Appendix E. Site Reports—Taiwan

OVERVIEW OF NANOPARTICLE / NANOTECHNOLOGY RESEARCH IN TAIWAN

David T. Shaw

In 1996, the total product value of integrated circuits (IC) produced in Taiwan reached $7.8 billion. From 1995 to 1997, IC products have grown at an average of 50-60% per year. The current state of IC manufacturing and product technology in Taiwan, as summarized in Tables E.1 and E.2, is two to four years behind the leading countries. However, the technology gap is closing fast as Taiwan invests heavily in nanotechnology R&D. In l996, more than 400 research projects amounting to more than $7 million were supported by the National Science Council in such diverse microelectronic fields as VLSI technology, amorphous silicon, microelectromechanical systems, and electronic packaging. These projects share a common theme: the development of submicron or nanometer technology.

TABLE E.1. Current State of IC Manufacturing Technology in Taiwan

Item	Taiwan's Level	Leading Country	Leading-edge Technology Level
CMOS	0.25 µm (R&D) 0.35 µm (production)	Japan, U.S.	0.18 µm (R&D) 0.25 µm (production)
BiCMOS	0.8 µm (production)	Japan	0.35 µm (production) 0.25 µm (R&D)
Bipolar	2.5 µm	Japan	1.0 µm (production)
GaAs	Circuit design and 0.6 µm process	U.S.A., Japan	0.35 µm (R&D)

TABLE E.2. Current State of IC Product Technology in Taiwan

Item	Taiwan's Level	Leading Country	Leading-edge Technology Level
DRAM	64 M (R&D) 16 M (production)	Japan, Korea	1G (papers published) 256 M (production)
SRAM	4 M (pilot run) 1 M (production)	Japan	64 M (papers published) 16 M (production)
ROM	Introduction of 64 M mask ROM in 1994 by UMC	Japan	Introduction of 64 M mask ROM by Sharp
Flash Memory	4 M Flash (production) 16 M Flash (pilot run)	U.S., Japan	64 M/256 M Flash (R&D) 32 M (production)
MCU	4 bit, 8 bit	U.S.	16 bit (production) 32 bit (announced)
MPU	RISC CPU	U.S.	RISC: 64 bit 200 MIPS
A/D D/A converter	A/D: 8 bit, 20 MHz D/A: 8 bit, 120 MHz	U.S., Europe	A/D: 8 bit, 650 MHz D/A: 8 bit, 100 MHz
Power IC	Discrete bipolar Discrete MOS	Japan, Europe	Smart power

Site: **National Taiwan University (NTU)**
1, Sec. 4, Roosevelt Rd.
Taipei, Taiwan ROC

Date Visited: 16 April 1997

WTEC: D. Shaw (report author)

Hosts: Prof. C.Y. Mou, Department of Chemistry
Fax: (886) 2-3636359
Prof. S.F. Cheng, Department of Chemistry

BACKGROUND

NTU is widely considered to be the most prestigious university in Taiwan. The first university on the island, established nearly 100 years ago, it is also the most renowned and the most competitive university in Taiwan. NTU alumni play key leadership roles in all levels of government, industry, and academia. I met with about a dozen professors from various departments (Chemistry, Chemical Engineering, Physics, and Electrical Engineering) and had an informal exchange of information on nanoparticle technology.

DISCUSSION

During the discussions, it became clear that R&D on nanoparticle technology is generally new on campus. All the departments represented at this meeting are considered to be large departments, having more than 50 faculty members. Most of the research in the Electrical Engineering Department covers traditional silicon-based IC processing with some limited optoelectronic device studies. Research programs on submicron photoresistance are being initiated by the Department of Chemical Engineering, while programs on quantum lasers are being conduced by the newly established Institute of Optoelectrical Engineering.

A project in the Chemistry Department is of interest to nanostructure scientists: "Synthesis and Application of Mesoporous Molecular Sieves" (Project Principal Investigator, Prof. C.Y. Mou; Co-Principal Investigators, Prof. S.F. Cheng, Prof. P.Y. Wan, and Dr. S.P. Liu). The investigators have successfully synthesized mesoporous aluminosilicate MCM-41, which consists of hexagonal arrays of nanometer-sized cylindrical pores (*Science*

1996, 273:765). As illustrated in Fig. E.1, a liquid crystal phase-transformation mechanism was used for formation of the nanostructure. The complex tubules-within-a-tubule structure is now being explored for various applications, including catalysis, separation technology, and optoelectronics (Fig. E.2).

SUMMARY

Besides the mesoporous membrane project discussed above, the related nanoparticle/nanostructure projects at NTU are generally in their early stages. There is, however, a considerable amount of interest in this research area. The Institute of Optoelectrical Engineering is very well equipped and is staffed by a group of enthusiastic graduate students. Most of the projects under consideration are related to the development of silicon IC devices.

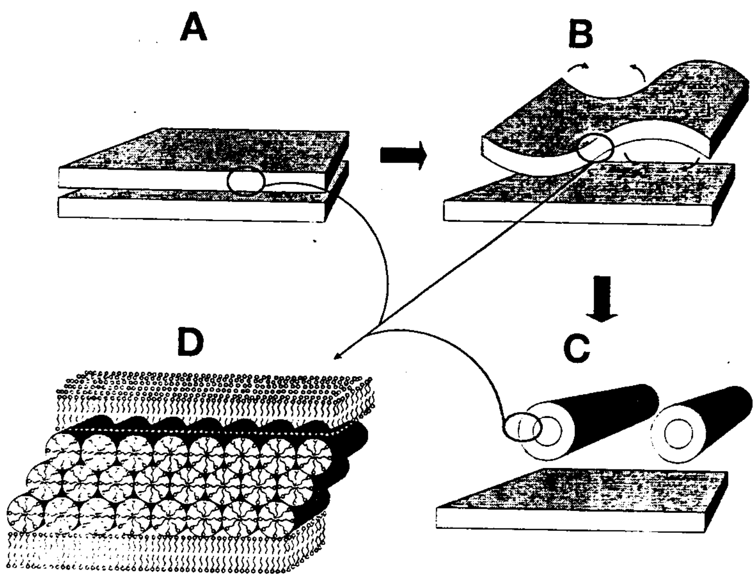

Figure E.1. Proposed mechanism for the formation of the microtubular morphology of MCM-41: (A) mixed lamellar-hexagonal membrane phase; (B) acidification leads to membrane curvature; (C) neutralization bends the membrane into tubules; (D) the membrane consists of a hexagonal array of cylindrical micelles.

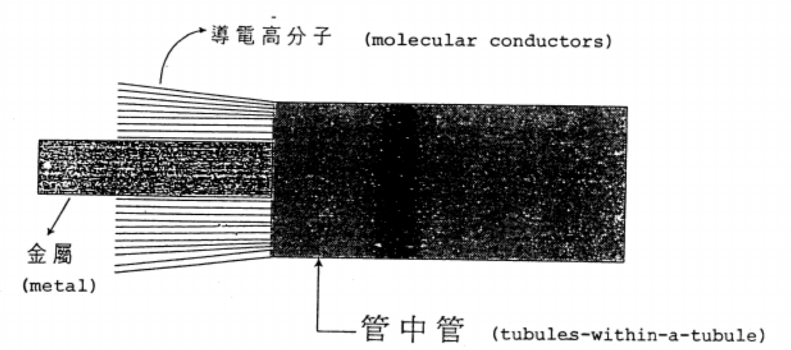

Figure E.2. Molecular conducting device.

Site: **National Chiao-Tung University (NCTU)**
Hsinchu, Taiwan ROC

Date Visited: 17 April 1997

WTEC: D. Shaw (report author)

Hosts: Prof. M.S. Feng, Deputy Director, National Nano Device Laboratory,
Department of Materials Science and Engineering
Dr. M.C. Jiang, Associate Researcher, National Nano Device Laboratory
E-mail: mcj@mail.ndl.nctu.edu.tw

BACKGROUND

NCTU has the most abundant resources for microelectronic research among the universities in Taiwan in terms of manpower, equipment, and research funds. It boasts of six research institutes in the College of Electronics Engineering and Computer Sciences, covering such subject areas as information engineering, control, communication, optoelectronics, and computer science. The Institute of Electronics, the biggest of the six institutes, has more than 40 faculty members, whose research ranges from model simulation and nanometer-sized MOS and bipolar devices, to thin-film deposition and multilayer superlattice fabrication. In addition, there is a Semiconductor Center, which appears to be a training center for semiconductor production engineers. A complete line for IC processing based on 10 cm wafers is housed in its Class-10,000 cleanroom facilities. Situated near the Science/Industrial Park in Hsinchu, NCTU is a major force in Taiwan's high-tech industry. Its close relationship with industry is also reflected in the university's numerous research grants and contracts from industrial firms. According to university officials, in 1995 NCTU ranked first among the institutes worldwide in publications in IEEE *Transactions on Electronic Devices* and *Electron Device Letters*. The crown jewel of NCTU is the National Nano Device Laboratories (NDL).

I was met by Prof. M.S. Feng, Professor at NCTU's Institute of Materials Science and Engineering and Deputy Director of NDL. During an official briefing, Prof. Feng told me that NDL was founded in 1993 as Taiwan's response to the increasingly competitive world of VLSI R&D. By the end of 1995, NDL had completed advanced R&D work on 0.18 micron IC process modules. Prof. Feng told me that NDL's goal is to reach 0.13 micron processing by the year 2000. Overall, unlike the corresponding facilities at Cornell University in the United States, NDL is a production R&D facility with a carefully laid out roadmap for the development of IC technology.

DISCUSSION

Dr. M.C. Jiang, an associate researcher at NDL, led me through a guided tour. He showed me some of the key modules completed so far by the NDL personnel:

- the design, technologies, and manufacturing of 250 nm and 180 nm devices
- growth of ultrathin (4 nm) oxide and shallow trench isolation for p-channel 120 nm processes
- SiGe-based microwave device technology
- process development and application of ECR-RIE etching
- selective tungsten CVD for 0.20 µm via holes
- CVD-TiN, CVD-Al and CVD-Cu for advanced metallization
- Al Damascene process for 0.25 µm metallization
- chemical-mechanical polishing (CMP) processes for dielectrics and metals
- low-K (SiOF, SOG) and high-K (BST, Ta_2O_5) dielectrics
- shallow junction process for 120 nm devices
- surface characterization of semiconductors (SIMS, ESCA, AFM, etc.)
- 100 nm e-beam lithography

In addition to the module development work, NDL provides equipment services to universities and other organizations for semiconductor-related research. The four major universities mentioned in the Overview in this Appendix are all frequent users of NDL's equipment. In fact, many of the research achievements in NDL would not be possible without the input from the other universities, which have their graduate students conduct their experiments at NDL.

SUMMARY

To integrate resources among research organizations, Taiwan's National Science Council (NSC) and Taiwan's Ministry of Economy have encouraged cooperation between major universities and research institutes to conduct massive-scale R&D projects on advanced technology. The joint project between NDL and the Synchrotron Radiation Research Center (SRRC) on

X-ray lithography is a good example of such principles at work. The project started in April 1996 and will last for three years. SRRC will build a beam line and a cleanroom to house lithographic tools under the guidance of NDL. Both sides will share their equipment, expertise, and manpower. This project marks Taiwan's first attempt towards deep submicron X-ray lithography.

Site: **National Tsing-Hua University (NTHU)**
No. 101, Sec. 2, Kuang Fu Road
Hsinchu, Taiwan 300, ROC

Date Visited: 18 April 1997

WTEC: D. Shaw (report author)

Hosts: Prof. M.K. Wu, Chairman, Research and Development Council, Materials Science Center and Physics Dept.
E-mail: mkwu@phys.nthu.edu.tw
Prof. C.C. Chi, Director, Materials Science Center and Physics Dept.

BACKGROUND

Compared to NCTU, which is very technology-oriented, NTHU's R&D strength lies mainly in basic R&D. Physics, Chemistry, and Materials Science have been the strongest fields of study at NTHU. Nanoparticle/ nanostructure R&D, however, is in its initial stage and is carried out mostly at the Materials Science Center.

DISCUSSION

There are several groups actively working on projects related to nanoparticle technology.

Professor David Z.Y. Ting, a condensed matter theorist, has developed techniques to study (1) disorder effects in semiconductor alloys and superlattices; (2) electronic and optical properties of quantum wells and superlattices; (3) heterostructure tunnel device physics; (4) 3-D modeling of quantum transport in nanostructures; and (5) light extraction from light-emitting diodes. His current research projects include

- clustering effects in alloy tunnel barriers
- thermoelectric properties of type-II superlattices
- 3-D simulations of magnetotunneling in nanostructures
- multiband quantum transmitting boundary methods for non-orthogonal basis
- magnetotunneling in interband tunnel structures
- resonant tunneling via InAs self-organized quantum dot states

Professor S. Gwo of the Physics Department has been involved in the growth of self-organized semiconductor nanostructures by MBE. He has ample experience in nanostructure fabrication for advanced electronic and optoelectronic devices. He is also involved in the atomic-scale studies of dopants in semiconductors and in the development of UHV scanning probe microscopy and spectroscopy for optical measurements. Professor T.P. Peng of the Department of Materials Science and Engineering (in collaboration with Professor M.K. Wu and Dr. S.R. Sheen of the Materials Science Center), has been working on the preparation of nanoparticles by vapor condensation, high-energy ball milling, or magnetron sputtering. Their current research projects cover

- sintering or grain growth behavior of nanoparticles
- chemical reactivity of nanoparticles and application of nanoparticles in catalysis
- characterization of the interface structure of nanoparticles
- chemisorption, diffusion, and solution of gases in nanocrystalline materials
- fabrication and structural characterization of metal/metal or metal/ceramic nanocomposites
- effects of particle size on the second-order phase transitions, such as order-disorder, superconductivity, ferroelectricity, and piezolectricity
- kinetics and mechanism of nucleation and growth of nanoparticles in an amorphous matrix

SUMMARY

Impressive progress has been made in nanoparticle/nanostructured research at NTHU. Under the leadership of Professors M.K. Wu and C.C. Chi, the university has established a network connecting the microfabrication capabilities of NCTU, the chemical processing techniques of NTU, and the analytical and materials processing capabilities at their own Materials Research Center to perform the only organized research effort in this area. They also plan to expand their characterization capabilities to include some of the atomic force microscopy techniques developed at the Academia Sinica. Their future research activities will be directed toward semiconducting functioning materials and nanophase materials for biological sensor applications.

Site: **National Chung-Chen University (NCCU)**
Taiwan 621, ROC

Date Visited: 11 April 1997

WTEC: D. Shaw (report author)

Hosts: Prof. W.H. Lee, Chairman, Department of Physics
E-mail: whlee@phy.ccu.edu.tw
Prof. D.P. Tsai, Associate Professor, Department of Physics
E-mail: dptsai@phy.ccu.edu.tw
Prof. C.C. Chen

BACKGROUND

NCCU is a relatively new university in the south of Taiwan, but its scientific research laboratories are very well equipped. I visited the Physics Department, which is small, having about fourteen faculty members. The department is guided by its energetic leader, Prof. W.H. Lee, who joined the university from the Industrial Technology Research Institute in Hsinchu. Prof. Lee, who is an old acquaintance of mine, told me that they had been fortunate enough to attract a group of young energetic researchers, most of whom had received their advanced degrees in the United States.

DISCUSSION

During an informal gathering, I first gave a brief summary on the R&D activities in nanoparticle/nanostructure technology in the United States. This was followed by discussions with several professors, most of whom have joined the university during the last four to five years. The most impressive research was presented by Prof. C.C. (Jay) Chen, who had just come back from working with Prof. A.P. Alivisatos at the Lawrence Berkeley Laboratory (University of California at Berkeley).

Prof. Chen's work (*Science* 1997, 276:398) shows that there is a practical optimal size for metastable nanocrystals, which is also the largest size at which the nanocrystals can be synthesized defect-free. Thus, a much wider range of materials may be metastable in nanocrystals than in bulk solids. Figure E.3, taken from Prof. Chen's paper, illustrates the various size evolution of the kinetic barriers to structural transformation in defect-free nanocrystals. For small nanocrystals ($d < 2$ nm), the barriers are small and the kinetics are dominated by interface contributions. Eventually, the barriers will be volume-dominated. This understanding of solid-solid phase transition kinetics will help us to define general rules that are important in the future synthesis of new metastable nanocrystals.

Prof. C.R. Wang of the Chemistry Department is developing an innovative electrodeposition technique for the synthesis of metallic particles. Prof. D.P. Tsai is a leading authority in Taiwan on atomic force and scanning near-field optical microscopies. He has developed a working relationship with Prof. P.C. Cheng at SUNY/Buffalo and is applying some of his AFM and SNOM techniques to nanotribological and other nanotechnological problems.

SUMMARY

One of NCCU's problems is its inability to attract top-notch graduate students, partially because qualified students are attracted to more prestigious universities such as NTU, NTHU, and NCTU in the north part of the island. This situation may change when the government formally establishes a second Science/Industrial Park a short distance from the campus in 1999.

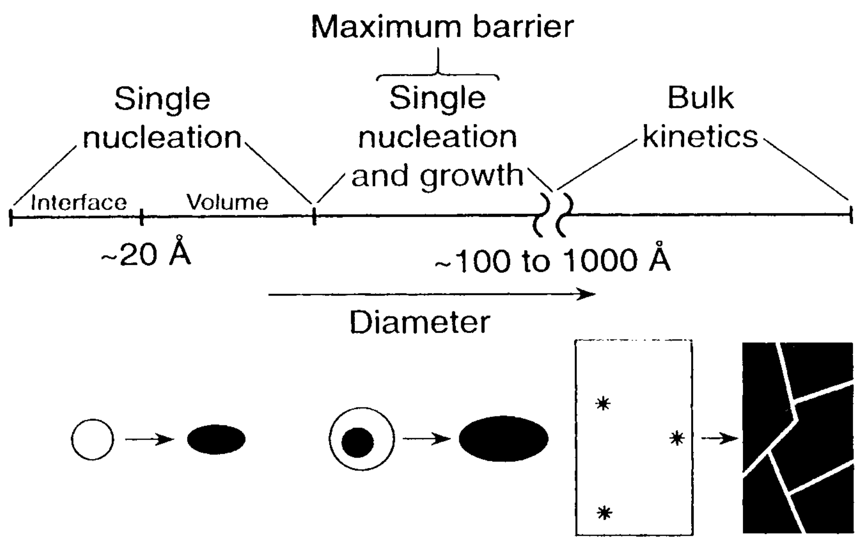

Figure E.3. Illustration of the various size regimes of the kinetics of solid-solid phase transitions. Defects, which act as nucleation sites, are indicated by asterisks in the cartoon of the bulk solid.

Site: **Industrial Technology Research Institute (ITRI)**
Materials Research Laboratory (MRL)
195-5 Chung Hsing Rd., Section 4
Chutung, Hsinchu, Taiwan 310, ROC

Date Visited: 19 April 1997

WTEC: D. Shaw (report author)

Hosts: Dr. L.C. Lee, Director, Materials Research Laboratory
Fax: (886) 35-958662
Dr. C.M. Wang, Deputy Director, Materials Research Laboratory

BACKGROUND

Located at the center of the Science/Industrial Park in Hsinchu, ITRI is the largest research organization in Taiwan devoted to production-oriented R&D of industrial technologies. Unlike the other institutions previously discussed, which are supported by the National Science Council (corresponding with our National Science Foundation), ITRI is supported by Taiwan's Ministry of Economic Affairs (MOEA). There are six laboratories and three centers, among which only the Materials Research Laboratory (MRL) is related to nanotechnology.

DISCUSSION

I was received by Dr. L.C. Lee, Director, and Dr. C.M. Wang, Deputy Director, of MRL. They mentioned that MRL's materials development programs cover such areas as electronic polymers, magnetic materials, organic-photoelectronic materials, superconducting materials, organic composites, and ceramics. With suitable molecular structure design, formulation, and synthesis, polymers have given the electronics industry photoresistant, low-EM interference materials. Organic composites have produced lightweight, high strength, fatigue-resistant, and anticorrosive structures. Ceramics with specified mechanical or electromagnetic characteristics at various temperature ranges have been developed. Superconducting materials have been prepared for certain high-precision, low-temperature applications.

In the area of nanoparticle technology, my hosts candidly admitted that MRL is a very new player. They introduced me to Dr. Geoffrey W. Shuy who recently joined MRL and is in charge of nanoparticle R&D. Dr. Shuy showed me MRL's laboratory for ceramic and diamond thin-film synthesis. He also mentioned the institute's interest in semiconducting nanoparticles because of their novel optical properties.

SUMMARY

One of the constraints for all research programs at ITRI is that the Institute receives only 50% of its budget from MOEA; the rest must be contributed by industry. This rigid industrial cost-sharing requirement from MOEA makes it necessary to conduct only those projects that are close to commercialization. During the discussion about future research projects in nanoparticle technologies, this cost-sharing requirement repeatedly came up as an obstacle to doing any electrooptical projects (e.g., semiconducting nanocrystals). Instead, the laboratory's R&D work will probably be directed to coating- and structural-materials-related applications.