Boucaud, J.-M Gerard, V. Thierry-Mieg, Phys. Rev. B58, p10562 (1998)

35 L Chu, A Zrenner, G Bohm, G Abstreiter, Appl Phys Lett. 75(23), p3599 (1999)

36. K W Berryman, S A. Lyon, M. Segev, Appl. Phys. Lett. 70(14), p1861 (1997)

37 V Ryzhii, Semiconduct Sci. Technol 11, p759 (1996).

38 R.L Williams, G C Aers, P.J. Poole, J. Lefebvre, D. Chithrani, B. Lamontagne, J. Cryst Growth, 223, p321 (2001)

39 Y Toda, O Moriwaki, M Nishioka and Y. Arakawa, Phys. Rev. Lett 82, p4114 (1999).

40 E S Kim, N Usami, Y Shiraki, Appl Phys Lett 72(13), p1617 (1998).

41 A E Romanov, P.M. Petroff, J.S Speck, Appl. Phys. Lett. 74(16), p2280 (1999).

42 A Zrenner, M. Markmann, A Paassen, A.L. Efros, M. Bichler, W. Wegscheider, G. Bohm, G Abstreiter, Physica B256, p300 (1998)

43 E. Dekel, D. Gershoni, E Ehrenfreund, D Spektor, J.M. Garcia, P.M. Petroff, Phys. Rev Lett 80, p4991 (1998).

44 M. Bayer, A Kuther, A Forchel, A. Gorbunov, V.B. Timofeev, F. Schafer, J.P. Reithmayer, T.L Reinecke, S N Walck, Phys Rev. Lett. 82, p1748 (1999).

45 M Bayer, T Gutbrod, A. Forchel, V.D Kulakovskii, A. Gorbunov, M. Michel, R. Steffen, K.H Wang, Phys Rev. B58, p4740 (1998)

46 P Hawrylak, G Narvaez, M Bayer, O. Stern , A. Forchel, Phys.Rev.Lett. 85, p389 (2000)

47 R Warburton, C S. *Dürr, K.* Karrai, J P. Kotthaus, G. Medeiros-Ribeiro and P M. Petroff, Phys. Rev Lett 79, p5282 (1997)

48 E Dekel, D Gershoni, E Ehrenfreund, D Spektor, J M. Garcia and P.M. Petroff, Phys Rev Lett 80, p4991 (1998)

49 A Zrenner, L V Butov, M Hagn, G Abstreiter, G *Böhm and G.* Weimann, Phys Rev Lett. 72, p3382 (1994)

50 M Bayer, O Stern, P. Hawrylak, S Fafard, A Forchel , Nature 405, p923 (2000).

51 M Bayer, P Hawrylak, K Hinzer, S Fafard, M Korkusinski, Z R Wasilewski , O Stern, A Forchel , Science 291, p451 (2001)

52 D Gammon, E S Snow, B V Shanabrook, D S Katzer, D Park, Phys. Rev Lett 7, p3005 (1996)

53 S.W Brown, T A Kennedy, D Gammon, E S. Snow, Phys. Rev. B54, pR17339 (1996)

54 D Gammon, A L Efros, T A Kennedy, M. Rosen, D.S. Katzer, D Park, S.W. Brown, V L Korenev, I A Merkulov, Phys Rev Lett 86(22), p5176 (2001).

55 G Chen, N H Bonadeo, D G Steel, D Gammon, D.S Katzer, D Park, L.J. Sham, Science 289, p1906 (2000)

56 J. D Joannopoulos, R D Meade, J N Wim, '*Photonic Crystals*', Princeton University Press (1995)

57 V Pacradcuni, W J Mandeville, A R Cowan, P. Paddon, J.F. Young and S Johnson, Phys Rev B62, p4204 (2000)

58 A Scherer, Opt Photon News 10, p21 (1999)

59 A Forchel, www.physik.uni-wuerzburg.de/TEP/

60 S Noda, A Chutinan, M Imada, Nature 407, p608 (2000)

61 A. Blanco, E Chomski, S Grabtchak, M Ibisate, S John, S. W Leonard, C Lopez, Nature 405, p437 (2000)

62. D Norris, NEC, www.neci.nj.nec.com/homepages/dnorris/sapc.html

63. C. Weisbuch, H Benisty (to be published)

64 T Lundstrom, W Schoenfeld, H Lee and P.M. Petroff, Science 286, p2312 (1999).

65 P Hawrylak, M Grabowski and J A. Tuszynski, , Phys. Rev. Lett. A165, p148 (1992).

66 K.J Resch, J S Lundeen and A M Steinberg, Phys Rev Lett (to appear).

67 P Michler, A. Imamoglu, M D Mason, P J Carson, G F Strouse, S.K. Kuratto, Nature 406, 968 (2000)

68 C. H Bennett, F Bessette, G Brassard, L Salvail,, John Smolin, J. Cryptology 5, p3 (1992)

69 J Kim, O Benson, H Kan, Y Yamamoto, Nature 397, 500 (1999).

70 C Santori, M Pelton, G Solomon, Y. Dale, Y Yamamoto,·Phys. Rev. Lett. 86, 1502 (2001)

71 P Michler, A Kiraz, C Becher, W V. Schoenfeld, P M. Petroff, L. Zhang, E. Hu, A Imamoglu, Science 290 2282 (2000)

72 J M Shi, CSC2001 Conference Proceedings, 638, Montreal, May 26-31 (2001).

73 M A Baldo, M E Thompson, S.R. Forrest, Nature, 403 (6771), p750 (2000).

74 H Sirringhaus, T Kawase, R H Friend, T Shimoda, M. Inbasekaran, W. Wu, E.P. Woo, Science, 290, p2123 (2000)

75 P K H Ho, D S Thomas, R.H Friend and N Tessler, Science 285, p233 (2001).

76. J H Schon, C Kloc, A Dodabalapur, B. Batlogg, Science, 289, p599 (2000).

77 W H Steier, S S Lee, S Garner, A.Chen, H Zhang, L.R.Dalton, H.Fetterman, A Udupta, D Bhattachaya, Shi Yangiany, LEOS '98 Conference Proceedings, 2, p3 (1998)

78 A Otomo, M Jager, G I.Stegeman, M.C Flipse, M.Diemeer, Appl. Phys. Lett. 69, p1991 (1996)

79 S Tomaru, Appl. Phys Lett 68, p1760 (1996)

80 T Verbiest, S Van Elshocht, M. Kauranen, L.Zhellemans, J. Snauwaert, C. Nuckolls, T J Katz, A. Persoons, Science, 282, p913 (1998).

81 Yongqiang Shi, Cheng Zhang, Hua Zhang, J H. Bechtel, L.R. Dalton, B.H Robinson, W.H Steier, L Dalton, Science, .288, p119 (2000).

82 M. Albota, D Beljonne, J-L.Bredas, J E Erlich, J-Y. Fu, A.A.Heikal, S.E.Hess, T.Kogaj, M D Levin, S.R.Marder, D McCord-Maughon, J W.Perry, H.Rockell, M Rumi, G Subramaniam, W W We, X-L.Wu, C.Wu, Science 281, p1653 (1998).

83 O A Matthews, A.N Shipway, and J F Stoddart, 1998. Prog. in Polymer Sci. 23, 1

84 S Brittain, K Paul, X -M Zhao, G Whitesides, Physics World, 11, p31 (1998)

85 S Smith, B G Orr, R Kopelman and T Norris, Ultramicroscopy 57, p173 (1995).

86 K Dickmann, J Jersch, F Demming and J Hildenhagen, Photonics Spectra, 30, p80 (1996)

REFE *'Nanotechnology Database'*, http://itri.loyola.edu/nanobase/

APEC Nanotechnology Position Paper

Nanobiosystems

A Background Document for the APEC Meeting on Nanotechnology
Nov 5-7, 2001
Ottawa, Canada

V. Braach-Maksvytis, B. Raguse
Commonwealth Scientific & Industrial Research Organization
Australia

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 a,l 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

- 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

Overview of Selected Areas of Research:

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

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 nanobiosystems research.

Examples of the use of biological receptors with physical amplification techniques have been investigated for a number of years (Gopel, 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 microorganisms. 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.

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

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)

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)

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

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 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

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 the how 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.

Contact details:

Dr Vijoleta Braach-Maksvytis
Program Leader Nanoscience and Systems
and
Chair CSIRO Science Forum
Executive Team
CSIRO Telecommunications and Industrial Physics
Bradfield Rd PO Box 218
Lindfield NSW 2070
Australia
Tel. 61 02 9413-7264
Fax 61 02 9413-7202
mobile 0407100126

Dr Burkhard Raguse
Project Leader, Biomimetic Engineering
CSIRO Telecommunications and Industrial Physics
Bradfield Rd PO Box 218
Lindfield NSW 2070
Australia
Tel 61 02 9413-7549
Fax 61 02 9413-7202

References:

Adleman, L M (1994), *Science*, 266, 1021

Bar-Cohen, Y. (2001) http://ndeaa.jpl.nasa.gov/nasa-nde/lommas/eap/EAP-web.htm

Birge, R R (1995), *Sci. Amer.*, March, 66

Braach-Maksvytis, V , Raguse, B (2000), *J. Am. Chem. Soc.*, 122, 9544.

Braun, E., Eichen, Y., Sivan U , Ben-Yoseph, G. (1998), *Nature*, 391, 775.

Brinker, C J ; Lu, Y F., Sellinger, A., Fan, H (1999), *Adv. Mater.*, 11(7), 579.

Chen, T , Barton, S C , Binyamin, G, Gao, A ; Zhang, Y ; Kim, H-H, Heller, A (2001), *J. Am. Chem. Soc.*, *123*, 8630

Cochlear, (2001) http://www.cochlear.com/rcs/cochlear/publisher/web/home/index.jsp

Cornell, B A , Braach-Maksvytis V., King, L., Osman, P., Raguse, B., Wieczorek, L.; Pace, R. (1997), *Nature*, *387*, 580 [http://www.ambri.com/]

Cox, C C , Cohen, D S , Ellington, A.D (1999), *Trends in Biotechnology*, 17, 151

Gopel, W (2000), *Sens. Actuators B* , 65, 70

Gopel, W (1996), *Microelectronic Eng.*, 32, 75

Graetzel, M (2001), http://dcwww.epfl.ch/icp/ICP-2/icp-2.html

Hirsch, R., Katz, E, Willner, I (2000), *J. Am. Chem. Soc.*, 122, 12053

Liu, J , Feng, X., Fryxell, G E , Wang, L-Q, Kim, A Y., Gong, M. (1998), *Adv. Mater.*, 10, 161.

Lu, G Q M (2001) http://nanomac.uq.edu.au/

Lu, G Q ; Li, H.D., Ishizaki, K ; Kormarneni, S ; (2001), *Colloids & Surfaces A*, 179, 131.

Nikoobakht, B , Wang, Z L , El-Sayed, M A , (2000), *J. Phys. Chem. B*, 104(36), 8635 .

Noji, H , Yasuda, R ; Yoshida, M ; Kinosita, K (1998), *Nature*, 386, 299

Ringsdorf, H , Schlarb, B , Venzmer, J (1988), *Angew. Chem. Int. Ed. Engl.*, 27, 113

Seeman N C (1997), *Acc. Chem Res.*, 30, 357

Seeman, N C (2001) http://seemanlab4.chem.nyu.edu/homepage.html

Simpson, M L., Sayler, G S , Fleming, J T , Applegate, B (2001), *Trends in Biotechnology*, 19(8), 317

Soong, R K., Bachand, G D ; Neves, H.P., Olkhovets, A.G , Craighead, H G , Montemagno, C.D. (2000), *Science*, *290*, 1555

Soten, I , Ozin, G A. (1999), *Curr. Opinion Coll. & Interface Sci.*, 4, 325.

Srinivasarao, M (1999), *Chem Rev*, 99, 1935.

Steinberg-Yfrach, G , Liddell, P A , Hung, S-C, Moore, A.L.; Gust, D.; Moore, T.A (1997), *Nature*, 385, 239

Steinberg-Yfrach, G ,Rigaud, J-L, Durantini, E.N ; Moore, A.L.; Gust, D.; Moore, T.A. (1998), *Nature*, 392, 479

Storhoff, J J , Mirkin, C.A. (1999), *Chem. Rev.*, 99, 1849.
[http.//www nanofabrication.northwestern edu/faculty/mirkin.html]

Ullmann, A (1996), *Chem. Rev.*, 96, 1533

Wei, Y. (1998), *Supramolecular Sci.*, 5(5-6), 723

Willner, I (1997), *Acc. Chem. Res.*, 30(9), 347

Willner, I , Heleg-Shabtai, V , Katz, E,, Rau, H K , Haehnel, W (1999), *J. Am. Chem. Soc.*, 121, 6455

Willner, I , Willner, B (2001), *Trends in Biotechnology, 19(6)*, 222

APEC Nanotechnology Position Paper - Nanoelectronics

Akira Toriumi, Takuji Takahashi, Hiroshi Ishihara, Toshiro Hiramoto, Yasuo Wada

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

About the authors·
1. Akira Toriumi: The University of Tokyo, Graduate School of Engineering
2 Takuji Takahashi The University of Tokyo, Institute for Industrial Science
3 Hiroshi Ishihara: Tokyo Institute of Technology, Frontier Collaborative Research Center
4 Toshiro Hiramoto. The University of Tokyo, Institute for Industrial Science
5 Yasuo Wada· Advanced Research Laboratory, Hitachi, Ltd and CREST, JST

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 5,000cm^{2}V/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^{2}PROM (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.

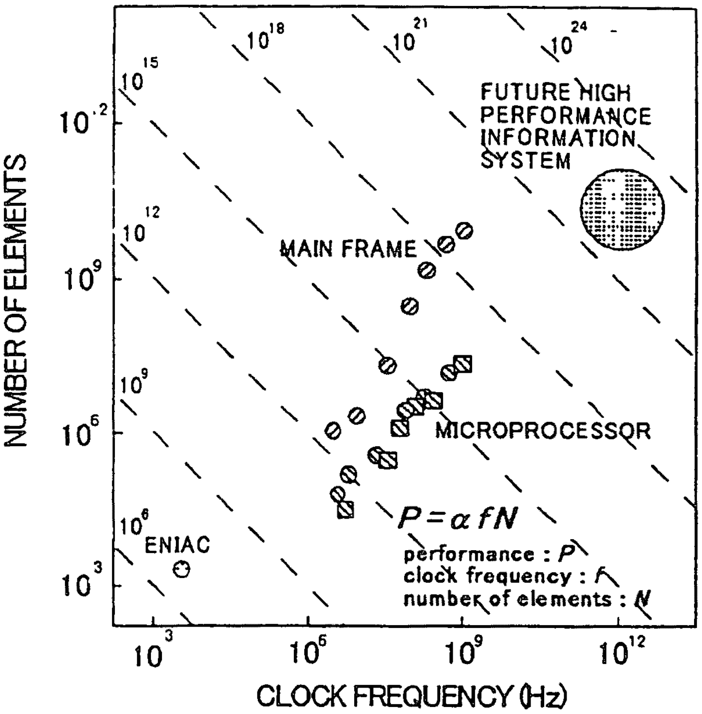


Fig 1 Number of elements and clock frequency relationship of historical information processing systems

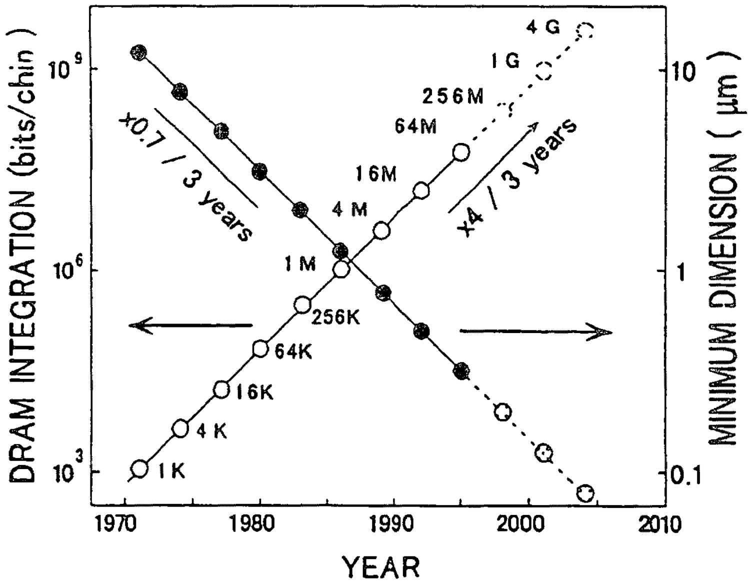


Fig 2 Trend curve of silicon ULSIs the minimum dimension has been shrunk by a factor of 0 7 while the integration quadrupled every 3 years for more than 30 years

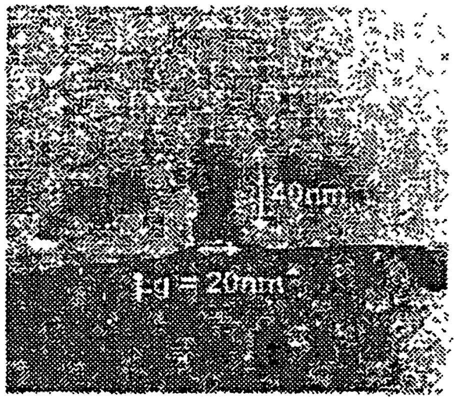


Fig 3 TEM image of [illegible]tronics Workshop, p. 2, (2001).

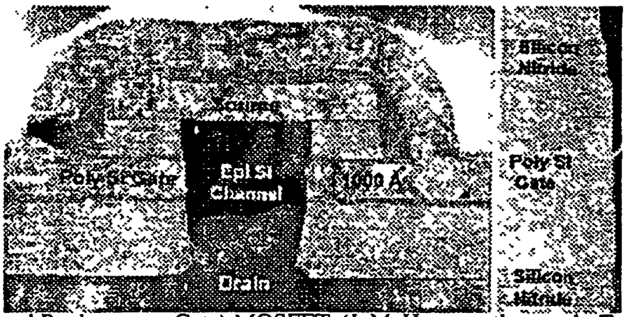


Fig 4. VRG(Vertical Replacement Gate) MOSFET. (J. M. Hergenrother et al., Tech. Dig. IEDM'99, p. 75, (1999)

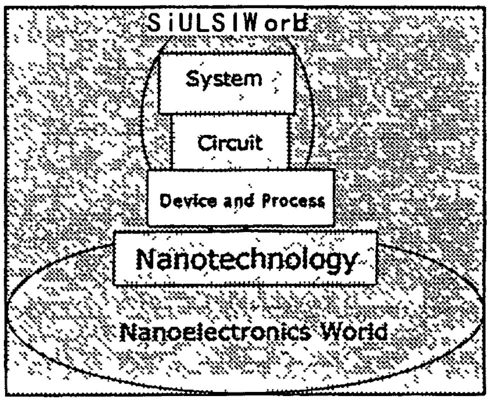


Fig 5 A technology hierarchy for ULSIs The most advanced device size of ULSI world is in a nanotechnology region.

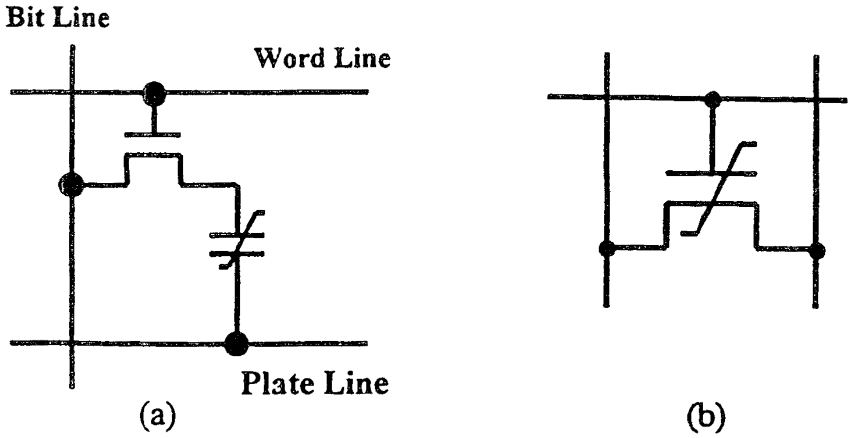


Fig.6 Classification of FeRAM. (a) 1T1C-type (b) 1T-type

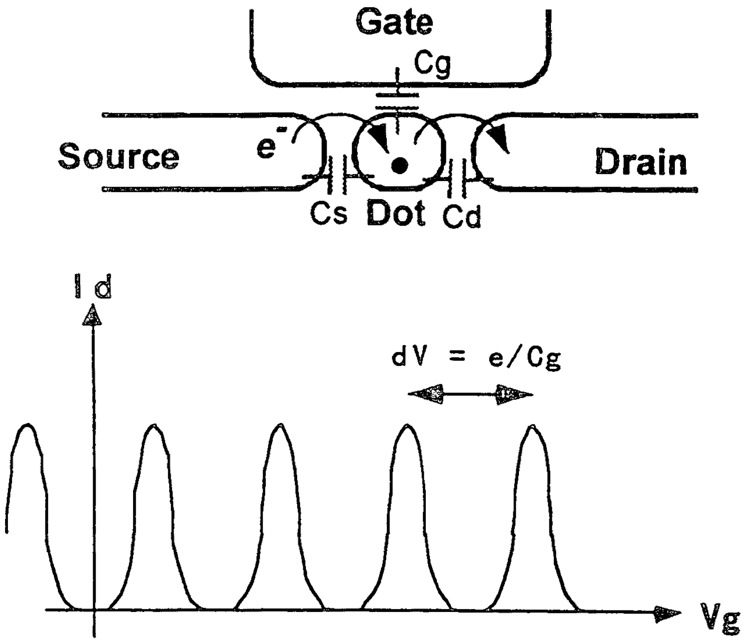


Fig. 7 Schematics of a single-electron transistor and Ids-Vds characteristics..

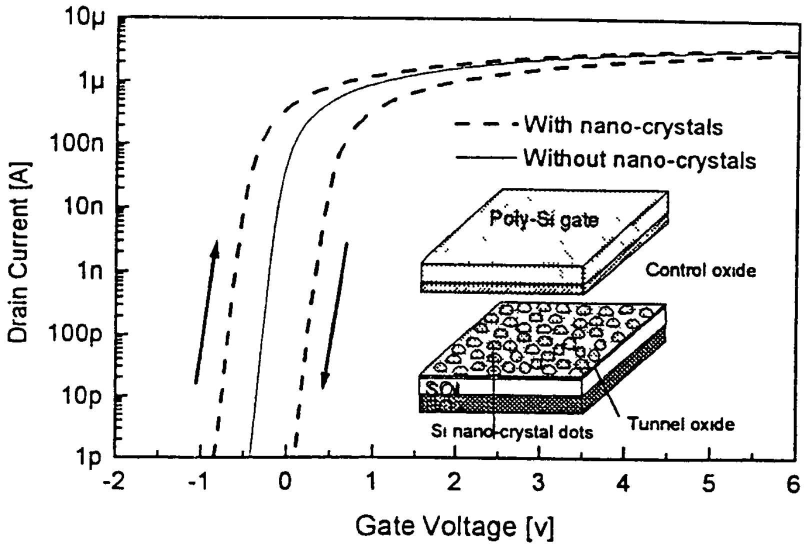


Fig 8 Characteristics of silicon quantum dot memory. The inset shows a schematic of device structure