The Highlights in the Nano World

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Invited Paper

In this highlight paper, the key structures and devices in nanoelectronics and spintronics are described. The successful realization of magnetic RAM (MRAM) by using nanotechnology has been demonstrated through the integration of 1-Mb chip. In this design, the pseudo spin valve (PSV) technology has been applied. Key quantum devices like quantum dot surface emitting lasers, quantum dot intersubband detectors, and molecular electronics are presented. In the emergent nanobiotechnology, nanodevices fabricated by using biotechnology and nanobiomedical applications using nanoparticles have been addressed. Since universities play important roles in both research and education, innovative nanotechnology education efforts in universities such as the National Nanotechnology Infrastructure Network have been described. Finally, the leading role of the IEEE in promoting worldwide nanotechnology research and education is addressed and future advances in nanotechnology are expected.

Keywords*—Magnetic RAM chip, magnetic RAM devices, nanobiotechnology, nanoelectronics, nanotechnology education, nano world highlights, quantum devices, spintronics.*

I. Introduction

As semiconductor technologies continue rapid progress in the nanometer regime, the nanotechnology era has arrived. Advances in modern physics, chemistry, and biology have opened up tremendous research opportunities for scientists and engineers. As the size of objects is scaled down to the nanometer regime between 1 and 100 nm, superconducting or supercatalyst effects have revealed novel electrical or thermal properties with great potential for promising applications. Quantization of nanoparticles in two-dimensional (2-D), one-dimensional (1-D), or zero-dimensional (0-D) devices has shown interesting characteristics on ultralow threshold current lasing, ultrasensitive sensing, etc. Biological molecules such as DNA, protein, and biocells can be manipulated by nanotweezers or self-organized by nanobiotechnologies to form new nanostructures or nanodevices. The application fields of nanobiomedical sciences and technology are truly unlimited.

With the fast advancement in physics of silicon devices and nanodevices/nanostructures, advanced research on the integration of billions of these tiny devices into low-voltage, low-power, and ultrahigh-frequency gigascale nanosystems has been very astonishing. Meanwhile, design of nanoelectronic processors/computer systems or bioelectronic devices and systems using quantum phenomena is being actively explored. The research on nanoelectronics and that on gigascale systems are closely coupled together. They present new challenges and opportunities to scientists and practicing engineers.

In the following sections, the key aspects of nanoelectronics/spintronics and the integration of large-scale magnetic memories will be presented. Consecutively, the recent results of quantum devices and the future possibility of molecular electronics are demonstrated. Then, some nanobiomedical applications are addressed. A section on innovative nanotechnology education in universities is presented. Finally, a brief conclusion is given.

II. Nanoelectronics and Spintronics

New-generation nanometer-scale semiconductor electronic devices will operate based upon the transfer of relatively small numbers of electrons (from 1 to around 1000 electrons) over very short distances (approximately 1 to 100 nm). Development of two broad classes of nanoelectronic devices can be traced: devices which exploit quantum effects in solid-state structures and molecular electronic devices. For the solid-state devices, a clear advantage is that the fabrication can be based on accumulated experience of the semiconductor industry of over 50 years [1].

The most important solid-state nanostructures based on the quantum-mechanical characteristics of the electronic properties are: 1) quantum wells and resonant tunneling devices [i.e., structures with two classical degrees of freedom (DOFs)]; 2) nanowires and nanotubes (i.e., structures with one classical DOF); and 3) quantum dots (i.e., structures with zero classical DOFs).

The composition, shape, and size of semiconductor nanostructures give a wide range of nanoelectronic devices.

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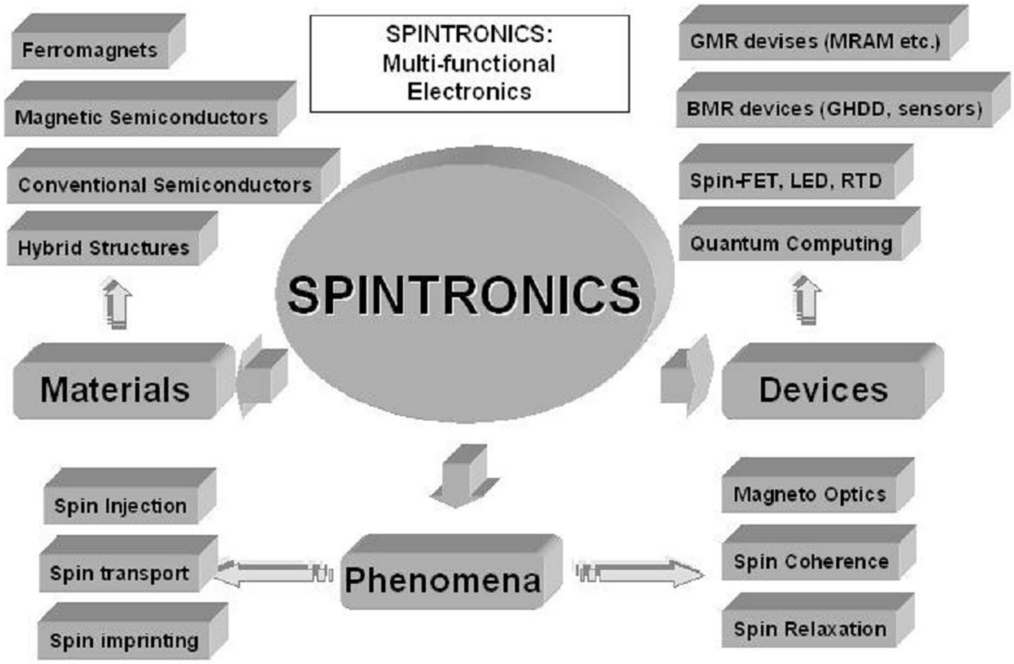

Fig. 1. Spintronics at a glance.

Controlling these factors by means of known semiconductor technology opens up an opportunity to employ quantum effects in different ways. For instance, 1-D or 2-D semiconductor structures are used for resonant tunneling devices [2], 0-D quantum dots for single-electron transistors [1], quantum wells and dots for lasers [3], electron spin operation in quantum dots, artificial molecules, and rings for elements of quantum computers [4].

Well-known applications of photonics and optoelectronics include long-distance fiber-optic communication, short-distance local-area interconnections for data processing systems, optical sensing, and imaging. To expand the number of applications, an emerging development should be made in new classes of optical sources, guides, and detectors in the ultraviolet and infrared ranges by means of semiconductor nanostructures [3], [5].

The functionality of semiconductor nanodevices in the future will rely on the control of the electronic charge and the spin as well. This new branch of nanoelectronics is called spintronics, as shown in Fig. 1. Known industrial applications utilizing electron spin are realized in metallic structures with a giant magnetoresistance effect, such as the hard drive reading heads and magnetic RAM (MRAM) [6]. However, only the control of spin in semiconductors together with modern semiconductor technology can advance the future of the spintronics and result in more valuable industrial applications. For instance, quantum dots with controllable electron spins are the most promising candidates to realize quantum computing, as shown in Fig. 2. Further development of the modern microscopic theory for the nanostructured semiconductor devices has started to emerge [8].

It is extremely difficult to comprehensively predict all principally new classes of nanoscale semiconductor devices that will bring key breakthroughs in this field in the future. Development of this field will significantly affect many

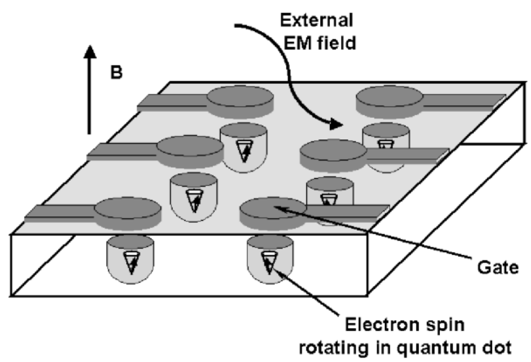

Fig. 2. Schematic diagram of a quantum computer based on the array of quantum dots. The spins of electrons confined in dots (quantum bits) are controlled by dc and ac electromagnetic fields (after Loss and DiVincenzo [7]).

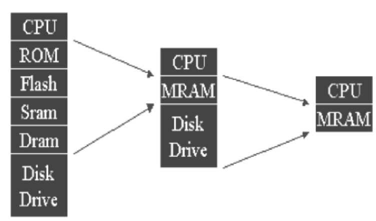

Fig. 3. Using MRAM to replace memory components for PCs.

aspects of our lives in the future. The successful realization of magnetic devices such as MRAM by using nanotechnologies is described in Section III.

III. Magnetic RAM

MRAM is nonvolatile. It has the fast read-and-write performance of static RAM (SRAM), and the high data storage capacity of dynamic RAM (DRAM). MRAM can replace many other types of memory including SRAM, DRAM,

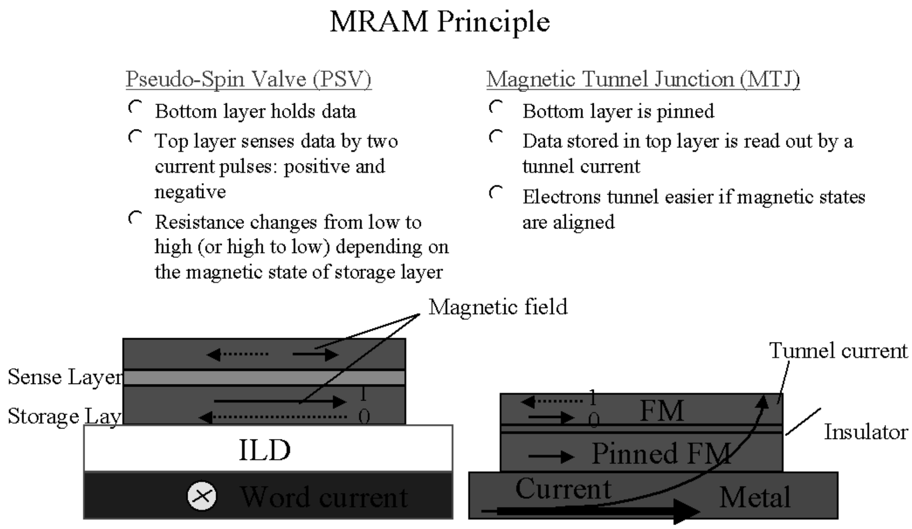

Fig. 4. Comparison of MRAM devices from PSV and MTJ.

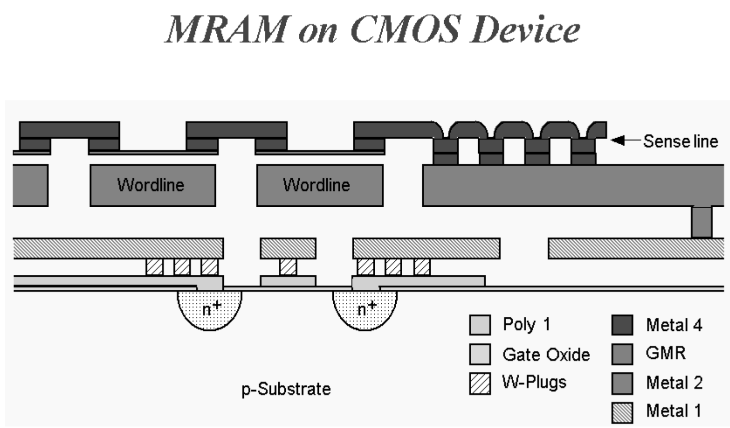

Fig. 5. Cross section of MRAM device.

ROM, electrically erasable programmable read-only memory (EEPROM), Flash EEPROM, and ferroelectric RAM (FRAM), as shown in Fig. 3. MRAM is very suitable for realization of system-on-a-chip (SoC) approach.

A. Pseudo Spin Valve Technology

MRAM technology has a major advantage both in product design and fabrication over other memory technologies because products are designed and built on industrial standard substrates as shown in Fig. 4. The designs and products from Union Semiconductor Technology Corp. (USTC), Chippewa Falls, WI, are based on the pseudo spin valve (PSV) technology [9]–[11]. By using the nanolayers PSV technology, the formation of the memory cells requires a back-end metallization step with the use of the magnetic thin-film deposition tool and a magnetic anneal furnace.

B. Magnetic Tunnel Junction Technology

Infineon Technologies AG and its partner IBM Microelectronics as well as Motorola Inc. use a different MRAM approach called the magnetic tunnel junction (MTJ). The MTJ device structure, as shown in Fig. 4, comprises two sandwich

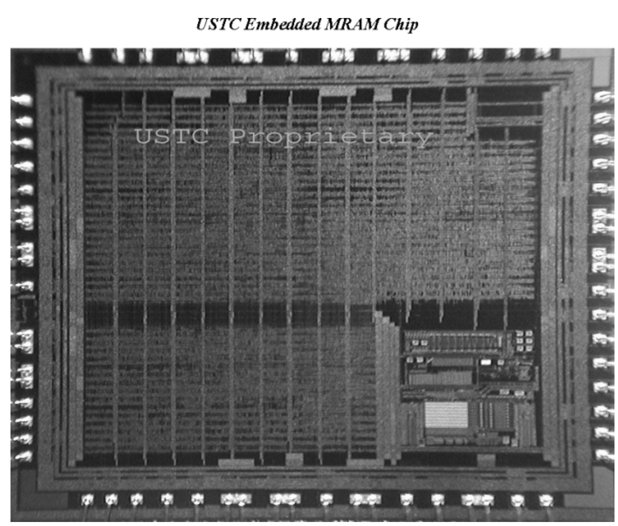

Fig. 6. Embedded MRAM (courtesy of Union Semiconductor Technology Corp., Chippewa Falls, WI, and National Chiao Tung University, Hsin-chu, Taiwan, R.O.C.).

layers of the magnetic film each with 10–20 atomic layers, encasing a central layer of four to five atomic layers. With the MTJ approach, the conduction path is perpendicular through

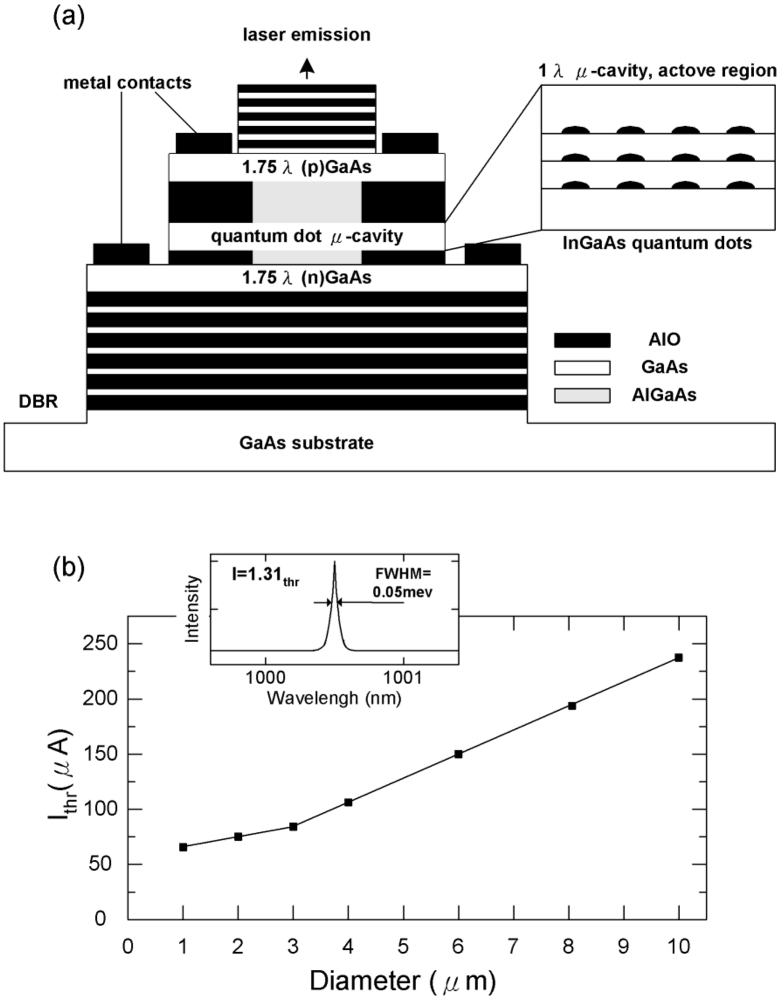

Fig. 7. Quantum dot surface emitting lasers [16].

the sandwich layers of the magnetic film. The key disadvantage of this approach is the requirement of very thin layers and also the uncertainty of the interface between the magnetic films and the central layer along the conduction path, which result in the MTJ device being very difficult to manufacture.

The 1-Mb MRAM based on the PSV technology has been successfully fabricated through the collaboration between USTC and National Chiao Tung University (NCTU), Hsin-chu, Taiwan, R.O.C. The nano oxide layer (NOL) technology [14], [15] is critical to fabricate this device. This approach enables USTC to be a pioneering MRAM manufacturer to offer MRAM products to the users.

Devices fabricated with the PSV technology, as shown in Figs. 4 and 5, are easy to produce and suitable for the stand-alone replacement and embedded markets. A pioneering commercial MRAM embedded chip, as shown in Fig. 6, has been fully functional.

IV. Quantum Devices

Quantum well lasers, currently available in the market, reveal many unique properties, such as high temperature stability, low threshold current, and good coherency. Quantum dot surface emitting lasers are shown in Fig. 7. Quantum dots have an extremely large differential optical gain which implies lower laser threshold current densities, negligible or little temperature influence on the threshold, and higher

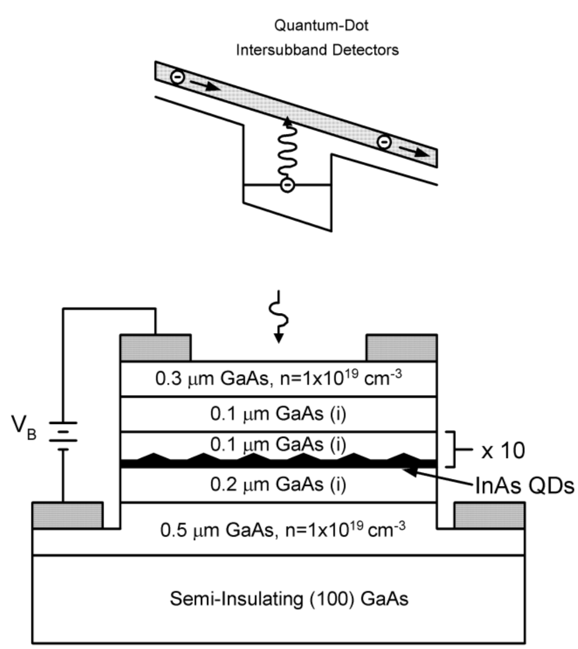

Fig. 8. Quantum dot intersubband detectors [17].

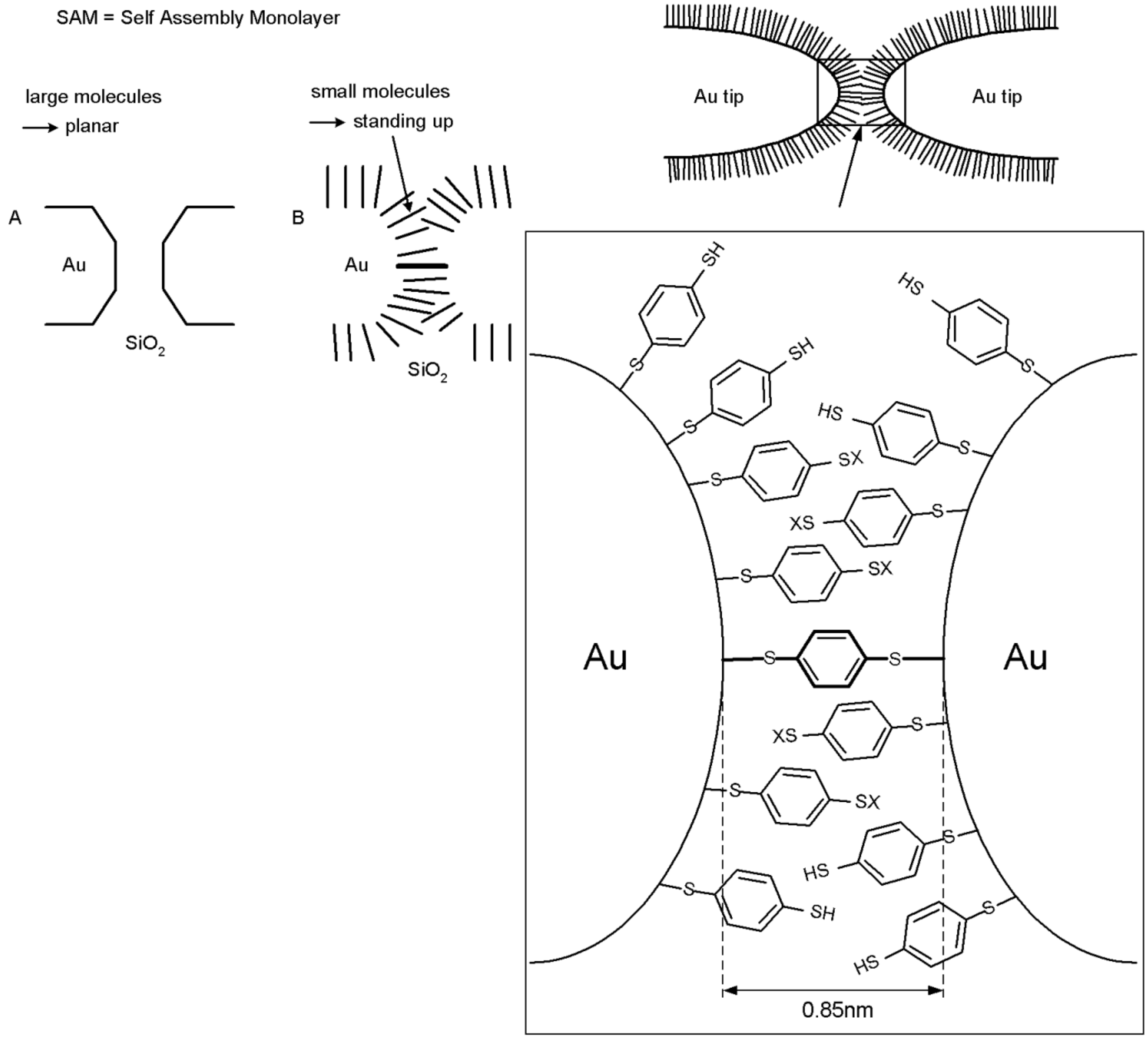

Fig. 9. Molecular electronics [18].

frequency limits for modulation. InGaAs quantum dots are made on GaAs substrates by self-assembly, and many quantum dots can be stacked on top of one another in an active waveguide region. The optical gain is so large that laser emission perpendicular to the waveguide occurs [16].

Quantum dot intersubband detectors are shown in Fig. 8. InGaAs quantum dot arrays embedded in GaAs can be used as novel optical detectors for the infrared range. A photon can lift up an electron from the quantum dot level to the GaAs conduction band. The position of the quantum dot level can be shifted through the size and, hence, the wavelength response [17].

Molecular electronics are shown in Fig. 9. Nanotechnology has reached sizes down to those of single organic molecules. Fundamental studies consider the possibility to use these molecules in molecular electronics. Recently, reliable contacting of a single molecule was achieved and current voltage characteristics could be measured [18].

V. NANOBIOTECHNOLOGY

Nanobiotechnology is an interdisciplinary field of research integrating engineering and biology through the development of very small physical and biological devices using nanofabrication techniques. The research areas are quite broad including the manipulation of biomolecules, microanalysis of bioselective surfaces, molecular filtration, sparse cell isolation, diagnostics, therapeutics, and medical technology [19].

Molecular electronics has been widely studied since Aviram and Rartner proposed the first molecular rectifier in 1974. Over the past 30 years, some molecular devices have been synthesized and tested, but constructing high-level circuits and systems is still a very challenging topic. The most difficult parts are in the interconnection between individual components and the ordering of the molecular devices on immobile surfaces.

Calixarenes, a class of bowl-shaped macrocycle molecules formed from the condensation of a p-substituted phenol with formaldehyde, act as excellent hosts for the complexation of metal ions or neutral molecules (such as amines, aromatics, and fullerenes). These supramolecules are utilized to immobilize molecular devices (such as molecular wires) on the substrate by the self-assembly strategy of host–guest interaction. First, calixarenes are immobilized on silicon

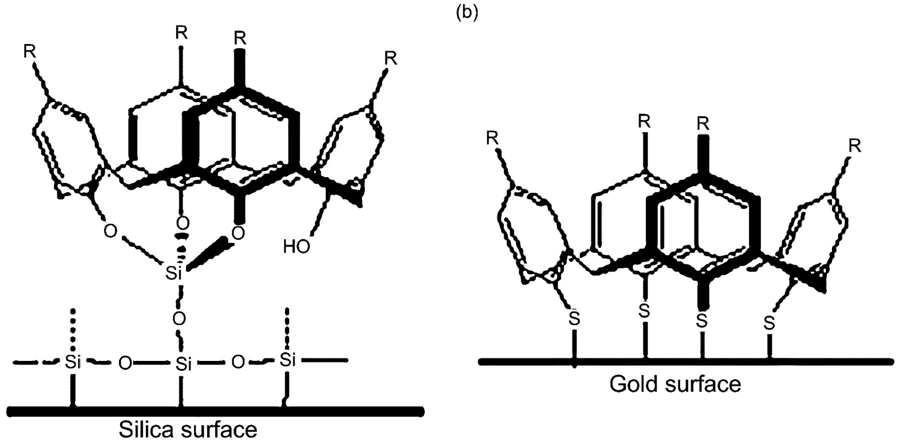

Fig. 10. The immobilization of calixarenes on (a) silica and (b) gold surfaces [20].

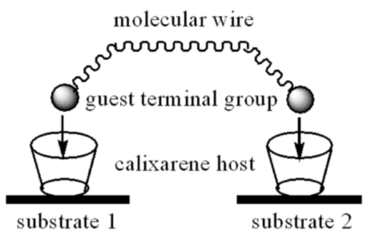

Fig. 11. The schematic diagram of self-organized molecular wire [20].

wafer and gold electrode substrates to make a self-assembly monolayer (SAM), as shown in Fig. 10 [20]. Chemical and physical characterizations of the SAM are performed by scanning electron microscopy, transmission electron microscopy, surface plasma resonance, etc. Then some pi-conjugated long chain molecules (such as oligopyrrole and oligothiophene) with proper guest terminal groups at both ends can be synthesized. The host–guest chemistry between these calixarenes and pi-conjugated molecular wires is studied. Finally, a few molecular wires can be bridged between two bulk electrodes (with calixarenes on the surface) simultaneously by the host–guest self-assembly interaction, as shown in Fig. 11 [21], and the electrical properties can be measured and characterized for further applications in molecular electronics.

CdSe nanoparticles (NPs) have shown the superior photoconductivity as the particle size is shrunk to the nano scale. By utilizing this property, a new photo-sensing nanodevice with CdSe and Au NPs can be constructed as shown in Fig. 12 [21]. At the same time, DNA oligonucleotides serve as the linker that makes a connection between CdSe and Au NPs (the same as Au NPs and electrode contacts). Furthermore, the CMOS silicon interface circuits can process the signals of the sensor.

One of the most attractive areas, which is recently under development in the College of Biological Science and Technology at NCTU, is on the rapid clinical diagnosis via antigen–antibody interaction. For example, by using antibody conjugated gold nanoparticles in red, as shown in Fig. 13 [22], diagnostic laboratories can essentially utilize this conjugated antibody for conducting a pregnancy test in 2 min. The technique thus far, however, has been hampered due to the lack of stability of prepared nanoparticles. The commercially available gold particles, however, are not stable and often form a large aggregate. By using an additional sonication procedure combining the conventional reduction method [19], stable and uniform gold nanoparticles can

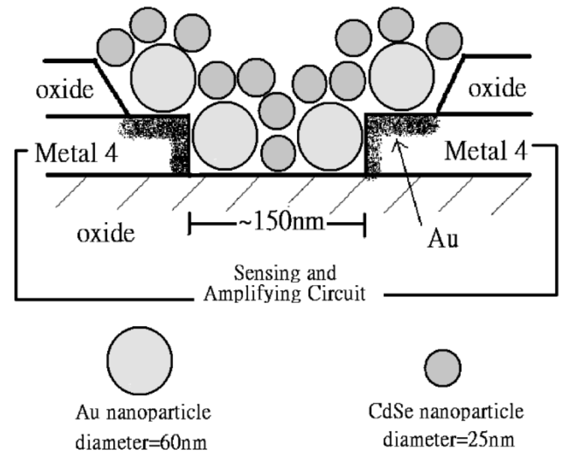

Fig. 12. A new photo-sensing nanodevice [21].

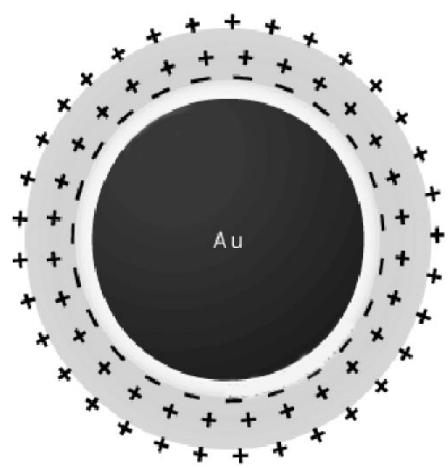

Fig. 13. Proposed structure of gold nanoparticles. The positive charges in the outer layers maintain the particles in solution as colloidal sol and allow the molecules to crosslink with a protein of interest [22].

be produced. The average size of the particles is between 8 and 12 nm in diameter as observed under the electron microscopy. Photospectroscopic analysis shows that these particles are resistant to high salt solution (0.15 M NaCl) as compared to that prepared from the conventional approach. The breakthrough in the technology for the preparation of colloidal gold is based on the colloidal properties of the sold, resulting from a combination of van der Waals, electrostatic, and short-range repulsive interaction potentials. Ideal gold particles will be ready for protein or antibody coupling in few minutes, so that proteins will be tagged with color irreversibly as those covalent bonding. Alternatively, optical tweezers [23] provide a unique tool to study the antigen–antibody interaction, particularly when antibody is conjugated to the electron-dense particles or beads. Optical tweezers behave similar to a three-dimensional spring which traps a small particle via the gradient dipole force produced by a converging laser beam. Typically, the trapping force is on the order of piconewtons $(10^{-12}\ \mathrm{N})$. The size of the trapped particles ranges from a few tens of nanometers to a few tens of micrometers. The optical tweezers system is operated by precisely focusing a laser beam through an objective into a laser point on the sample plane of a microscope. In the past decade, optical tweezers were widely used in capturing, moving, and manipulating a single biocell or a single bead. By using a water-drag-force method, the trapping force of the optical tweezers can be calibrated. Consequently, the calibrated trapping force can be used to balance and measure the bioforce generated by a single antibody conjugated with beads. In summary, the optical tweezers system is a powerful tool in nanobiotechnology for antigen–antibody manipulation. Specifically, it may work as a platform for antigen–antibody binding measurement under the visible microscope. Laser-based research attempting to address the dynamics between antigen–antibody interactions has also been conducted

VI. Nanotechnology Education

It is estimated that about 2 million engineers and scientists in the nanotechnology field will be needed worldwide in the next decade. Therefore, education in nanotechnology is extremely important. However, it presents a major challenge for existing educators and curriculum developers because it has wide-reaching connections to many academic disciplines and areas of relevance, as well as the fact that its applications are ubiquitous. On one hand, educators should offer a broad knowledge base for new students. On the other hand, the interdisciplinary nature of the various subjects and skills needs to be emphasized. Traditional engineering education, which largely focuses on a particular domain, is no longer adequate for this new nanotechnology era [24]. Recently, some dedicated undergraduate and graduate programs in nanotechnology were initiated. For example, the University of Washington, Seattle, with direct funding from the U.S. National Science Foundation (NSF), has launched a pioneering Ph.D. program in nanotechnology. The program is tied closely to nine science departments, and students will earn concurrent degrees in nanotechnology and in a conventional discipline of science, engineering, and medicine [25]. In addition to higher education, innovative education models and curriculum structures in nanotechnology are needed to better prepare K to 12th-grade students. It is recommended to develop interdisciplinary curricula for these grades to integrate science, technology, and other relevant fields when preparing future engineers/contributors in the nanotechnology society.

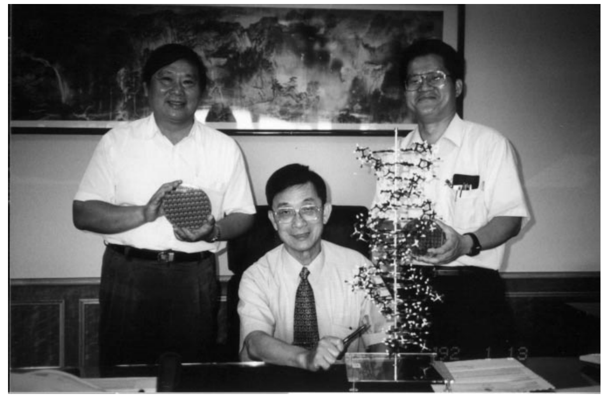

Fig. 14. Brainstorming by Profs. P. (C.-Y.) Wu, C.-Y. Chang, and B. Sheu (from left to right) on nanosilicon and nanobiology.

Many outstanding researchers have devoted their best efforts to promote education and research in nanotechnology. Key educators gathered to brainstorm for innovative educational approaches at NCTU, as shown in Fig. 14. We all felt that nanotechnology/biology at the atomic or molecular levels will be the key research field in the future, and needs enhanced emphasis/promotion.

In preparation of the forthcoming decade, the NSF has announced an open solicitation for proposals to establish a National Nanotechnology Infrastructure Network (NNIN) that will support the future infrastructure needs for research and education in the burgeoning nanoscale science and engineering field. The success of a network of user facilities under the National Nanofabrication Users Network (which was initiated in 1994 with ten-year NSF funding) has demonstrated that NSF must advance an expanded national infrastructure that is capable of providing researchers in academia, small and large industries, and government with the appropriate nanofabrication and characterization tools, instruments, and capabilities to enable the broadest range of ideas for innovation and education. The NNIN goal of developing a flexible and enabling infrastructure is an important component in the investment strategy of the National Nanotechnology Initiative (NNI).

Recently, a multiuniversity proposal led by Prof. M. Schmidt at Massachusetts Institute of Tchnology (MIT), Cambridge, was formed to establish a network of shared facilities across the U.S. to support research in nanotechnology. The major research universities participated in this NNIN proposal include (but not limited to) MIT, the University of California, Berkeley, and the University of Illinois, Urbana-Champaign. This network approach can be supported by the NSF for a period of ten years, beginning in 2004. In Taiwan, the NCTU has strong research teams in

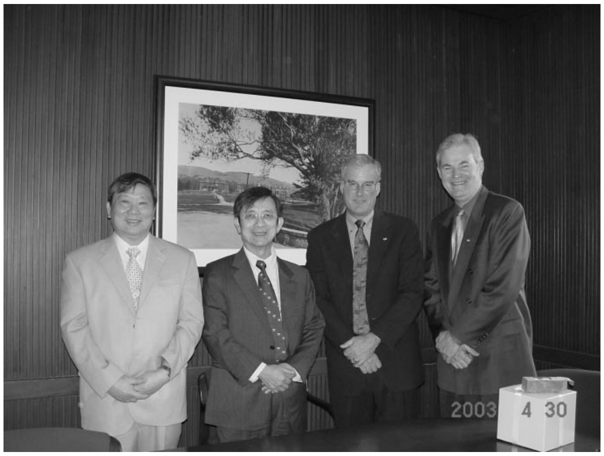

Fig. 15. Extensive discussion by Professors P. (C.-Y.) Wu, C.-Y. Chang, P. Gray, and R. Newton (from left to right) on future collaboration of globalization leadership in nanotechnology research and education.

nanotechnology, including nanoelectronics, nanomaterial, nanodevices, and nanobiology. The students at NCTU also formed the Nano-Century Student Association to gain timely knowledge of nanotechnology through invited lectures series and study groups. The National Science Council in Taiwan has established the National Nano-Device Laboratories (NDL) at NCTU, where excellent nanofabrication facilities are available for advanced research. The 2003 President of NDL is Prof. S. Sze. In addition, NCTU has been invited to participate in the NNIN endeavor via the University of California, Berkeley, to connect with MIT.

To further enhance globalization leadership in nanotechnology research and education, the Engineering College of the University of California, Berkeley, and the College of Electrical Engineering and Computer Science at NCTU have been preparing to establish a formal exchange program for students and scholars. Key leaders of both universities held extensive discussions at the University of California, Berkeley, campus, as shown in Fig. 15. In this program, undergraduate and graduate students from one university can study at the other university for a predetermined period with recognized course credits toward academic degrees.

VII. Conclusion

In the 21st century, nanoelectronics and nanoscience/nanoengineering will advance rapidly and have profound and long-lasting effects on the science and technology development, affecting many aspects of our daily lives. In view of this subject's great importance and significance, emphasis and promotion should be done to encourage worldwide increase on research and development investment. More research funding and research centers are to be established in universities, research institutes, and industry. IEEE has taken the leading role by establishing the Nanotechnology Council, the new IEEE Transactions on Nanotechnology, and the annual International Nanotechnology Conference. More activities in high-quality publications, conferences/workshops, and interregional collaborations need to be facilitated in the future. With many outstanding researchers/scholars contributing in the nanotechnology field, due recognition with awards and citation shall be regularly granted. This will encourage young researchers/engineers to devote their efforts to this field. Besides basic and applied research, education on nanotechnology for a new generation is also very important. This will lay a solid foundation for sustained advances in nanotechnology for human society.

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