# PROCEEDINGS OF THE KOREA-U.S. FORUM ON NANO SCIENCE AND TECHNOLOGY

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# Notes of Preparation

This proceedings document was compiled from transcripts of audio tapes of the conference sessions and from printed texts of speeches submitted by the speakers. Wherever possible, for accuracy, the available printed texts were given precedence over the audio transcripts. In both cases, the presentations appearing in this document have been edited for clarity.

# Preface

The “new economy” is a global phenomenon based on science and technology. Although knowledge from the physical and life sciences provide much of the input to the new economy, a supportive policy environment is of equal importance. Today’s challenge to leaders in government, academia, and industry is to provide the necessary financial and political support to assure that both knowledge and policy evolve in step with each other.

Nano science and technology is at the cutting edge of both academic research and industrial development. Perhaps no other field of inquiry includes such intimate relationships between a basic understanding of nature and visions of radically new engineering possibilities, and concepts of possible future markets. Nano science and nano technology are emerging together and jointly challenge researchers, policy makers and entrepreneurs.

The Korea-U.S. Nano Science and Technology Forum successfully brought together world leaders in research as well as those who shape policy from both nations. The reader of these proceedings will find important scientific explanations of recent research developments juxtaposed with clear exposition of related governmental policies and industrial opportunities. This integration of technological opportunities with the underlying science, in parallel with the relevant policy considerations, should be of interest to a wide variety of leaders in both the U.S. and Korea, as well as other countries.

This forum did more than examine the science, technology and policy issues of the present. It also laid the groundwork for continued cooperation in the future. The Recommendations adopted by the forum participants on September 22, 2000 provide guidance to the sponsoring and interested institutions in both countries. The real measure of success of this forum will be measured in future years, not today, and will depend on the many individual and institutional cooperative programs and projects.

The Organizing Committee was responsible for the intellectual content of the forum. They are listed on page 136 of this proceedings volume. We are grateful all of them for their invaluable role in assuring the high quality of both the program and the speakers.

We also wish to thank the Ministry of Science and Technology of Korea (MOST), for its support and participation. On the U.S. side speakers from the White House Office of Science and Technology Policy (OSTP), and the U.S. National Science Foundation (NSF) added immensely to the credibility of the program. The forum would not have been possible without a grant from Korea Institute of Science and Technology Evaluation and Planning (KISTEP).

The Massachusetts Institute of Technology (MIT) Laboratory for Manufacturing and Productivity and the George Mason University (GMU) Center for Technology & Law were responsible for the organization of the Forum on the U.S. side. Special thanks are due to MIT for hosting the Forum in its superb facilities.

Moon Ho Chang
President
Korea Institute of Science and Technology Evaluation and Planning

J. Thomas Ratchford
Distinguished Visiting Professor
National Center for Technology & Law
George Mason University School of Law

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# Agenda

# KOREA–U.S. FORUM ON NANO SCIENCE AND TECHNOLOGY

September 21–22, 2000

Killian Hall
Massachusetts Institute of Technology (MIT)
Cambridge, Massachusetts USA

## THURSDAY, SEPTEMBER 21

0900–1700 ***Laboratory Visits by Korean Participants***

1800–1930
6:00 – 7:30 p.m.

***Reception***
University Park Hotel

Remarks by:

***Alex d'Arbeloff***
Chairman
The MIT Corporation

***Howard Ho Chung***
President
KSEA

## FRIDAY, SEPTEMBER 22

0730
7:30 a.m.

***Continental Breakfast/Registration***

0815
8:15 a.m.

***Keynote Session***

**Policy Overview:** ***NATIONAL INITIATIVES IN NANO SCIENCE AND TECHNOLOGY***

**Presiding**:

***Honorable Moon Ho Chang***
President
Korea Institute of Science and Technology Evaluation and Planning

***Honorable J. Thomas Ratchford***
Distinguished Visiting Professor
National Center for Technology and Law
George Mason University School of Law

**Remarks**: ***Thomas L. Magnanti***
Dean of Engineering and Institute Professor
MIT

**Keynote Addresses I**

***The Honorable Jung Uck Seo***
The Minister of Science and Technology
Republic of Korea

***The Honorable Duncan Moore***
Associate Director for Technology
Office of Science and Technology Policy
The White House

**Keynote Addresses II**

***Robert Trew***
Director of Research,
U.S. Department of Defense

***Jong-Oh Park***
Director
Intelligent Microsystem Program

***Jo-Won Lee***
Director
The National Program for Tera Level Nano Functional Devices

1030 **Coffee Break**
10:30 a.m.

1045 **PLENARY SESSION I**
10:45 a.m.

***KEY SCIENTIFIC AND ENGINEERING CHALLENGES***

**Presiding**: ***Seth Lloyd***
Professor, Department of Mechanical Engineering
MIT

***MEMS***

***Sukhan Lee***
Samsung Advanced Institute of Technology

***Ken Wise***
University of Michigan

***Nano Lithography***

***Henry I. Smith***
MIT

***Haiwon Lee***
Hanyang University

1230
12:30 noon **Lunch**

**Presiding**: ***Jung-Hoon Chun***
MIT

**Speaker**: ***Nam P. Suh***
Mechanical Engineering Department
MIT

1400
2:00 p.m. **PLENARY SESSION II**

***KEY SCIENTIFIC AND ENGINEERING CHALLENGES (continued)***

**Presiding**: ***Stephen Y. Chou***
Department of Electrical Engineering
Princeton University

*Characterization and Instrumentation*

***Sang-il Park***
Chairman and CEO
PSIA Corporation

***Charles Lieber***
Harvard University

*Nano Materials and Devices*

***Lionel C. Kimerling***
MIT

***Doh-Yeon Kim***
School of Materials Science
Seoul National University

1550 **Coffee Break**
3:50 p.m.

16:05 **Policy and Technical Roundtable**
4:05 p.m.

**Co-chairs:** ***Robert Trew***
Director of Research
U.S. Department of Defense

***Min-Koo Han***
Secretary General
Korea Research Foundation

**Panel members**: ***Seth Lloyd***
MIT

***Mihail C. Roco***
U.S. National Science Foundation

***Stephen Chou***
Princeton University

***Suk Han Lee***
Samsung Advanced Institute of Technology

***Jo-won Lee***
National Program for Tera Level Nano Devices

***Jong-Oh Park***
Intelligent Microsystem Program

***Kyoungwan Park***
Electronics & Telecommunications Research Institute

**General Discussion**

6:00 p.m. **Adjourn**

# Keynote Session

# THOMAS L. MAGNANTI

## *DEAN OF ENGINEERING AND INSTITUTE PROFESSOR MASSACHUSSETTS INSTITUTE OF TECHNOLOGY*

## PAST ACHIEVEMENTS, FUTURE OPPORTUNITIES

It is a pleasure to welcome everyone to MIT. My colleagues and I are grateful to the organizers of this Forum for bringing us all together to address the important topic of nano technologies and we are delighted to extend a particular welcome to our Korean guests.

To begin, I would like to offer a few brief comments about MIT's long-standing history of effective interactions and collaboration with Korea.

First, we are fortunate to have a number of Koreans as members of the MIT faculty. You will hear from some of them today, particularly Professor Nam Suh, the Head of our Mechanical Engineering Department, who will be our luncheon speaker.

Over the last ten years, Korea has the fourth largest number of all foreign students at MIT. We have had rich collaborations in a wide variety of fields; fields as far ranging as chemical engineering, mechanical engineering, materials science, physics, political science, the International Motor Vehicle Program, and a assortment of other programs. Korean companies have funded four chairs at MIT. We are delighted to recognize the accomplishments of our faculty as well as the extent of our relationship with Korea through these distinguished chairs. Indeed, their presence on campus speaks a lot about our relationship with Korea. Korea also provides about $1million of research funding per year. These varied sources of support have contributed to the long-term viability of the Institute as well as valuable ongoing research support, but I think, most importantly, they reflect a strong sense of mutual admiration and collaboration.

We come together today to examine one of the most exciting new technologies likely to alter the landscape of science and engineering. One measure of the excitement surrounding nano structures and nano technologies is the significant funding that the United States and other governments are devoting to this topical domain, and it is exciting to imagine its potential to change the landscape of our university system.

To stimulate our thinking, I thought I might start this morning with a bit of history. As we look forward to the coming years and decades, I would like to reflect a little upon the last century. Patrick Henry said, "I like the dreams of the future better than the history of the past," so I look back to the past with a sense of trepidation. But I ask us all to reflect on the following: what are the greatest engineering achievements of the last century? The United States National Academy of Engineering developed the following list, in reverse order:

**Greatest Engineering Achievements of the 20th Century**

20) high performance materials
19) nuclear technology
18) fiber optics
17) petroleum and petrochemical technology
16) health technologies
15) household appliances
14) imaging
13) Internet
12) spacecraft
11) highways
10) air-conditioning and refrigeration
9) telephone
8) computers
7) agriculture mechanization
6) radio and television
5) electronics
4) water supply and distribution
3) airplanes
2) automobile
1) electrification

What must households have been like all around the world at the turn of the century with lighting provided by kerosene lamps and with none of the electrical technologies that provide us with daily comfort and convenience. What would our industrial enterprises be like today without the ready availability of electricity? With electricity so pervasive throughout society, we can understand why electrification is number one on this list.

This list provides a retrospective view of our previous accomplishments. Now we at MIT and other universities such as KAIST, should look forward. What do we believe will be the major engineering achievements of the next century? I am not smart enough to tell you what those will be. In fact, imagine yourself in 1900 trying to imagine the technology developments of the impending century. What I can share with you, however, is the results of a strategic planning exercise at the School of Engineering at MIT. We have identified four important technologies, or thrust areas, that the School will pursue vigorously over the next few years. Hopefully, these developments will lead to some of the major engineering achievements of this coming century.

The first is bioengineering—the application of engineering thinking and model-based analysis onto the world of biology and, simultaneously, the use of biology in engineering. Some 50 years ago, MIT and other major engineering universities embraced physics, applying this discipline to the world of engineering, and sparking the electronics and computer revolutions.

We refer to our second thrust as engineering systems. In this context, rather than creating specific components or products, we are examining how these components or products work in a broader context—an environmental system, a manufacturing system, a product development system, or a biological system.

The third thrust is information, computation, and communication in engineering, which is important as we move increasingly from a physical to a digital world. General Motors, spends upwards of $1 billion a year on physical modeling. Imagine the potential impact of using digital modeling instead. Our mechanical engineering department, for example, is investigating instrumentation in bioengineering, which is the use of information systems, and technology in biology. Our aeronautical engineering department is examining imbedded software in both satellite and airplane systems. The Internet, supply chain management, computational biology, computational materials, and simulation and optimization of complex systems provide other important examples. Information, computation, and communication are becoming pervasive throughout engineering. The implication to what we teach in engineering and to our research agenda can be staggering.

The fourth area is most pertinent to today's Forum. I am starting to describe this thrust as "tiny technologies." By this I mean both miniaturization—making technologies smaller and then smaller and then smaller again—and nano technology, which often starts at the molecular level and builds technologies using such methods as self-assembly. Tiny technologies will be an important part of our future at MIT.

As you reflect upon about these thrusts over the next day, particularly in the context of an overall nano technology effort, I believe it will be useful to think about what might be the major engineering accomplishments of the 21st century. Will the products of nano technology be on that list?

I wanted to begin this Forum by stimulating you to think a bit differently before we embark upon the technical presentations you will be hearing today. As you look forward, I would remind you of a saying of Mark Twain, "You cannot depend upon your eyes when your imagination is out of focus." As we consider these new technologies, nano structures and nano technologies, it is hard to imagine at this point exactly what the fruits of these developments will be. We can envision some of the underlying science and some of the technological challenges it will evoke, but I believe it is hard to imagine what the products of these technologies are going to be. I ask you all to invoke your imagination as much as you can to think about what new products we will invent in the years ahead.

Let me conclude by again welcoming our guests, especially those from Korea. It is real pleasure to have you all with us. I had the opportunity to visit Korea this past June. I had a wonderful visit, and I met such wonderful and warm people. I hope you will feel as warmly welcomed here at MIT and in the United States.

# JUNG UCK SEO

## *MINISTER OF SCIENCE AND TECHNOLOGY*

## KEYNOTE ADDRESS

### Greetings

Dr. Moore from the White House, Dean Magnanti from Massachusetts Institute of Technology, distinguished participants, ladies and gentlemen:

It is a great pleasure for me to join distinguished scientists and engineers from the United States of America and the Republic of Korea here at MIT, where the world model of science and engineering education and university research stands proudly.

I am also happy to extend my heartfelt congratulations to the organizers of this forum, particularly, Professor Ratchford from George Mason University for his time and efforts in making this forum such a success.

First of all, I would like to thank all of you for coming to the 8th Korea-US Forum on Science and Technology Cooperation to establish a new partnership in developing nanotechnology.

Walking through the road of information bit by bit, we entered in a road not taken: the so called “road of nanotechnology” atom by atom. Nanotechnology is a new science and engineering of building materials and component atom by atom. And, it is possible to integrate them into useful, beautiful and peaceful devices.

Nanotechnology is a new frontier built on new discoveries and invention. It utilizes new eyes like high-resolution microscopes and new hands like laser tweezers to handle the scale of a nanometer or one billionth of a meter—ten thousand times thinner than a human hair. It is possible to create useful, beautiful and peaceful devices.

### The Significance of the Korea-United States Forum

Nanotechnology thrives from the state of the arts in chemistry, physics, biology, engineering and material research. It integrates biological, chemical materials and physical sciences and engineering disciplines.

Therefore, this forum indeed deserves a special significance because it is the first forum in the new millennium and focuses on nanotechnology—the new frontier at the dawn of 21st century.

As we all well aware, the breakthroughs in information technologies brought revolutionary changes in our way of thinking, working and living. With the recent advances in bio-science and technology such as cloning and genome research, we can anticipate that even more drastic changes will take place in the near future.

## Korea's New Science and Technology Policy

Our new science and technology policy is to secure core competence in the areas of information, communications, bio-science and technology, new materials, etc; support university research as a means of developing creative scientists and engineers; promote small and medium-size enterprises; and improve national research and development (R&D) infrastructure.

Under the new policy guidelines, we launched last year the 21st Century Frontier R&D Program with an aim to developing key technologies for a knowledge-based economy. This new program is open to foreign scientists and institutions.

We are now working on a "Framework Act on Science and Technology," as a new legal framework for the science and technology policy.

The new framework places greater emphasis on international cooperation in science and technology. We will strengthen our participation in and contribution to international scientific R&D programs, particularly with the United States in challenging global issues like global warming, climate change, human cloning, alternative energy, etc.

## Korea-US Cooperation in Nanotechnology

Korea-U.S. cooperation in nanotechnology may take various forms: exchange of scientists, engineers, technicians and experts; exchange of information; joint organization of seminars, symposia, conferences and forums like this; implementation of joint R&D projects as well as exchange of the experiences of R&D activities.

Many countries already have taken major initiatives in nanotechnology because their scientists, engineers and national leaders have agreed that it has the potential to be a major economic engine during the next several decades.

The United States established the National Nanotechnology Initiative (NII) to ensure economic and national security leadership. Japan and Europe are also enhancing their science and engineering capability to the same quality and breadth of that done in the United States.

Nanotechnology will inspire the public and the next generation workforce. Our future workforce in science and technology is declining, in part because a great many young people perceive that bright prospects is no longer in science and engineering. They do not see how science and technology contributes to the world as they know it.

Yet chemistry, physics, biology and material science and engineering are at the core of nanotechnology. They will play a pivotal role long into the future. Therefore, nanotechnology programs should parallel investments in R&D with creative and entrepreneurial programs that provides young scientists and engineers with a truly interdisciplinary education.

Nanotechnology prepares the next generation of researchers and industrial leaders. As nanotechnology develops, the core disciplines of physical science, engineering and biomedicine in research communities will become much more intimately coupled to each other. Future research efforts in these fields require trans-disciplinary cooperation among each other and a closer communications with industry and society as a whole.

The relevance and inherent excitement of nanoscale R&D should attract young men and women to science and engineering as never before and also create exciting challenges and important career opportunities for them.

Korea has embarked on two major nanotechnology programs as part of the 21st Century Frontier R&D Program. A total of 800 million U.S. dollars will be invested during the next ten years. First, there is the "Intelligent Microsystem Program," and second, the "National Program for Tera-level Nanodevices." I am not going to talk about them because the Drs. Park and Lee from Korea will introduce them in detail later.

However, these are by no means easy tasks for Korea to undertake by itself. To make them successful, international cooperation is essential. As nanotechnology is a newly emerging area, individual countries have yet to nurture research personnel and an advance scientific knowledge base for research in this area. Therefore, it will serve mutual interest to collaborate in establishing a network that will allow scientists to find and share information and work with each other.

I would like to go one step further to advocate that some kind of international arrangements need to be made for international sharing of large-scale research facilities which are indispensable to nano science and technology research.

## Concluding Remarks

I would like to emphasize that a Korea-U.S. partnership should go beyond merely pursuing bilateral interests, but should also contribute toward the sustainable development of the world community. This is the way to assure that the traditional Korea-U.S. alliance is sustainable in the new century.

In closing, I would like to remind all of you that when radically new technologies are developed, ethical, legal and social issues problems also arise. Accordingly, a modest resource must be set aside to cope with such implications of nanotechnology.

We must develop a new generation of skilled workers in the multidisciplinary perspectives necessary for rapid progress in nanotechnology.

Thank you.

# DUNCAN MOORE

## *ASSOCIATE DIRECTOR FOR TECHNOLOGY*
## *OFFICE OF SCIENCE AND TECHNOLOGY POLICY*

## KEYNOTE ADDRESS

I would like to talk about overall funding levels when we are looking at nanotechnology and how the United States came to think about nanotechnology as an initiative. I would like to lay the groundwork for why we do this sort thing at the national level.

We find that there are two ways to increase the budget for science and technology, particularly in the physical sciences and engineering. One of the problems for those of us in the physical sciences is that in the United States over the last ten years we have increased our funding for the biological sciences at enormous rates. The National Institutes of Health has received enormous increases and its budget has nearly doubled over the last five years. The reason that NIH has been able to double its budget is that it has been able to relate research that it is doing to things that people care about, namely their health. It is very easy for the people at NIH to make the claim that if you fund this research in fundamental cell biology, for example, it will help us understand new mechanisms that may lead to a cure for some disease. Everyone cares about good health. Unfortunately, in physical sciences and engineering, we have not been able to make that connection very well, even though those of us in this room who are scientists and engineers all understand the connection. When we talk to our neighbors who are not scientists and engineers, they haven't a clue what impact our research has on their lives. When I talk to my mother, who is actually trained as a chemist, and I try to explain to her what we are doing, it just doesn’t resonate.

One of the things that we have realized is that we can increase the budget for science and engineering in the National Science Foundation by inflation plus a couple of percent, but inflation plus a couple of percent will never double the funding unless inflation is rampant. So what we have done is to try to increase the budget in all fields and, in parallel, pursue what we call "initiative-based" research. That is, we determine that a certain area is so important to the economic growth of this country that it is important for the Federal government to make significant investments in it. We did that in information technology two years ago. Critics will say that with all these dot-com companies, why are we investing in information technologies? Well, as you know, the research that is being done by the dot-com companies tends to be very short-range. It is not leading to fundamental changes in research and ideas that are important over the next decade. While we call these things "tech", most of the work being done in this area and in nanotechnology is very fundamental science.

I would like to just take a slight digression on another area we do, and I will come back to nanotechnology in a moment. One of the first exercises I was involved in when I went to the White House three years ago was to take the President's State of the Union address from that year and look at all the themes from the address such as children, crime, and Social Security. We put the word tech after each theme. We generated projects like kid tech, crime tech, and elder tech (or technologies for successful aging). We are trying to take the needs of the American people as defined by that State of the Union address, and then determine how science and technology comes in behind them.

So let me briefly tell you about technology for successful aging, because we are having a two-day meeting on that in two weeks in Washington. The idea there is "How do we use technology to allow people to stay in their homes longer?" The idea is that if you can stay in your own home longer, the quality of life is higher, the cost to the individual is lower, and the cost to the Federal treasury is lower. Nanotechnology actually plays into this.

One of the devices we are looking at is a visual hearing aid. A visual hearing aid consists of the following parts, and we need basic research for these: I want to build in the bows of my glasses directional microphones. I want the directional microphones to be such that as I am looking at a certain person, I only hear his voice. All the rest of the field is blanked out. Because, as we know, voice recognition systems for computers do not work well when you have a lot of background noise. So we want to limit the background noise.

The second part, which is where nanotechnology comes in, is that we need speaker- and accent-independent voice recognition. The voice recognition systems that we have today require you to speak clearly and distinctly and to train the computer on your voice. We, however, are interested in interacting in real time, and you have not been trained on my voice recognition system. Furthermore, when you use your own voice recognition system, you know when the computer makes a mistake and you can immediately correct it. If we are speaking in real time, I don't know what word you said. So the accuracy has to be very high, and it has to be packaged so that I can put it in the rims of my glasses. So I am going to need to be able to store enormous amounts of information in a very small volume.

Finally, what I need is a system that displays the words inside of my glasses, so that as I am looking at you, the words you are speaking are coming across the field of view on a marquis display. That way I can maintain eye contact with you and have a real conversation, even though I am completely deaf.

These are some of the things we are considering as we look at initiative-based research that allows us to deal with societal issues.

Let me go back to information technology for a moment. This year, funding for information technology is $1.7 billion. This is a 32% increase over last year. We could never have gotten a 32% increase for the National Science Foundation alone. But what we did do was to get a group of agencies to work together. We have the Department of Energy, the National Science Foundation, NASA, NIM, DoD, and NOAA working together toward a common goal. We developed an operating plan for the agencies to work together and to coordinate their activities. In 2001, we are proposing an additional increase of 35%. None of the budgets has been passed by the Congress, but we are hopeful that all of this will come through.

The initiative for 2001 is nanotechnology. I would like to discuss how we made that decision and what will be the next initiative. Neal Lane, who is currently Science Advisor to President Clinton, said in 1998 when he was Director of the National Science Foundation:

> If I were asked for an area of science and engineering that will most likely produce the breakthroughs of tomorrow, I would point to nanoscale science and engineering often called simply "nanotechnology"; …only recently have scientists been able to glimpse Feynman's vision by creating rudimentary nanostructures.

Remember, Richard Feynman made this comment about 40 years ago. It took 40 years before an initiative came around. Why did it take so long? Well, we know that some of the basic instruments needed to manipulate a molecule just did not exist. The atomic-force microscope had not been invented; many of these near-field probe instruments had not been invented.

When we rolled this initiative out, IBM wrote the letters in the graphic shown below which were done in red, white, and blue. Each dot is a single molecule of carbon monoxide on a copper surface. There are 112 of these molecules on this surface. Each one of these letters is 3 nanometers by 4 nanometers. One could write 250 million of these characters on the cross-section of a human hair. That is 300 three-hundred-page books. So when you are talking about storing enormous amounts of information, you can see how you might be able to do it.

The history of this goes back to a working group started in September 1998. It took two years to get this initiative through. That is fairly standard when you have significant amounts of money (over $100 million) behind an initiative. In January 1999, NSF and a group of agencies held a meeting to talk about nanotechnologies. They had people come in from overseas to talk about what was going on in other countries. It was important to compare how the United States was doing as compared with other countries in the technology. It creates a bit of a competition.

If other countries are spending more, then we feel compelled to spend more. Sometimes there is a ratcheting-up effect with the end result of helping scientists and engineers in several countries.

Between January and November there was a series of meetings between the agencies and with outside organizations to develop a program. But in order to get programs through the Congress, we needed to have individuals totally outside the government come together and look at the initiative and give their stamp of approval. Therefore, in November 1999, we called on the President's Committee of Advisors on Science and Technology (PCAST), which is chaired by John Young, the former CEO of Hewlett Packard, to set up a special panel to look at the nanotechnology program. The chairman of that panel was Chuck Vest, the president of MIT. He organized a panel of external experts to evaluate the program. One of the recommendations they made is that there should be more money for social, ethical, and legal issues. We did not want to end up with a problem that occurred with genetically-modified organisms. The panel wanted the program to look at these issues before products were generally available to the public. As a matter of fact, Mike Roco from NSF is going to be having a conference next Thursday and Friday in which participants will begin to look at these issues. They will look into whether or not there are legal or intellectual property issues that need to be addressed as well.

PCAST then sent a letter to the President endorsing the initiative and explaining why it would be beneficial to the country. The culmination of all of this was another quote by the President of the United States when he announced the initiative at the California Institute of Technology on January 1, 2000, in which he said:

> My budget supports a major new National Nanotechnology Initiative, worth $500 million…the ability to manipulate matter at the atomic and molecular level. Imagine the possibilities: materials with ten times the strength of steel and only a small fraction of the weight -- shrinking all the information housed at the Library of Congress into a device the size of a sugar cube -- detecting cancerous tumors when they are only a few cells in size. Some of our research goals may take 20 or more years to achieve, but that is precisely why there is an important role for the federal government.

Once the President said that, the initiative became a reality. During the budget process that occurred in late December of 1999, the President turned to Neal Lane in a cabinet meeting and asked what nanotechnology was all about. Once you have the President saying that, you know that he believes in it.

The initiative consists of several important components. The first is fundamental research. Any one of our initiatives promotes fundamental research. In the case of nanotechnology, depending upon how the budget comes out, we estimate that somewhere between 60% and 70% of the money funded for this initiative will end up as university-based fundamental research.

The second important component of the initiative is meeting grand challenges. One of the things we try to do is follow the NIH philosophy of relating the research to everyday needs. One of the grand challenges proposed in the initiative is "How do you store the whole Library of Congress in the volume of a sugar cube?". While you probably would never do that, there is relevance to other applications, like the visual hearing aid I spoke about earlier. You need to have an enormous amount of storage capacity in order to be able to do voice recognition. So there is a challenge that we can relate to something that the vast majority of people can understand. Another example is "How do you make a material that is 10 times stronger than steel but is a fraction of the weight?". While most people don’t relate to that, if you start talking to them about automobiles and airplanes and our ability to make them stronger but lighter weight, you can fundamentally change the manufacturing process.

We had a two-day meeting in July on crime technology to address how technology can help in reducing the cost of policing, incarceration, and the judicial system. We spend $100 billion in this country on those three parts. Attorney General Janet Reno spoke about nanotechnology. She noted how important nanotechnology is for body armor. This is just another situation in which nanotechnology can play a role but one we may not have thought about. Nanotechnology becomes an enabler for many things. Thinking about grand challenges is part of the selling process. It is important for those of us in the science and engineering field to start relating our work to everyday needs. That will be an important way to sell science and technology research to the public.

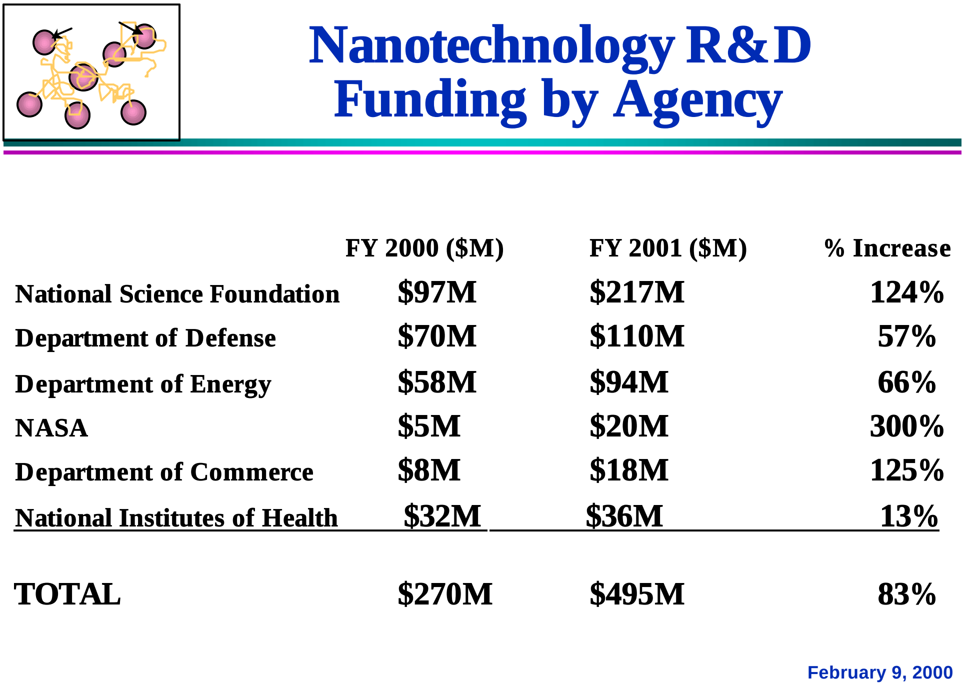
A third component of the initiative is to create up to ten centers of excellence in nanotechnology that will be funded by several agencies.

Fourth, we recognize that there is going to be the need for new, expensive instrumentation. We will be spending mega bucks for nanotechnology.

Finally, there are the ethical, legal, and social issues, as well as workforce issues. We hope that this initiative will get young people enthralled with physics, chemistry, biology, material sciences, and the interfaces between those fields. It will be at those interfaces that exciting research is going to be done. Can the American university system adapt to a field that is really interdisciplinary? That is not natural for universities to do.

Finally, let me show you where the money is coming from. Table 1 [nanotechnology R&D funding by agency] below shows the six agencies that participate in the initiative. In the year 2000, we budgeted $270 million. In 2001, we are proposing a budget of about $495 million. The key will be to get all six of the agencies to work together to convince the Congress and the American people that this is a better way of doing business than just funding one agency by itself. Cooperation is the key.

Thank you very much.



## Nanotechnology R&D Funding by Agency

| | FY 2000 ($M) | FY 2001 ($M) | % Increase |
|---|---|---|---|
| National Science Foundation | $97M | $217M | 124% |
| Department of Defense | $70M | $110M | 57% |
| Department of Energy | $58M | $94M | 66% |
| NASA | $5M | $20M | 300% |
| Department of Commerce | $8M | $18M | 125% |
| National Institutes of Health | $32M | $36M | 13% |
| TOTAL | $270M | $495M | 83% |

February 9, 2000

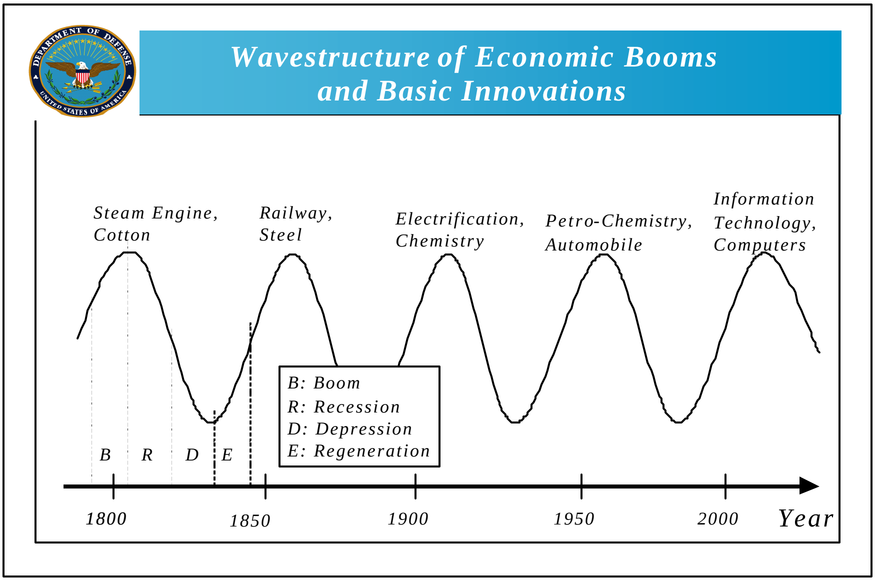
# ROBERT TREW

## *DIRECTOR OF RESEARCH*
## *U.S. DEPARTMENT OF DEFENSE*

### THE EMERGING REVOLUTION IN NANOTECHNOLOGY RESEARCH

The economic history of the United States has been dominated by cyclic waves of periods of boom, recession, depression, and regeneration. The main factor in each peak period is a push from a technology, generally associated with a primary commodity. We are currently in such a peak period, based upon information technology, which is based upon the computer revolution. Computers, in turn, are derived from transistor scaling, which is a nanotechnology. Figure 1 illustrates these cyclic waves and the technology driver of each.

Figure 1



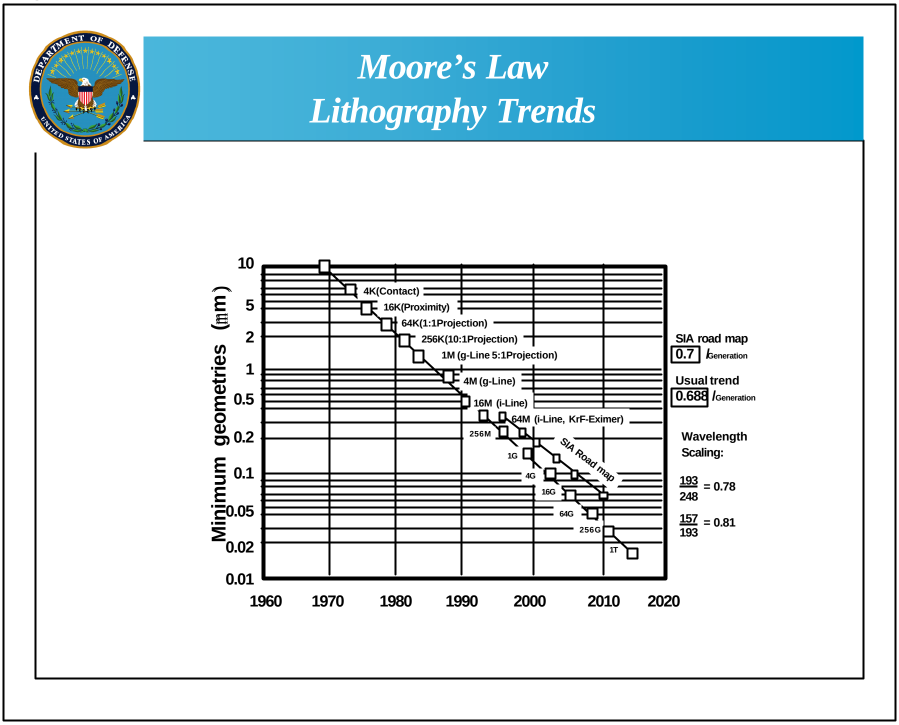
When we look at where we are going, I will refer back to a paper that John Gibbons, the former Director of the Office of Science and Technology Policy, published in the IEEE proceedings in March of 1988 in which he said "..If you can have technological advancement in only five areas, that is sufficient to produce global economic transformation." The five areas he named in 1988 were computers, telecommunications, biotechnology, nanotechnology and alternate energies. This may be a little misleading because nanotechnology is really a support technology that really underwrites the rest of these technologies. It is the advancements in scaling and the ability to make more precise structures that really enables these other areas.

The Department of Defense has identified six areas for focused support. These areas are called 'Strategic Research Areas', and identify thrust areas in which advances will be important to future DOD systems. These six areas are:

- Biomimetics
- Nanoscience
- Intelligent Systems
- Smart Materials and Structures
- Information Technology
- Compact Power

Although 'Nanoscience' is listed as a separate area, it is, in fact, a part of all other areas.

Figure 2

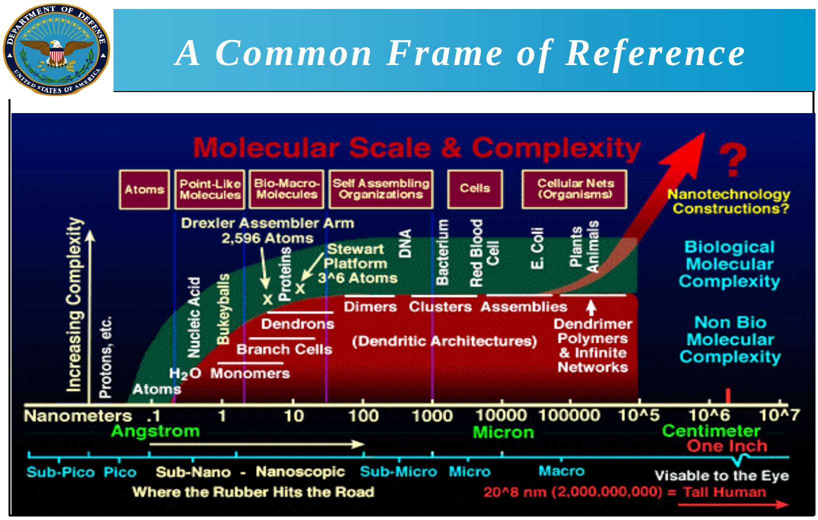


***Moore's Law***
***Lithography Trends***

Figure 2 demonstrates Moore's Law. An experimental observation made by Gordon Moore, a founder of Intel, that indicates that computer functionality essentially doubles every 18 months. Remarkably, the *Law* has held true for almost 30 years. We are still on this curve. The only issue that is happening now is that we are getting into the regions where we are dealing with nanotechnology and there is the feeling that we will have to reach saturation at some point.

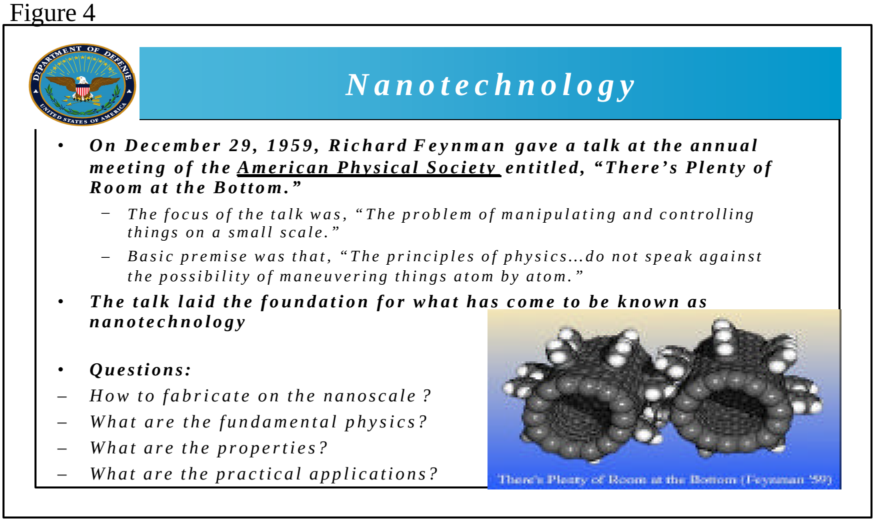
As figure 3 illustrates, at the atomic and molecular level, all fields reduce to essentially the same. That is, at the most fundamental level, there is essentially no difference between materials, physics, chemistry, biology, etc. Nanotechnology is inherently a "multi disciplinary" activity that requires researchers from a wide spectrum of backgrounds.

Figure 3



(from http://nanozine.com/scale.htm)

Figure 4



## *Nanotechnology*

- ***On December 29, 1959, Richard Feynman gave a talk at the annual meeting of the American Physical Society entitled, "There's Plenty of Room at the Bottom."***
  - *The focus of the talk was, "The problem of manipulating and controlling things on a small scale."*
  - *Basic premise was that, "The principles of physics...do not speak against the possibility of maneuvering things atom by atom."*
- ***The talk laid the foundation for what has come to be known as nanotechnology***

- ***Questions:***
  - *How to fabricate on the nanoscale ?*
  - *What are the fundamental physics?*
  - *What are the properties?*
  - *What are the practical applications?*

There's Plenty of Room at the Bottom (Feynman '59)

Dr. Richard Feynman, back in 1959 opened up the issue of dealing at an extremely small scale. At that time, his basic premise of maneuvering things atom by atom was very futuristic. This established the foundation of what has come to be known as nanotechnology. There were a lot of questions at the time which are still relevant. However, parallel advances in the technologies listed in Fig. 5 make it now possible to build practical systems on the nanoscale.

Figure 5

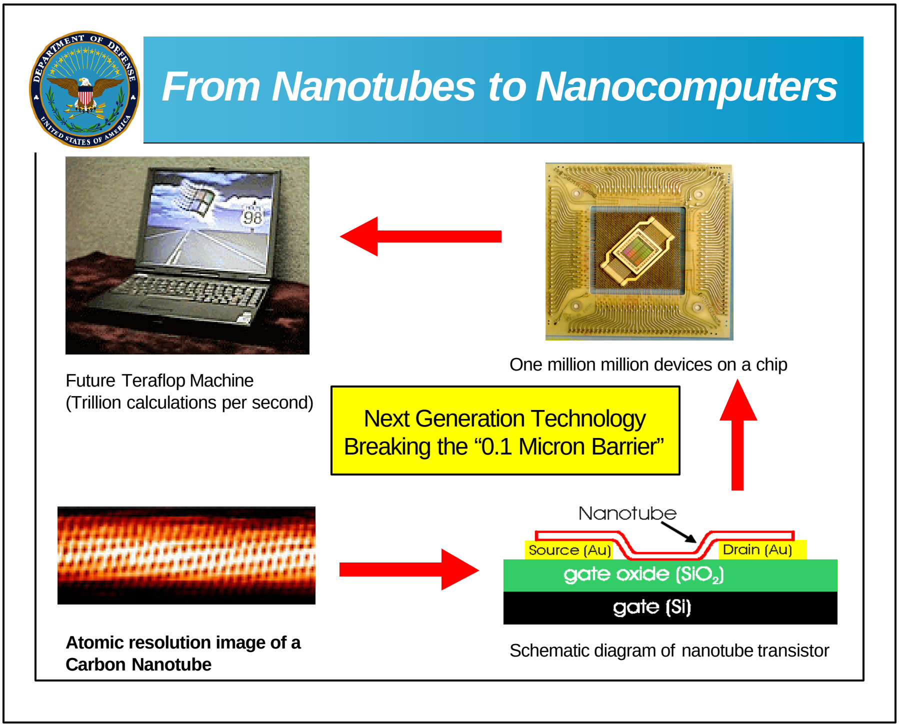
## *Nanotechnology Enablers*

- ***Materials Growth/Nanostructure Fabrication***
  - *MBE, OMCVD*
  - *Self-Assemby, supramolecules, cluster, nanocrystal*
- ***Patterning - Nanolithography***
  - *Deep UV*
  - *EUV, Scalpel, x-Ray, Microstamping*
- ***Imaging***
  - *SEM, BEEM, FFM, SNOM*
- ***Manipulators***
  - *STM, AFM, SFM*
- ***Characterization and Testing***
  - *Picoprobes, Sampling Techniques, etc.*

MBE (molecular beam epitaxy)
OMCVD (organo-metallic chemical vapor deposition)
Deep UV (deep ultra-violet)
EUV (extreme ultra-violet)
SEM (scanning electron microscopy)
BEEM (ballistic energy electron microscopy)
STM (scanning tunnel microscopy)
AFM (atomic force microscopy)
SFM (surface force microscopy)
OMCVD (organo-metallic chemical vapor deposition)

Deep UV (deep ultra-violet)

Figure 6



From Nanotubes to Nanocomputers

Future Teraflop Machine
(Trillion calculations per second)

One million million devices on a chip

Next Generation Technology
Breaking the “0.1 Micron Barrier”

**Atomic resolution image of a Carbon Nanotube**

Schematic diagram of nanotube transistor

Probably the single most important immediate application of nanotechnology is in the area of computers and information technology. It is almost universally agreed that the current silicon technology will be hitting the limits of physics at about 0.01 microns by the year 2015. Continued growth in the semiconductors industry and computers will require nanoscience and nanotechnology to break through that barrier and permit continued advances to be made. As shown here, research in nanoscience will lead to nanoscale devices, to tera-scale (a million million) devices on a single electronic computer chip, and ultimately to teraflop computing machines that are the size of the portable computer today. Nanoscience research will lead to future generation of computing technology, including:

- Data acquisition. This includes sensors of all types as mention in the previous slide. These sensors will allow the miniaturization of payloads in UAVs and miniature satellites.

- Information processing. Nanoelectronic devices and nanostructures will lead to computer logic circuits that are orders of magnitude faster, denser, and lower power than what we have today. Nanoscale quantum and/or molecular devices will make it possible to achieve teraflop calculations per second. State-of-the-art nanostructures, such as resonant tunneling diodes and quantum cellular automatons, have already demonstrated logic circuits for use in computers. With millions and millions of transistor devices on a chip, a supercomputer combining the CPU and memory, called computer-system-on-a chip, is not far away.

- Data storage. Perhaps the most visible impact from nanotechnology is going to be in the area of data storage and computer memories. Nanotechnology such as Giant Magneto Resistance (GMR) devices have already increased the density of memory storage by orders of magnitude to the order of 10 Gbits/cm$^2$. In a decade, using nanotechnology, it is projected terabits/cm$^2$ is possible. Recording the story of the entire Bible on the head of a pin may prove to be technologically feasible with nanotechnology.

- Displays. Last but not least, nanostructures have the promise of dramatic improvement in low power display brightness and flexibility. Nanometer-sized semiconductor clusters provide the possibility of tunable fluorescence used in displays with high brightness, full color, and low power.

These are but a brief listing of the potentials for nanotechnology in leading to the next generation of computers and information technology. Information technology is an indispensable part of Defense, as shown earlier. With such tremendous potential, the future of nanoscience/nanotechnology is bright indeed.

# JONG-OH PARK

## *DIRECTOR*
## *INTELLIGENT MICROSYSTEM R&D CENTER*

## $21^{ST}$ CENTURY FRONTIER R&D PROGRAM IN KOREA

### Overview

**Program Goals**: The Intelligent Microsystem Program (IMP) is one of the $21^{st}$ Century Frontier R&D programs sponsored by the Korea Ministry of Science and Technology and other ministries. It aims to develop intelligent Microsystems integrated by various MEMS technologies such as electronics, mechanical engineering, materials, optics and so on. The intelligent Microsystems aim to spearhead high-value industries such as micro-scaled medical appliances and micro-scaled information appliances. Thus, it will induce us to build up our national infrastructure and to rank fifth best in the world in the relevant strategic technologies by 2010.

Figure 1: Two Main Categories of IMP

| | Micro medical appliances | Micro information appliances |
|---|---|---|
| Final Product | Endoscopic microcapsule | Micro-PDA |
| Size | Capsule type | Wrist-watch type |
| Characteristic | • It aims to develop high-valued products, components, and technologies.<br>• It promotes national medical welfare.<br>• It is suitable for medium-sized companies and venture business. | • It has the possibility of creating a huge worldwide market.<br>• It is suitable for large enterprises or industrial consortia. |

Figure 2: Progressive targets by each phase

| Year | 99 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Phase | 1st Phase | | | | 2nd Phase | | | 3rd Phase | | | |
| Target | • to develop fundamental technology components for endoscopic microcapsule & micro-PDA<br>• to promote commercialization of key components | | | | • to integrate fundamental technologies for endoscopic microcapsule<br>• to promote commercialization of partially integrated system | | | • to develop final microsystem and verification of system reliability<br>• to promote commercialization of the final system | | | |

Figure 3:R & D funding for each phase

| Phase | | 1st | 2nd | 3rd | Total |
|---|---|---|---|---|---|
| R&D Fund | government | 27.5 | 25.0 | 33.3 | 85.8 |
| | industry | 17.0 | 17.5 | 26.7 | 61.2 |
| Total | | 44.5 | 42.5 | 60.0 | 147.0 |

(Unit : million US dollar)

## Endoscopic Microcapsule

Final Goal: A capsule-type endoscope swallowed into human organs is to be developed. It consists of various components for actuation, sensing, data acquisition/processing, communication and power source. The development of the endoscopic microcapsule will encourage microsystem industries as well as medical industries.

Main Specifications of the Endoscopic Microcapsule:

- Less than 10mm in diameter, less than 30mm in length
- Serial link type, modular removable type
- Human organs for inspection: stomach, the small and large intestine, the duodenum, womb, chest, the urinary tract, and bladder

- The medical diagnosis can be operated by in-body infrared/ ultrasonic images, temperature, bio-medical data such as pH, hardness and human internal chemicals, and so on.
- Medical treatments sampling of body fluids, injection of medical drugs, cauterization, resection, removal of pneumothorax and so on.
- Movement of the microcapsule : forwarding, backwarding, pausing, fixing and rotating.
- Telemetry, teleoperation partially/autonomous control communication
- The mini battery has 2 Watts and 2 Wh (8mm in diameter and 8mm in length)

Figure 4: Conceptual Cross-sectional View of the Endoscopic Microcapsule

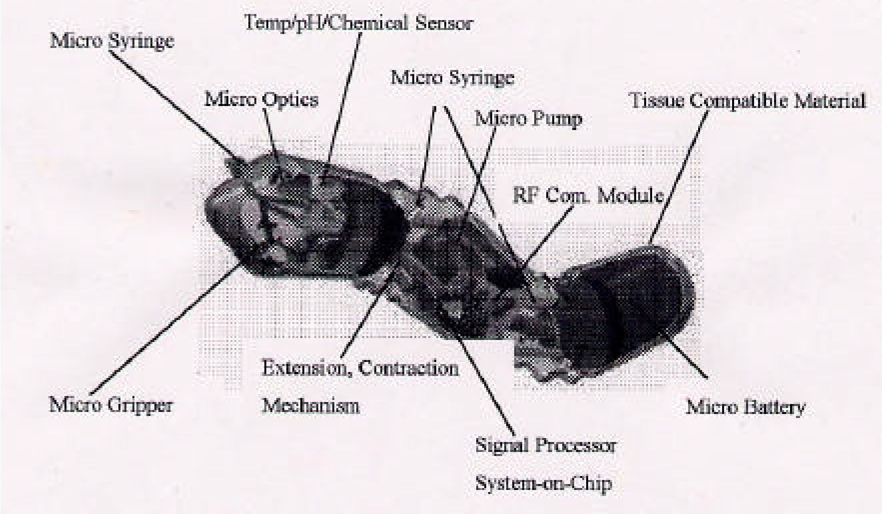
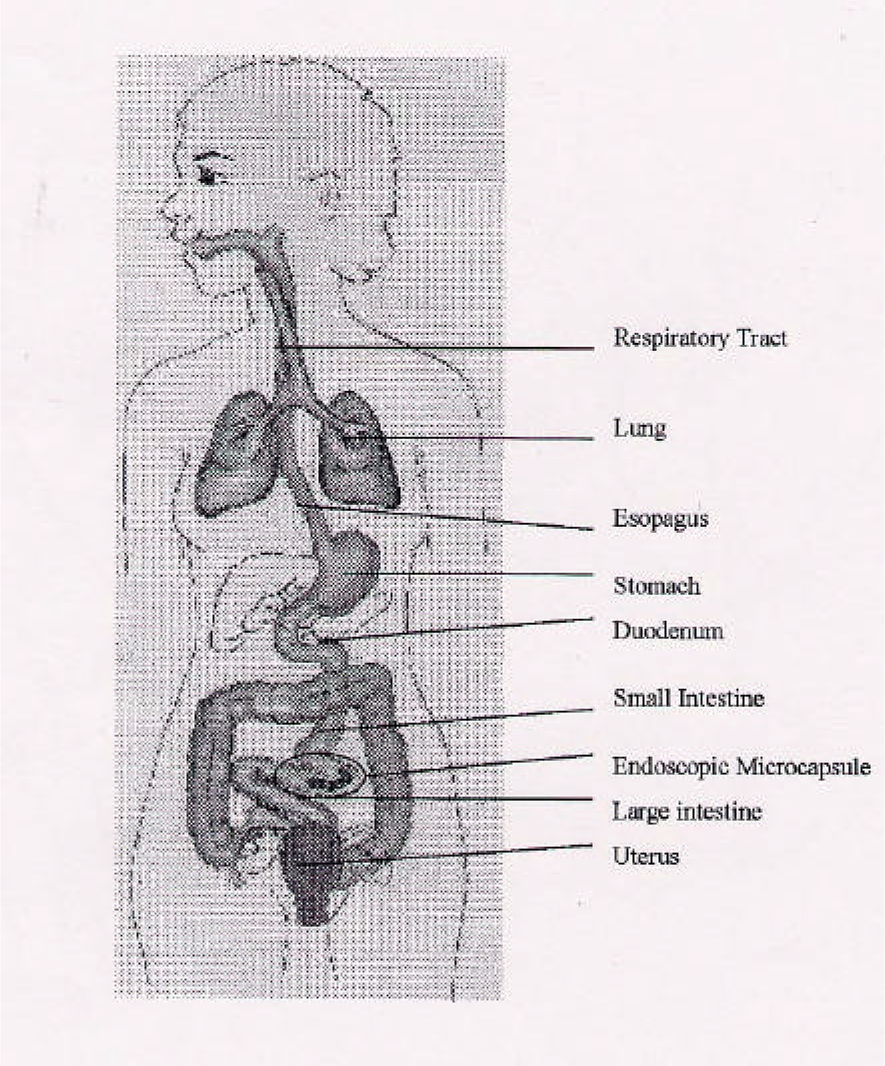


Figure 5: Human Organs for the Microcapsule



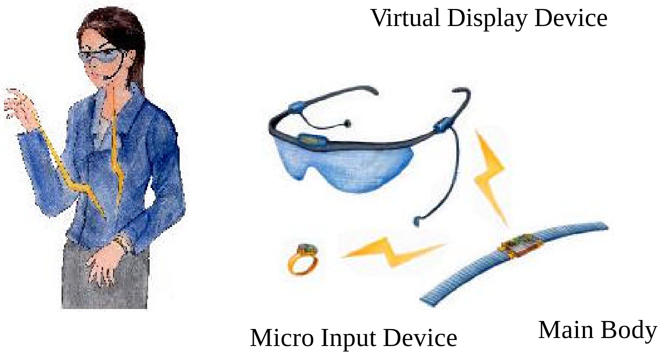
## Wrist-watch type Micro-PDA

Final Goal: The final goal of this project is to develop a miniaturized PDA system including telecommunication and computing functions with a new concept of it totally fitting within the size of a wrist-watch. It consists of various micro-devices for data storage, image, voice, communication and data processing besides personal information management.

Main Specifications:

- Wrist-watch
- Data storage: ½ inch in diameter, 5Gbyte in storage capability
- Micro hologram display
- Micro wireless pen-type input device
- Micro voice/image I/O devices
- Micro communication transceiver module

Figure 6: Conceptual Illustration



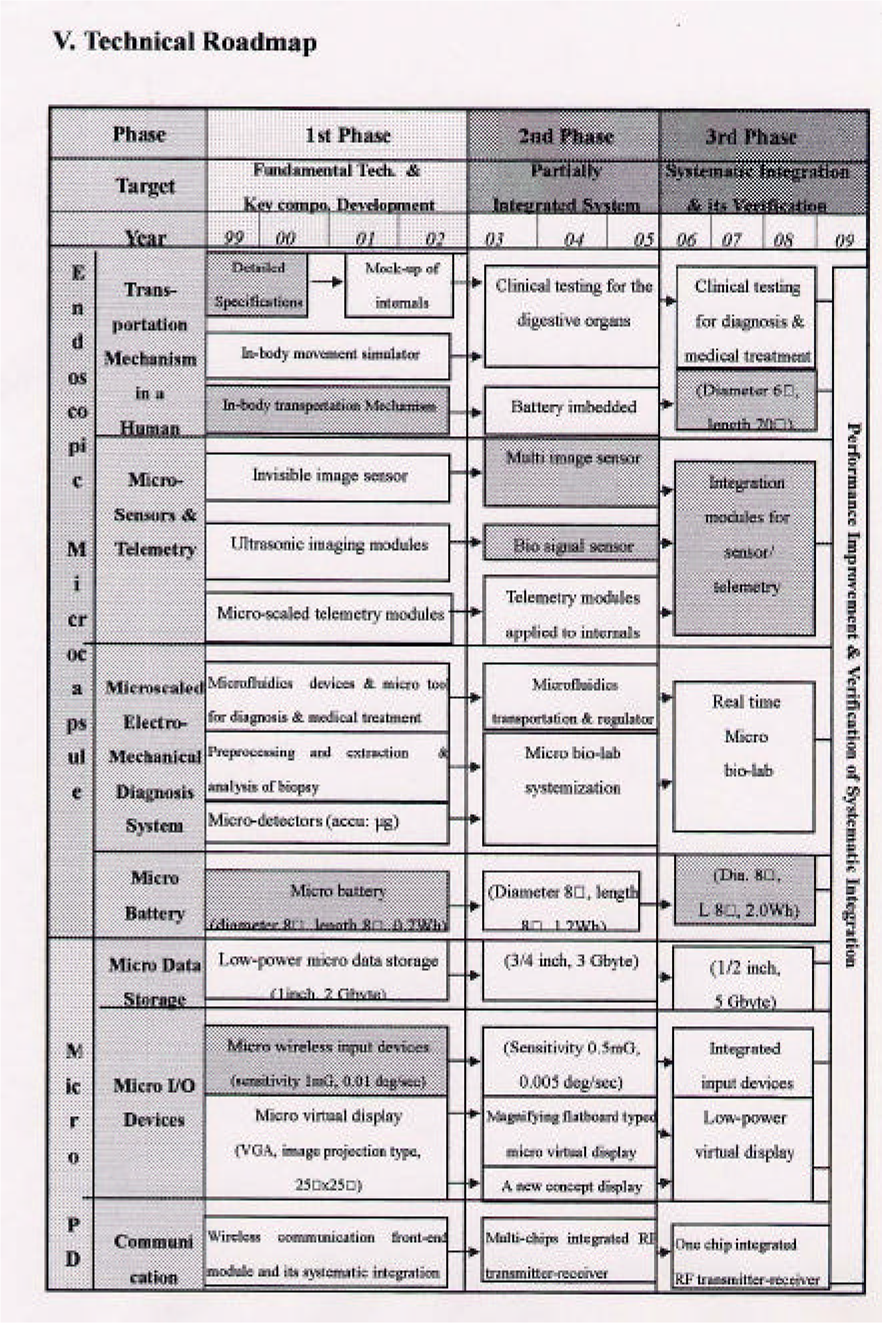
Micro telecommunication and processing functions are integrated into a small watch-size device. The main body is comprised of a processing part, a micro battery, an integrated projection module for display or separate display device, and interface modules and a RF MEMS module. The micro input device serves the function of recognizing human finger motion and transmitting motion data to the main body. As a display module various new ideas can be realized. In the first stage, head-mounted displays will be developed with the help of MEMS technology.

Figure 7: List of R&D Projects

| Field | Project No. | Title of Research Items |
|---|---|---|
| System Integration | 0-0-1 | System design, integration and verification |

| Target Product | Research Category | Research Item |
|---|---|---|
| Endoscopic Microcapsule | Transportation Mechanism in a human body | Development of in-body transportation mechanism |
| | | Medical verification for the endoscopic Microcapsule |
| | | Development of global transportation technologies for Micro Capsule |
| | Micro Sensors and Telemetry | Development of Infrared imaging Modules |
| | | Ultrasonic imager for endoscopic microcapsule |
| | | Development of fundamental technologies for a micro-scaled telemetry module |
| | Micro-scaled Electro-Mechanical Diagnosis system | Development of Microfluidic devices and micro tools for diagnosis and medical treatment |
| | | Development of Pre-processing and extraction, analysis of biopsy |
| | | Development of micro-detectors using functional thin films |
| Micro-PDA | Micro data storage | Development of a low-power micro data storage |
| | Micro I/O devices | Development of wireless input devices |
| | | Development of micro virtual display |
| | Micro Communication Module | Development of a wireless communication front-end module and its system integration |
| Common Technology | Micro power sources | Development of high-power micro battery |
| | 3D Micro-fabrication | Development of rapid prototyping technologies |
| | | Development of fundamental technologies for microsystem packaging |
| | | Development of micro machining center |
| | | Development of a micro assembly cell |
| | Creative Research | Various research items for creative concept investigation |

Figure 8: Technical Roadmap



## V. Technical Roadmap

| Phase | | 1st Phase | 2nd Phase | 3rd Phase | |
|---|---|---|---|---|---|
| Target | | Fundamental Tech. & Key compo. Development | Partially Integrated System | Systematic Integration & its Verification | |
| Year | | 99 00 01 02 | 03 04 05 | 06 07 08 09 | |
| Endoscopic Microcapsule | Trans-portation Mechanism in a Human | Detailed Specifications → Mock-up of internals | Clinical testing for the digestive organs | Clinical testing for diagnosis & medical treatment | Performance Improvement & Verification of Systematic Integration |
| | | In-body movement simulator | | | |
| | | In-body transportation Mechanism | Battery imbedded | (Diameter 6□, length 20□) | |
| | Micro-Sensors & Telemetry | Invisible image sensor | Multi image sensor | Integration modules for sensor/ telemetry | |
| | | Ultrasonic imaging modules | Bio signal sensor | | |
| | | Micro-scaled telemetry modules | Telemetry modules applied to internals | | |
| | Microscaled Electro-Mechanical Diagnosis System | Microfluidics devices & micro tool for diagnosis & medical treatment | Microfluidics transportation & regulator | Real time Micro bio-lab | |
| | | Preprocessing and extraction & analysis of biopsy | Micro bio-lab systemization | | |
| | | Micro-detectors (accu: µg) | | | |
| | Micro Battery | Micro battery (diameter 8□, length 8□, 0.73Wh) | (Diameter 8□, length 8□, 1.2Wh) | (Dia. 8□, L 8□, 2.0Wh) | |
| Micro PD | Micro Data Storage | Low-power micro data storage (1inch, 2 Gbyte) | (3/4 inch, 3 Gbyte) | (1/2 inch, 5 Gbyte) | |
| | Micro I/O Devices | Micro wireless input devices (sensitivity 1mG, 0.01 deg/sec) | (Sensitivity 0.5mG, 0.005 deg/sec) | Integrated input devices | |
| | | Micro virtual display (VGA, image projection type, 25□x25□) | Magnifying flatboard typed micro virtual display | Low-power virtual display | |
| | | | A new concept display | | |
| | Communi cation | Wireless communication front-end module and its systematic integration | Multi-chips integrated RF transmitter-receiver | One chip integrated RF transmitter-receiver | |

## Suggestions for International Collaboration

IMP allows an opportunity not only to Korean domestic research groups, but also strategically to competitive research groups worldwide since the IMP's goal is to develop world-leading products in medical as well as information technology. On the basis of international competitiveness we are planning to realize the following international collaboration.

A. Project partners in IMP

Some German and Italian expert groups are already involved in IMP after completing the same evaluation process applied to domestic participants. There are several research topics to be strengthened:

- Micro battery to cover the required energy consumption of endoscopic microcapsule;
- Active moving mechanism in human gastrointestinal tract; and
- New idea for virtual display method, etc.

B. Member of International Consulting Committee

IMC plans to get a technical support from international experts. The role of International Consulting Committee is to make a consultation for general IMP procedure and directions once or twice annually on an official contract base.

C. Job opening at IMC

IMC is searching for several foreign engineers with Ph.D. or M. S. as Post-Doc or contract-base researchers who will work at IMC together.

D. International Symposium

Annually one or two regular international symposiums on MEMS/Microsystem are being planned.

# JO-WON LEE

## *DIRECTOR*
## *THE NATIONAL PROGRAM FOR TERA-LEVEL NANODEVICES DEVELOPMENT*

## KEYNOTE ADDRESS

It is my great honor to present our tera-level nanodevice program. As the Honorable Minister Seo mentioned, this is one of Korea's 21$^{st}$ century programs.

There are two visions for this program. The first is to strengthen national competence in the nanoelectronics area. The second is to overcome technological limits imposed upon upcoming semiconductor technology.

Around the year 2010, as Duncan Moore said, we will have a worldwide computing system. That computing system should be real-time, programmable, and intelligent. To realize such a computing system, we will need a super power transistor. Such a transistor will need to have low power dissipation, tera-level memory and good high speed. For example, for real-time recognition of motion pictures, which is equal to HDTV-quality, you need 2,000 GIPS. Also, real-time translators are necessary for tera-level memory. Although we can enjoy such an intelligent system with a supercomputer, we cannot handle it by hand. That is why we need a very small system on a chip which compacts everything together. This is only possible by taking advantage of the nanotechnology.

However, nanotechnology is so broad. It covers everything from materials to DNA-based technology. Since Korea does not have enough resources to investigate the entire nanotechnology field, we have chose a few specific fields in which to concentrate our resources. Korea is very strong in semiconductor business. Therefore, we have chosen to concentrate our efforts on nanoelectronics.

Around the year 2040 we plan to have a tera-level DRAM memory. For this tera-level DRAM, the gate oxide thickness will be less than 10nm. This will be difficult to achieve. There is also a lithography problem. We do not have commercially available lithography tools to accomplish this. As I said before, Korea is very strong in DRAM memory. However, within five years we are going to have technological difficulty because we don't have what we need for the DRAM capacitor. Although TaO and BST are considered the next generation capacitor material, these materials have two problems: they have leakages and are very difficult to control.

As I mentioned earlier, we will have technological difficulties. If you thin down the gate oxide we will experience trouble with the electron tunneling. Secondly we anticipate a delay problem. Also, if we increase the integration level, we are going to have thermal dissipation. If you go down to less than 10nm gate length, we will have trouble with the conventional transistor.

So, what is the most feasible device. Based on a survey we conducted and consulting work, I chose four main areas of focus for our work. They are:

- nanoelectronics,
- spintronics,
- molecular electronics, and
- supporting work "technology."

We have already finalized all the projects through pear review and by an evaluation committee.

As I said before, around the year 2010, we are going to develop a tera-level device. With this device, we are going to make neuron devises and then we will also create new businesses based on the nano-devise such as intelligent computing system and very small pocket-size computers. We hope to create new industries and we are going to lead the new information society.

Thank you very much.

# Plenary Session I

# SUKHAN LEE

## *SENIOR VICE PRESIDENT*
## *SAMSUNG ADVANCED INSTITUTE OF TECHNOLOGY*

## MEMS

### Introduction

It is my great pleasure and honor to be here and to speak about Korean MEMS technology, especially in the presence of many distinguished leaders, scientists, and engineers in micro and nano technologies.

My talk will be composed of two parts. The first part will provide an overview of MEMS research and development in Korea, highlighting the recent progress in research and also in commercialization. I will end the first part by presenting issues involved in the industrialization of MEMS. In the second part I will propose issues and some items for research collaboration for the United States and Korea for the advancement of MEMS.

Let me begin with a brief introduction of MEMS especially as an extension of IC. MEMS enables planar 2-dimensional IC to be extended into 2.5D or 3D micro-mechanical structure where these structures have their geometric aspect ratio greater than 2:1, often reaching 100:1 or more. Furthermore, MEMS enables not only electrical but also mechanical, optical and fluid components to be constructed on a chip, and to be integrated with IC in the form of i-MEMS. This implies that MEMS extends the capability of IC in miniaturizing and integrating electrical circuits to the capability of miniaturizing and integrating not only electrical but also mechanical, optical, fluidic devices.

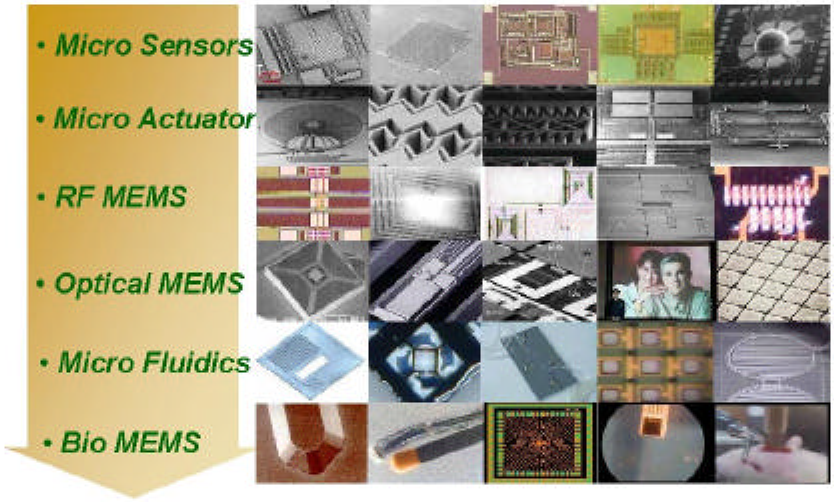
MEMS offers distinctive features such as miniaturization, batch processing and multifunctional integration. These features of MEMS provide small form factors, low power, low price and high reliability for product development. Thus, we can see MEMS widening its applications to many areas beyond traditional micro sensors and actuators to RF and optical telecommunications, bio and medical devices, chemical and pharmaceutical processes, to name only several..

### Status of MEMS R&D in Korea

With this short introduction of MEMS, I will move to the status of MEMS R&D in Korea. There has been a solid growth of MEMS R&D in Korea over the years. Statistics show that there has been a steady increase of human resources in MEMS not only in academia but also in industry and government sectors. Statistics also show that Korean MEMS is extending its application areas from micro sensors and micro actuators to RF MEMS, optical MEMS, microfluidics and bio MEMS.

Figure 1 depicts engineering prototypes produced recently in Korea. I will highlight some of these research results one by one shortly.

Figure 1. Korean MEMS R&D



I expect a continuous growth of MEMS R&D in Korea in the coming years. This growth will be fueled by two factors. First the government is willing to continue to support MEMS research in Korea. As you heard earlier, there are a variety of government research programs supporting MEMS. Not only is there the 21st century Frontier Initiatives by which the 10 year Intelligent Micro Systems National Project is funded, but there are other national initiatives that support MEMS R&D, for example the G7 MEMS initiative. The G7 MEMS initiative began seven years ago, and it has played a pivotal role to establish initially the foundation of MEMS technology in Korea.

The second factor that may fuel the growth of MEMS in Korea is that industry has now begun to look seriously into the possibility of applying MEMS to their products. For example, Daewoo has invested for almost seven years to develop a thin film micromirror array. Recently, they have successfully demonstrated a working prototype to the world community. LG is another big company in Korea and they have been actively engaged in developing optical MEMS. They have commercialized an IR sensor in the past. Recently, they have come up with a mechanically transferable reinforced jacket (MTRJ). Samsung has been successful in developing a commercial-grade micro gyroscope and a thermal inkjet head called DomeJet . The first shipment of mass produced MEMS micro gyroscope is about to take place.

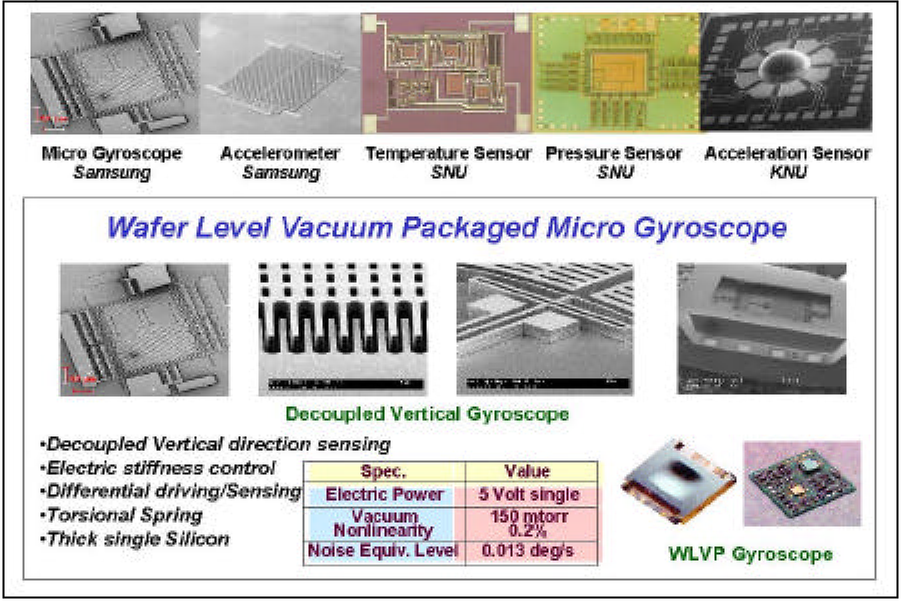
Now, I would like to report some of the recent results of MEMS R&D in Korea. Note that the list shown here represents what was available to me at the time of gathering information, and is by no means complete.

**• Micro Sensors**

First, there have been several achievements in the area of micro sensors.
They include: Micro gyroscope (Samsung), Temperature and pressure sensors (Seoul National University), Accelerometer (KyungPook National University), etc.

As an highlight, let me introduce the wafer level vacuum packaged micro gyroscope developed by Samsung. This gyroscope, shown in Figure 2, has many unique features. For instance, in order to increase the sensitivity of measurement, it was able to fabricate a high volume of moving mass based on silicon on glass and silicon on silicon technologies. Also, it features electric stiffness control of vertical vibration springs for setting an optimal operating condition under dimensional tolerances. This feature turns out to be especially useful since dimensional tolerance of MEMS is not small but rather large relative to feature size. In addition, its mechanical structure is designed in such a way that the structure for vertical direction sensing is de-coupled from the horizontal vibratory structure. A common mode electrical noise is removed out by applying differential driving to actuation.. The most critical feature, however, would be the implementation of wafer-level vacuum packaging for the micro gyroscope for mass production. We could have achieved the sensing resolution of 0.013 degree/sec of angular rate in the noise equivalent measure.

Figure 2. Micro Sensors



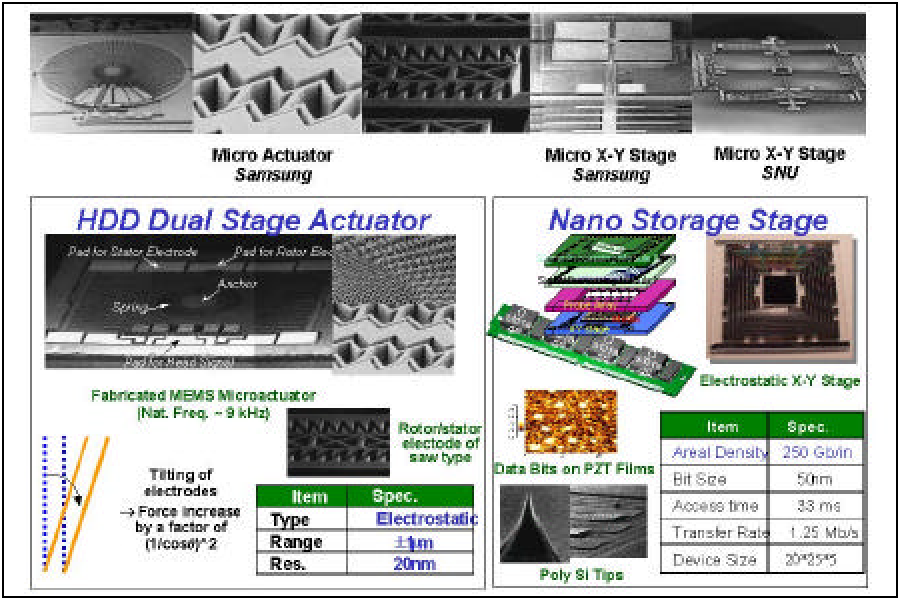
- *Decoupled Vertical direction sensing*
- *Electric stiffness control*
- *Differential driving/Sensing*
- *Torsional Spring*
- *Thick single Silicon*

| Spec. | Value |
|---|---|
| Electric Power | 5 Volt single |
| Vacuum | 150 mtorr |
| Nonlinearity | 0.2% |
| Noise Equiv. Level | 0.013 deg/s |

## Micro Actuators

Figure 3 shows a micro electrostatic XY stages developed at SAIT and at Seoul National University. The key issue in the design of micro actuators may be the achievement of a high force to volume ratio while maintaining the displacement range as large as possible. In other words, the achievement of a maximum power to volume ratio. It is discovered at SAIT that, in designing electrostatic actuators, we may increase the force an order of magnitude higher for a given displacement range by arranging the layout of rotors and stators optimally. Figure 3 depicts the optimal rotor-stator arrangement for a disc type electrostatic actuator. If we slant a pair of rotor-stator pairs while keeping the gap between them at their bottom constant, the horizontal displacement of rotor movement remains same. But the electrostatic force between the rotor-stator pair increases inversely proportional to the square of cos ($\theta$) with $\theta$ denoting the slanted angle. Based on this observation, we can design an optimal geometric layout of rotor-stator pairs on a disc. It turns out that the optimal layout of rotor-stator pairs on a disc results in a collection of a spiral form of rotor-stator pairs, as shown in Fig. 3. However, in order to compensate for weaker stiffness of a spiral form of actuator, we choose to use a saw-tooth form instead, which is equivalent to a spiral form, as the final geometry. The implementation of a rotary type electrostatic actuator based on the saw-tooth design provides us with the actuator force more than four (up to ten) times larger than what can be achieved from the conventional linear geometry. The force provided by the designed actuator is good enough to drive a HDD secondary stage actuator requiring a high band width.

Figure 3. Micro Actuators



| Item | Spec. |
|---|---|
| Type | Electrostatic |
| Range | ±1μm |
| Res. | 20nm |

| Item | Spec. |
|---|---|
| Areal Density | 250 Gb/in |
| Bit Size | 50nm |
| Access time | 33 ms |
| Transfer Rate | 1.25 Mb/s |
| Device Size | 20*25*5 |

The same design principle can be applied to the design of electrostatic XY stage, which we have been developing for nano storage devices. For application to nano-scale reading and writing, we have also been developing a piezo cantilever SPM probe with a very sharp poly-Si tip. The unique feature of our SPM tip may be in the monolithic probe fabrication process, where we do not need to provide an extra protection of tip during the process, resulting in a tip with sharper tip curvature and longer tip length.

**RF MEMS :** RF MEMS is becoming more and more important, as an alternative to such conventional RF components as RF switches, filters, VCOs, antennas, passive RF components like inductors. Some of the recent R&D results in this area include high Q inductors (LG), MEMS cavity based VCO module (Samsung), Integrated IF filter (Samsung), Micro relays (SNU), Resonator filter (SNU), Micro Transformer (KNU), to name several.

Figure 4. RF MEMS

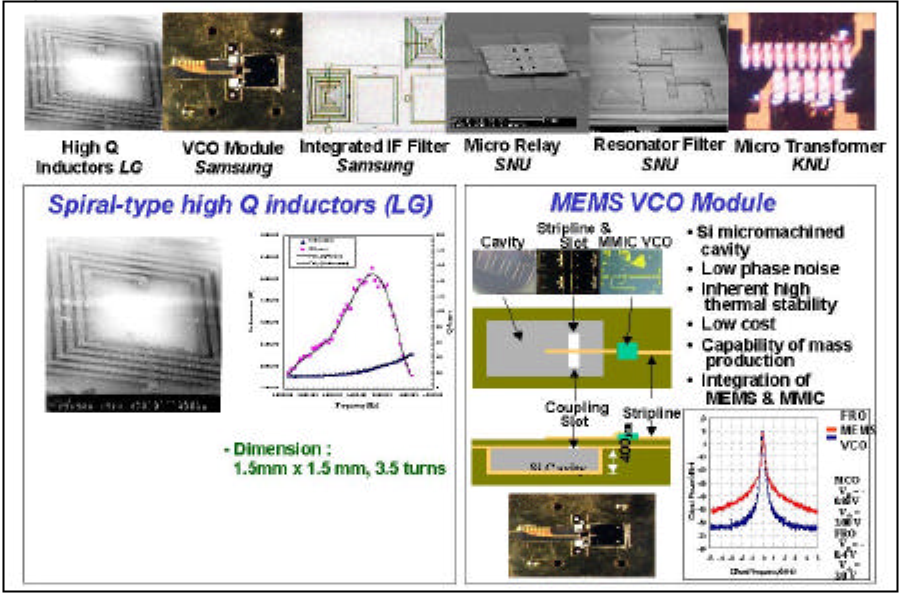


Figure 4 shows a suspended type of micro inductor. This technology can be essential for establishing the analog-digital integration required for a system-on-a-chip in RF devices. The MEMS VCO module shown in Fig. 4 uses a small micro cavity as a resonator that is integrated with an oscillator to have very high Q. This approach has originally been developed at the University of Michigan, but SAIT has expanded the approach and manufactured into a complete system to demonstrate a working prototype.

**Optical MEMS:** Optical MEMS has emerged as a hot enabling technology for optical networks, especially, for all-optical network infrastructure. As such, Micro optical mirrors have been popular in Korean MEMS R&D community. For instance, Daewoo has developed a working prototype of thin film micro mirror array (TMA), and applied it to a large screen projection displays . Samsung and LG have developed their own micro mirror arrays, although different in approach from Daewoo's piezo actuator based analog mode of operation. For one thing, the 7 years or so history of the development of Daewoo's TMA indicates the importance of robust design for the early success of complicated MEMS devices like TMA. In fact, the design of TMA made use of so called Axiomatic Design Principle to reach the final successful prototype after a few initial failures.

**Micro Fluidics:** With the perspective of commercial significance of MEMS fluidic devices, Korean MEMS community has geared its R&D activities in this area too. Examples include the micro cooling systems by Samsung, micro valves and PDMS based micro fluidic control channels by Seoul National University, and micro pumps by ETRI and KNU.

The PDMS based micro fluidic channels is based on PDMS plastic molding technology together with hydrophobic surface treatment to make flow of fuide discontinuous.

Figure 5. Micro Fluidics

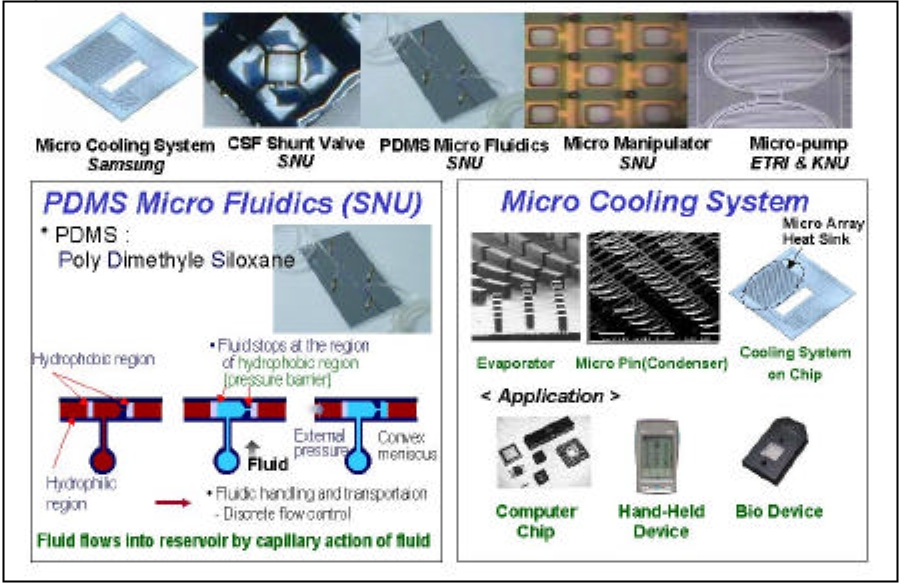
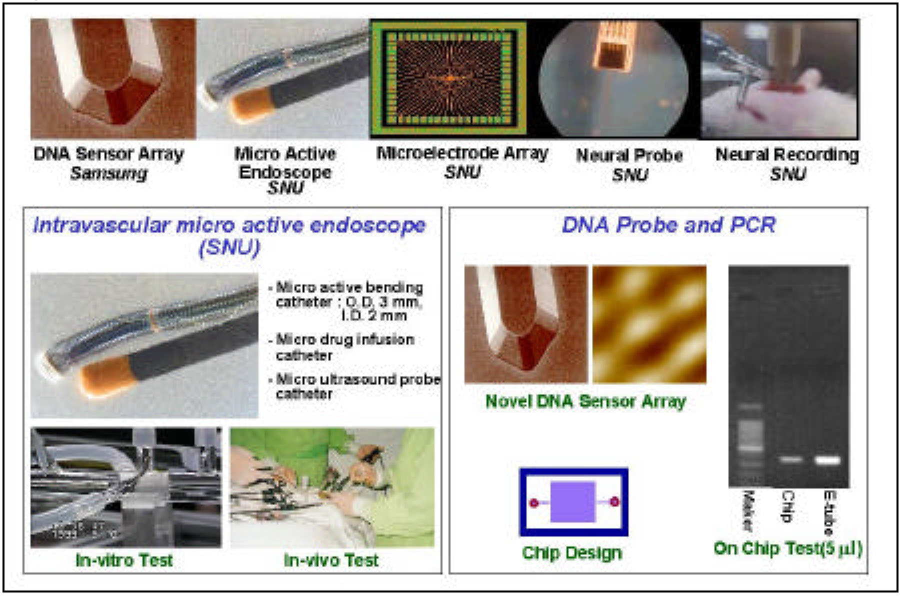


Figure 5 shows a CPL (Capillary Pumped Loop) based micro cooling system developed at SAIT. This micro cooling system has an evaporator with micro wick structure and a condenser, connected by flexible tubes. The 2.5D wick structure inside the evaporator is designed in such a way that it can make a good balance between capillary force and flow resistance. To increase the efficiency of condenser, a dense array of flexible micro fin is fabricated on its surface. These fins can vibrate by, even, a small amount of air movement, so as to remove out the boundary layer that blocks heat dissipation to the air.

**Bio MEMS:** The main activity of bio mems R&D in Korea is centered around DNA chips and biomedical applications. For instance, SAIT is developing a DNA chip based on micro reactors. The unique feature of SAIT DNA chip is the development of a SPM probe tip with MOSFET fabricated at the end of the probe tip, as shown in Fig. 6. Such a tip is capable of detecting small amount of charge, e.g., the charges associated with individual DNA bases. Another example shown in Fig. 6 is an intravascular micro active endoscope developed by SNU.

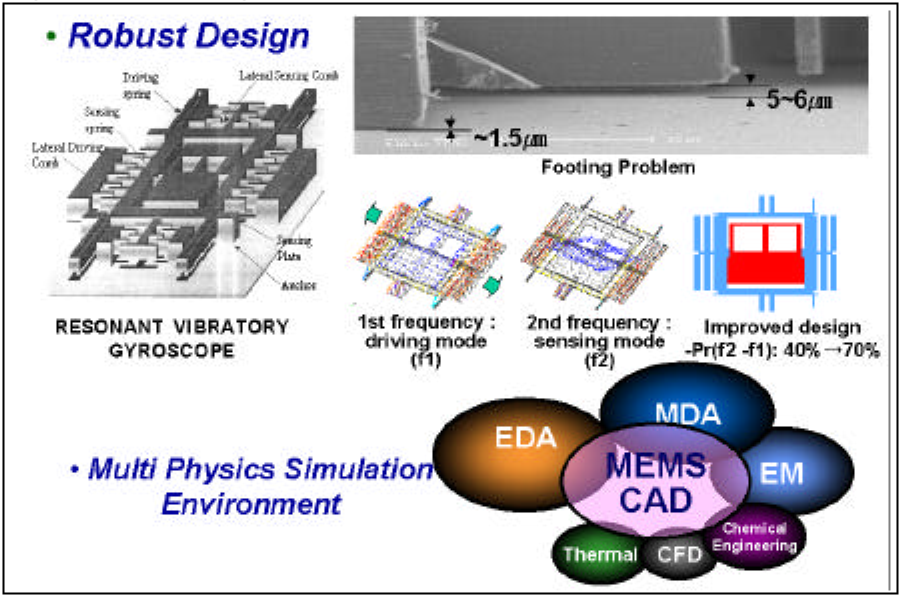
Figure 6. Bio MEMS



**MEMS Infrastructure:** MEMS fabrication and design facilities available in Korea include the facilities in SNU, in POSTEC, and in companies like Samsung, and LG. In particular, POSTEC has a synchrotron with a beam line dedicated to LIGA processing. In general, MEMS facilities in Korea offer capabilities of bulk micromachining, surface micromachining, deep etching, bonding, electro-forming, LIGA and LIGA-like, wafer-level packaging, etc. However, we need to pay attention to the fact that there exist certain pressures from the increasing demand of fabrication as well as design service facilities due to the increase of interest in MEMS from academia as well as from industry.

At this moment, I feel like to emphasize the importance of MEMS design for overall success of MEMS product development. As you may know, MEMS is not a precise machinery, but rather a crude machinery, considering the relative ratio between size and tolerance. One of the ways to handle this situation is through the application of robust design to MEMS. As shown in Figure 7, in the development of micro gyroscope, we initially suffered from low S/N ratio and yield due to fabrication tolerances and external disturbances. More specifically, the difference of the first mode of natural frequency between the actuation and the sensing mechanisms should be within certain range for maximum detection sensitivity. However, fabrication tolerances affect these frequencies in such a way that only low percentage of sensors in mass production could pass the given specification, resulting in low yield. We has applied robust design technology to the modification of the design, and we found that the yield has risen from 40% to 70%.

Figure 7. MEMS Design



The other issue of MEMS design that needs to be addressed is the capability of integrating multi-physics simulation and measurement environments with design tools. Understanding of physics involved in MEMS needs measuring and modeling of a system integrated with electrical, mechanical, fluidics, physics, and chemical principles, but there still remains a lot to do for the advancement in this areas.

## Vision of MEMS for the future and conclusion

MEMS can play key roles for on-going information and bio revolution. For instance, it can provide key technologies for wireless and mobile communication, optical network infrastructure, wearable computing devices, and digital automation and entertainment apparatus. As an enabling technology, it can be integrated with bio and nano technologies to provide tools for analysis, sensing, and fabrication for bio and nano systems.

Novel ideas of MEMS applications as well as robust design of MEMS seem important for the success of commercialization. Understanding of MEMS in terms of multi-physics simulation is rather essential for MEMS design. In terms of fabrication, it is good to see the increase of the number of foundry services throughout the world, including Korea. Since there will be much more competition in performance-cost measure for MEMS products, cost-effective MEMS fabrication technologies, including the use of new materials such as polymers, will be taken more seriously in the coming years.

# KENSALL D. WISE

## *J. REID AND POLLY ANDERSON PROFESSOR OF ELECTRICAL ENGINEERING AND COMPUTER SCIENCE AND*

## *DIRECTOR,*

## *NSF ENGINEERING RESEARCH CENTER FOR WIRELESS INTEGRATED MICROSYSTEMS*

## MICROELECTROMECHANICAL SYSTEMS: INTERFACING ELECTRONICS TO A NON-ELECTRONIC WORLD

Thank you very much. It is a real honor for me to be here and take the next few minutes to talk about the field of microelectromechanical systems (MEMS). I will try to do it from the standpoint of the United States, although a lot of the examples I will give are from the University of Michigan.

Wireless integrated microsystems, the title of our new NSF engineering research center at the University of Michigan, is an area that is going to grow tremendously over the coming decade. It is the area at Michigan into which we are going to put a considerable investment. I think it very closely mirrors the Korean activity in the MEMS area. Therefore, there is a tremendous opportunity to interact between the program at Michigan and the program in Korea. We would invite that cooperation and look for opportunities to cooperate.

I am going to talk about microsystems. This name has evolved. It used to be integrated sensors and then MEMS. From our view, we mean sensors and microactuators merged with electronics. It really needs to be micropower electronics, not all monolithic but at least on a common substrate. The three critical elements of our program at Michigan are MEMS, micropower electronics and wireless communication.

We are talking about putting the whole first-level control loop in a single module called a microsystem. A microsystem will have nano-scale components within it.

Micromachining started at Bell Labs about 40 years ago, and it has evolved and found major application in the microsensors area. It is amazing to me what you can do today with bulk micromachining. Ten years ago we would not have believed that you could fabricate structures like we can today using high-aspect-ratio bulk etching.

Surface micromachining is the other half of the coin. Figure 1 is an example taken from Clark Nguyen's work at University of Michigan. It almost seems like we are regressing, because now instead of using electronic circuit elements, we are using micromechanical components. In order to integrate the entire front-end of a communications transceiver on a single chip, you have to do something about power and you have to do something about size. This device does both. The microresonator is only 20µm across, and the entire device would fit in a cross-section of a human hair. The resonant frequencies are now over 100MHz. They will be going over a GHz very soon. This is one area that I know of in MEMS which today is really NEMS—it is really nano; it is submicron. The gaps in the figure are less than 0.1µm across and the dimensions of the coupling springs are all microns in size. These microresonators are undercut, double-end clamped beams that resonate at a given frequency and can be coupled together in the equivalent of electronic circuits. You can get very sharp bandpass characteristics out of these little mechanical vibrators. There is almost no power to drive these electrostatically, almost no size, and you can fabricate them right on top of a normal chip.

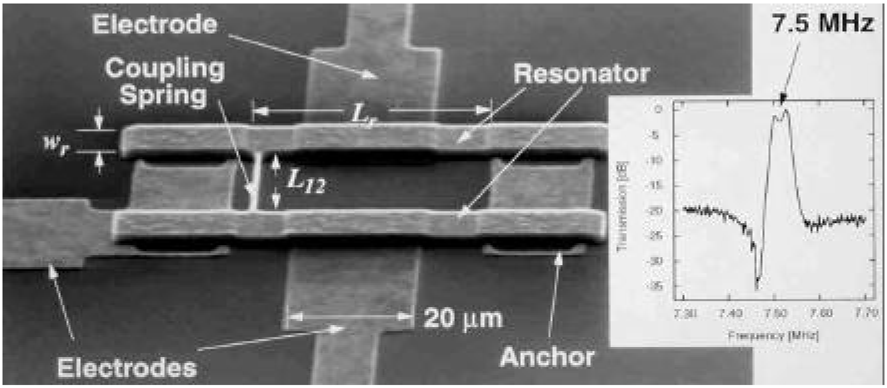


Figure 1: A surface-micromachined microresonator for telecommunications applications. *(Courtesy of Clark Nguyen, University of Michigan).*

There are many applications for these technologies. For example: inkjet print heads, high-density disk drives, and micromirrors. Many other things will come to pass. We are very excited about this technology, particularly as you join the three critical components together: micropower electronics, wireless communications, and MEMS.

I will give you several examples. I have picked the first one from something we have been working on for a long time at the University of Michigan and that is biotechnology. Biotechnology in MEMS is fairly new. Figure 2 depicts, arguably, the first micromachined silicon device that was ever fabricated: a neural probe capable of interfacing with the nervous system at the cellular level. The superimposed view of the earth shown in the background represents the diameter of a human hair at roughly the same magnification as the probe. These probes have been fabricated down to widths of about 5µm. There is clearly the need to go smaller, simply because what you would like to do is to get things into the cellular system that are so small that the cell doesn't know are there. There is a real drive to get these even smaller than they are today. They are formed from materials that electrical engineers know very well, Si,, $SiO_2$, $SiN_x$ and poly-Si and Ir, which helps couple to the tissue.

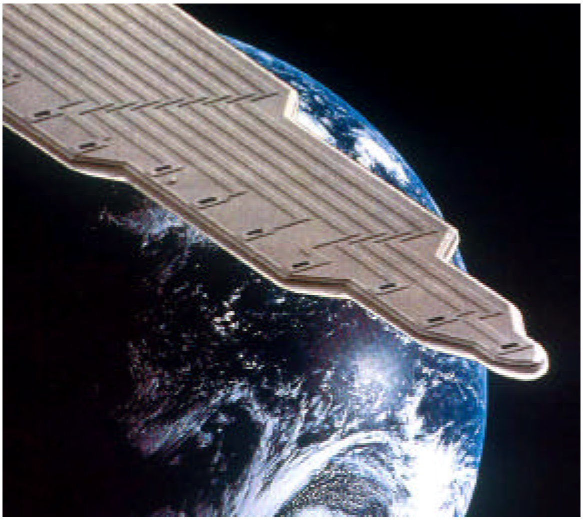
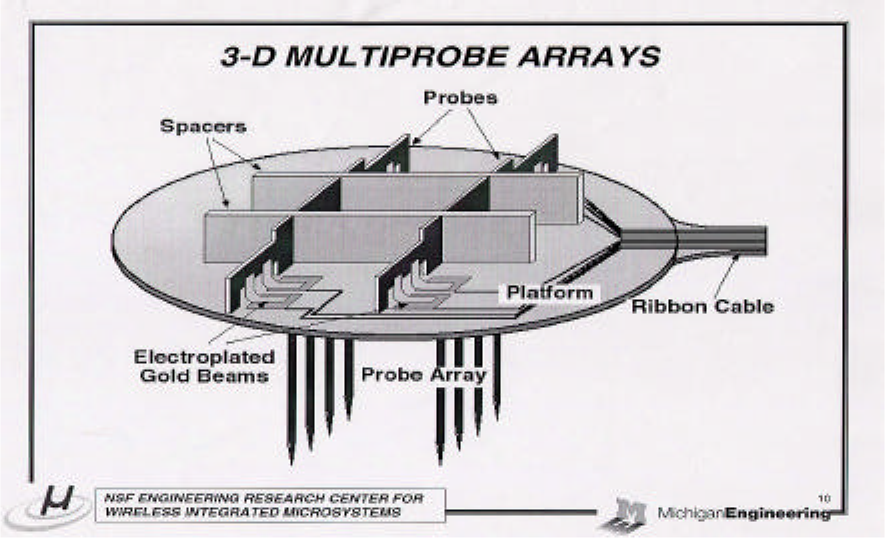


Figure 2: A silicon micromachined probe for recording from individual cells in the central nervous system.

These are some of the few devices that I know of that can be put into tissue and left there for periods of years and which will interface at the cellular level. They come in a variety of shapes and sizes and, by clustering sites around, you can actually do triangulation on where the active cells are located. We would like to know how things are wired and how they work. These types of structures are opening-up that area.

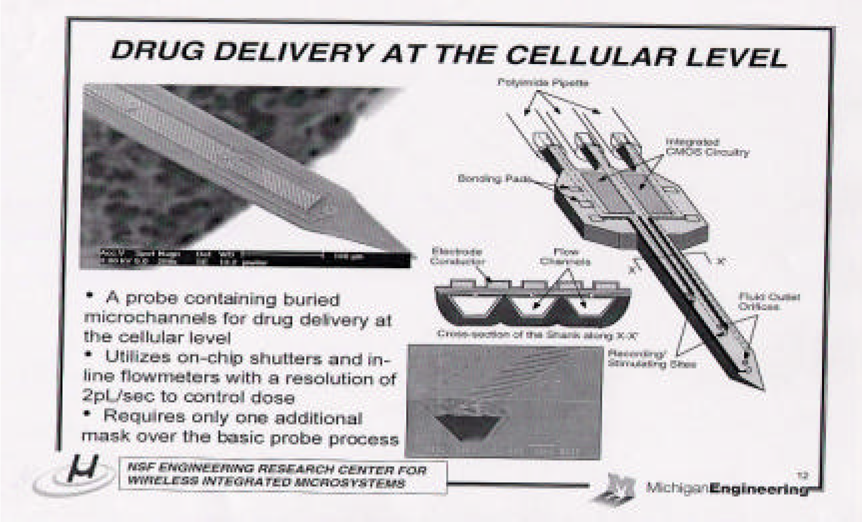
We would also like to be able to couple many sites as possible to a very few output leads and then interface those via RF telemetry to the outside world. That is being done, and they can be put together in three-dimensional arrays. This work gets into microtools and microassembly. Eventually you will have multiprobe arrays as shown in Figure 3 which will be the size of a shirt button and will include telemetry to the outside world but will allow an interface at the cellular level over long periods of time.



3-D MULTIPROBE ARRAYS

Figure 3: multiprobe array

Figure 4 is an example of a probe where we have flow channels embedded in the probe substrate. On the back of the structure are not only circuitry but also things like microvalves, micropumps, and microflowmeters. We have not done the pumps and valves yet, but we have done the flowmeters and the channels and the shutters over the orifices. The resolution required for the accurate control over drugs injected at the cellular level is about 2pL/sec. It is an interesting challenge.



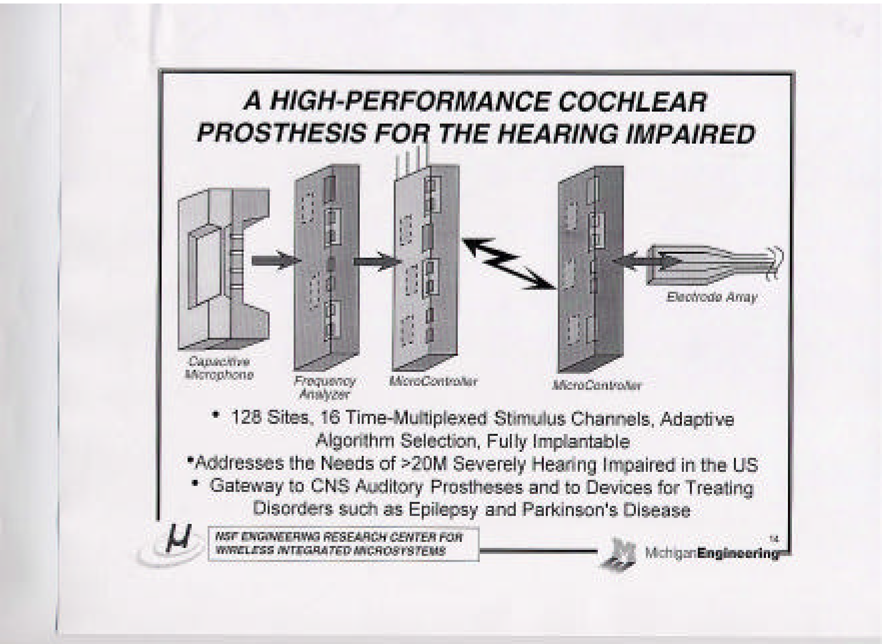
DRUG DELIVERY AT THE CELLULAR LEVEL

- A probe containing buried microchannels for drug delivery at the cellular level
- Utilizes on-chip shutters and in-line flowmeters with a resolution of 2pL/sec to control dose
- Requires only one additional mask over the basic probe process

Figure 4: Probe with flow channels embedded in the probe substrate

At the Center, as a first example of microsystem technology, we are working on a second-generation cochlear implant for the profoundly deaf. These are systems that are aimed at wiring around the hair cells of the inner-ear, the cochlea, and directly stimulating the auditory nerve that goes back to higher levels of the auditory system. This microsystem will have a capacitive microphone, a micromechanical frequency analyzer, a state of the art microcontroller, and an integrated multisite electrode array. We are looking at the feasibility of a totally implantable system. This system is also a gateway not only to central nervous system auditory implants but also into devices for treating disorders such as epilepsy and Parkinson's disease. These devices will detect the start of seizures at the cellular level and will then electrically or chemically suppress the discharge at that level while the seizure is still invisible to the host.

Figure 5 depicts a full DNA analyzer on a chip from the work of Carlos Mastrangelo and Mark Burns at Michigan. There are two ports for the entry of enzymes and DNA samples. They are wicked into the microchannels. They are valved, incubated thermally, and electrophoretically separated; there is an electronic readout that reads out the various samples. This kind of technology is going to put biotechnology in the doctor's office.



**A HIGH-PERFORMANCE COCHLEAR PROSTHESIS FOR THE HEARING IMPAIRED**

- 128 Sites, 16 Time-Multiplexed Stimulus Channels, Adaptive Algorithm Selection, Fully Implantable
- Addresses the Needs of >20M Severely Hearing Impaired in the US
- Gateway to CNS Auditory Prostheses and to Devices for Treating Disorders such as Epilepsy and Parkinson's Disease

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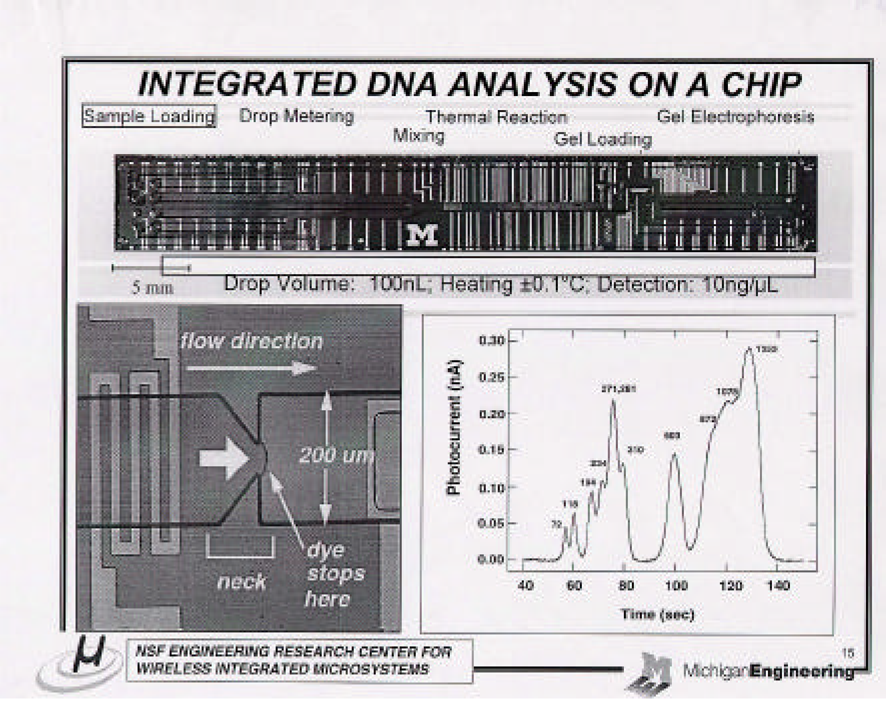
Figure 5: full DNA analyzer on a chip

A few other important areas are:

- Integrated pressure sensors, which are very important in automotive circles and also in medicine;
- vacuum packaging at the wafer level is a hot topic in MEMS in both Korea and the U.S.;
- thermopheumatically-operated gas flow controllers;
- surface-micomachined microaccelerometers and high-mass accelerometers formed using deep reactive-ion etching; and
- integrated ring gyros for inertial position sensing.

Figure 6 is the first reported ring gyro developed in conjunction with General Motors at Michigan. It is a Ni electoplated ring. Figure 6 also shows a second-generation all-Si ring gyro built on a poly-refilled trench technology. Its sensitivity and resolution have come down two orders of magnitude.

The Honeywell microbolometer will be familiar to many of you. It is really a paradigm shift in infrared imaging because it is done at room temperature. By doing it at room temperature, you open up all kinds of commercial applications. And also in the optics area, all good projectors use micromirrors! TI worked on theirs with DARPA support for a decade or more. It was a very long process. It is electrostatically controlled and very effective today.



**INTEGRATED DNA ANALYSIS ON A CHIP**

Sample Loading
Drop Metering
Mixing
Thermal Reaction
Gel Loading
Gel Electrophoresis

Drop Volume: 100nL; Heating ±0.1°C; Detection: 10ng/µL

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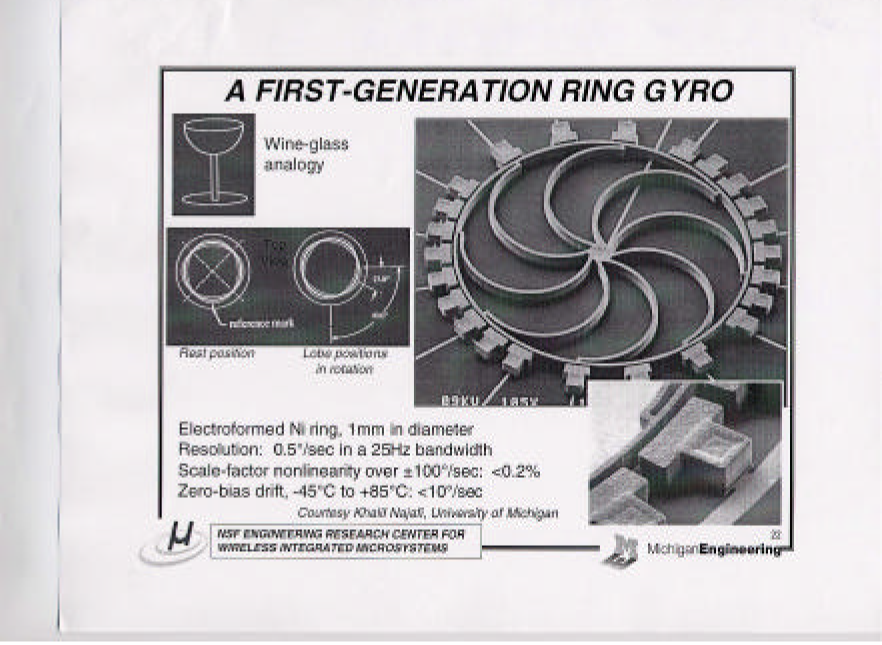
Figure 6

The emerging microsystems that we see in the future are the size of a sugar cube or wristwatch. They are wearable or you can throw them out in the field and take measurements. Power is the arch-enemy of all these systems. The power source controls the size of the module along with its communication range and lifetime. We are looking at small modular information-gathering and control nodes communicating into larger networks and featuring:

- micropower operation (0.1-1mW)=> long operating life;
- small size (1-5cc) and modular;
- high accuracy (to 16b) multi-parameter sensing/actuation;
- self-testing, programmable, and digitally-compensated;
- bi-directional wireless interface (0.1-1km);
- standardized internal/external protocols;
- reliable hermetic wafer-level packaging;
- rapidly configurable and reconfigurable;
- customized in software and by transducer selection; and
- low cost and pervasive.

We see a common platform with something that is serviced by the device depicted in Figure 7. You have a number of microinstruments out on the front end and then you have a microcontroller, wireless link, and some kind of power source. This is really the blueprint for a generic microsystem. In our case, one of the test beds under the new NSF Center is the cochlear prosthesis; the other one is an environmental monitor.



## A FIRST-GENERATION RING GYRO

Electroformed Ni ring, 1mm in diameter
Resolution: 0.5°/sec in a 25Hz bandwidth
Scale-factor nonlinearity over ±100°/sec: <0.2%
Zero-bias drift, -45°C to +85°C: <10°/sec

*Courtesy Khalil Najafi, University of Michigan*

Figure 7

All sensors really need to be capacitive otherwise they draw excessive current. You can read out a capacitive transducer in 10 microseconds, and that isn't very much energy even including the readout electronics. We are aiming at developing a full micro gas chromatograph targeting the top 45 EPA air toxics. The vapor concentration range will be from 10-100ppb with 1000-fold change in volatilities, and we want to do it in 1cc at less the 1mW. That is a big challenge. If you can do that, you can measure chemical constituents all over the place and be transparent to the user. The environmental monitor is also targeted at widespread distributed monitoring of environmental parameters including global change.

Transceivers may be micromechanical in the future. We are exploring a full micromechanical front-end. Everything from the antenna right down to baseband.

We have seen lots of generations of products in electronics. I would say if we could look back at the 21$^{st}$ century, 100 years from now, and ask what were the most significant developments, clearly nano systems and microsystems are going to be there someplace. We don't know where it is going to lead us, but it will be exciting. These little sugar cubes are going to sit out everywhere and they are going to monitor the environment that they are in, whatever that is. They are going to form a bridge between electronics and the nonelectronic world, including the cellular world of bio- and nano-technology.

In conclusion, MEMS is allowing the development of a wide range of devices and microstructures, including pressure sensors, accelerometers, gyros, tactile imagers, microvalves, microflow controllers, and other devices. MEMS technology offers a variety of approaches to creating many microstructures, and the process tool base is improving along with the availability of foundry facilities capable of assisting large and small companies alike. A wide variety of MEMS applications are being pursued. Many are potentially high in volume and will open important new areas to microelectronics. Microsystems involving micropower electronics, wireless interfaces, advanced packaging, and embedded microinstruments promise to be pervasive in a variety of these applications. There are a rich array of problems yet to be solved, and the field is still young enough to be highly innovative. The breadth of opportunities probably even exceeds that offered by microelectronics at a similar state of development some 30 years ago.

Thank you very much.

# HENRY I. SMITH

## *KEITHLEY PROFESSOR OF ELECTRICAL ENGINEERING, MASSACHUSETTS INSTITUTE OF TECHNOLOGY*

## THE ROLE OF LITHOGRAPHY AND THE PLANAR PROCESS

In order to create relief structures or other forms of patterning on a substrate, one exposes a radiation-sensitive polymer—a resist—to some pattern of radiation. The pattern is then developed, and transferred by etching, growth, doping or liftoff. The planar process is the basis for the electronics revolution. Today I will speak about what I see as the role of the planar process in the nanotechnology revolution. I will make some distinctions between what is done in the semiconductor industry, what is done in nanostructure research, and what may be done in the future.

The lithography process can be carried out in several ways. It can be done with a scanned beam of electrons, ions, or photons. One can also project images with any one of these particles. One can also utilize proximity-printing schemes with any one of these particles.

There is still another process of lithography which turns out to be conceptually very simple: interference lithography. In practice it is not so simple to carry out. Interference lithography plays a very fundamental role in metrology for the nano domain. Interference lithography depends upon overlapping plane waves of ultraviolet light. Where the beams overlap a standing wave is produced. This standing wave can be used as a radiation pattern to expose a radiation-sensitive film.

Figure 1 depicts a human hair in cross-section along with a 1-micron scale marker. On this same scale, the surface-acoustic-wave (SAW) devices that were being fabricated back in 1973 are depicted. SAW devices were well ahead of the semiconductor industry at that time. On the left of Figure 1 is a neuron from inside the human brain.

Figure 1

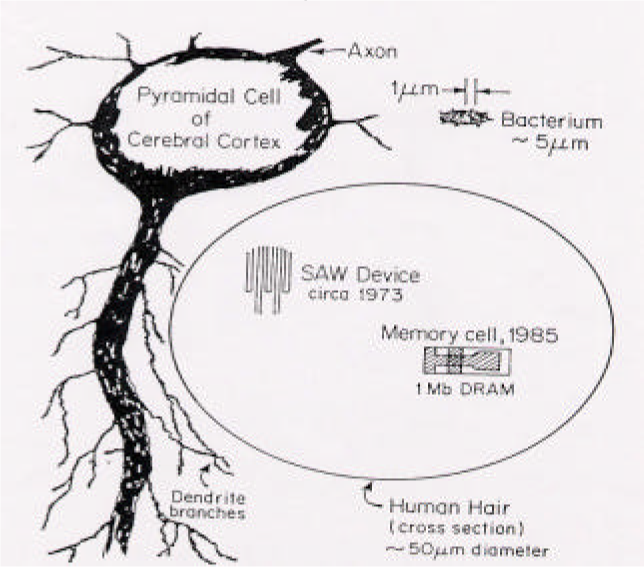
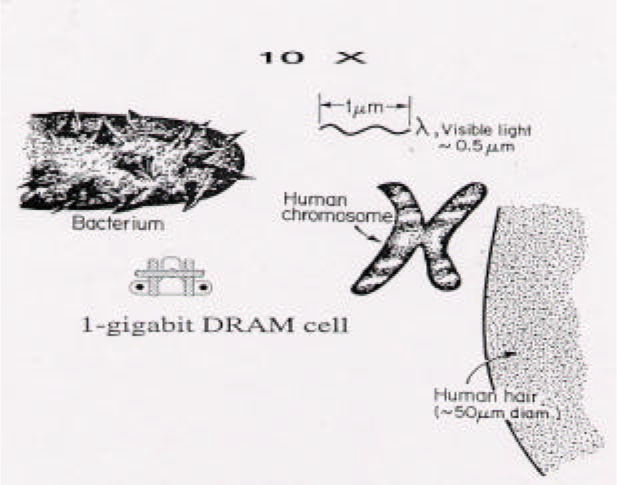


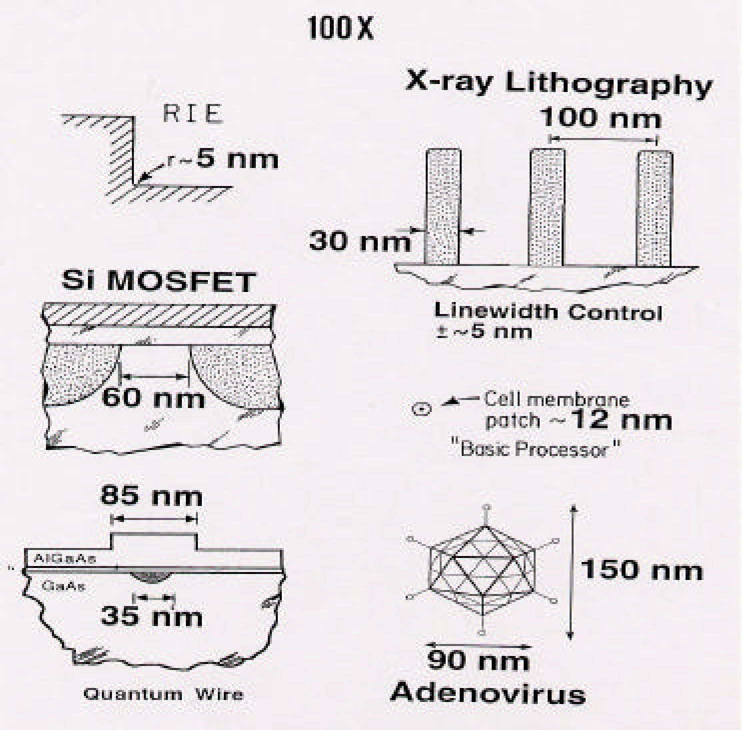
Figure 2 shows a magnification by a factor of 10 so that the wavelength of visible light looks like that shown, the human chromosome is on a scale similar to a 1-gigabit DRAM cell, which is also shown in figure 2.

Figure 2



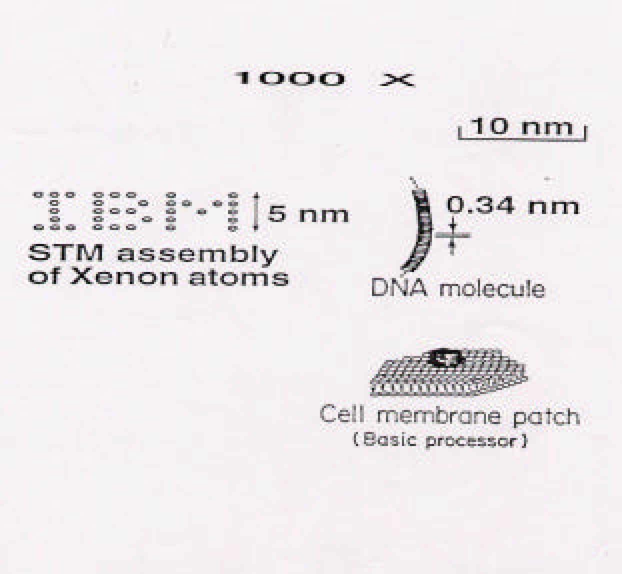
Magnifying by another factor of 10 gets us into the domain of the practical limits of the lithographic process. Figure 3 depicts some lithography results with x-ray lithography, various kinds of short-channel and quantum-effect devices that we have made in my group many years ago. The bottom right shows the approximate scale of the Adenovirus.

Figure 3



Another factor of 10 enlargement brings us to the true nanometer domain, which is actually beyond the range of the lithographic process as we know it. One of the points I hope to make today is the necessity of making a bridge between the limits of the lithographic process and the domain of the macro molecules, which is the true nanometer domain. In this domain, the biological systems have developed highly effective nano structures. One example is shown in Figure 4, a protein molecule sticking through the bilipid layer of a cell membrane. The role of this protein molecule is to act as a switch to either allow or disallow the passage of an ion from one side of the membrane to the other side.

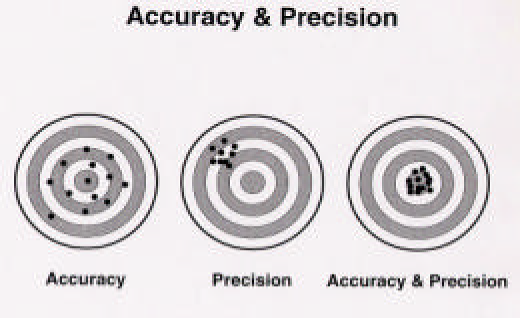
Figure 4



There are many industries and applications beyond the silicon semiconductor industry that utilize, or will utilize, 100 nm and sub-100 nm lithography. Some of these are:

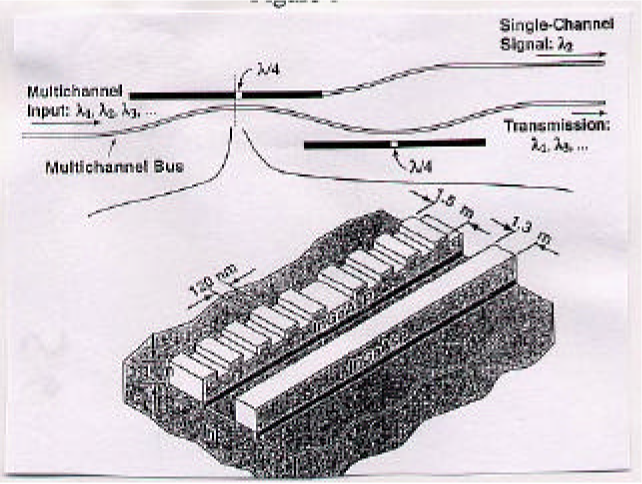
- Non-silicon semiconductors
- molecular electronics (research)
- optical communications (integrated optics)
- microphotonics
- magnetic information storage (e.g. MRAM)
- quantum-effect electronics
- biological research
- MEMS (microsystems)

Figure 5



In figure 5 the difference between accuracy and precision is illustrated. Integrated optical devices are an example of an application that requires accuracy and precision at the nanometer level. Figure 6 depicts an integrated optical device that we have developed called the channel-dropping filter. A surface waveguide carries a variety of different optical channels each of a different wavelength. When the waveguide is brought close to the grating, which is a resonant structure, wavelength lambda 2 is coupled into the upper guide, while wavelengths lambda 1 and lambda 3 continue to propagate on the bus. This is because lambda 1 and 3 do not phase match to the resonant structure. The device therefore drops lambda 2 into the upper guide for reception.

Figure 6



The device can also be used to add a channel; hence it is called a channel add/drop filter. This is an essential component in any complex optical communication system based on wavelength-division multiplexing. Today, optical communication systems are based largely on fibers. Ultimately, the real revolution will take place when optical systems are integrated on a chip, in much the same way that the real revolution in semiconductor electronics occurred when circuits were integrated on a chip.

Figure 7

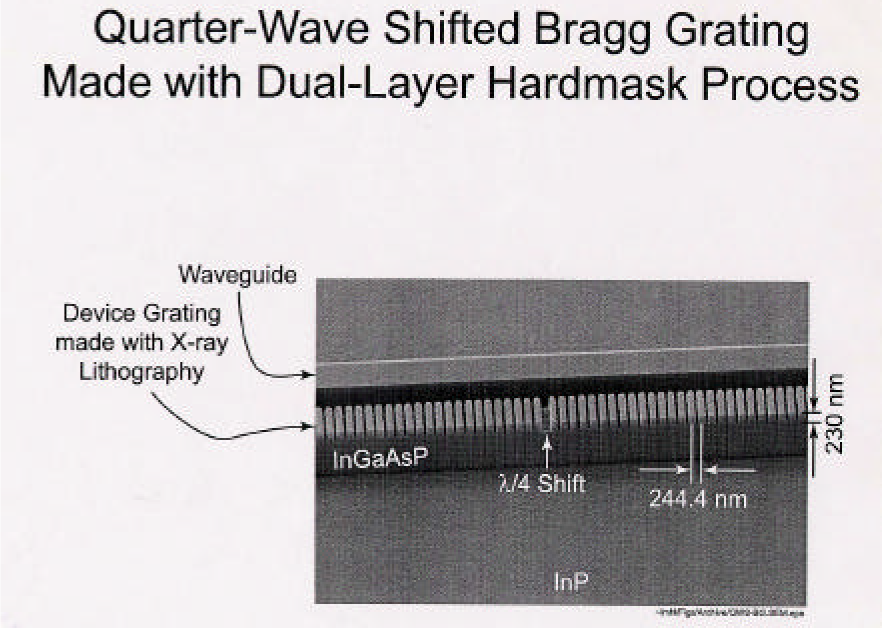
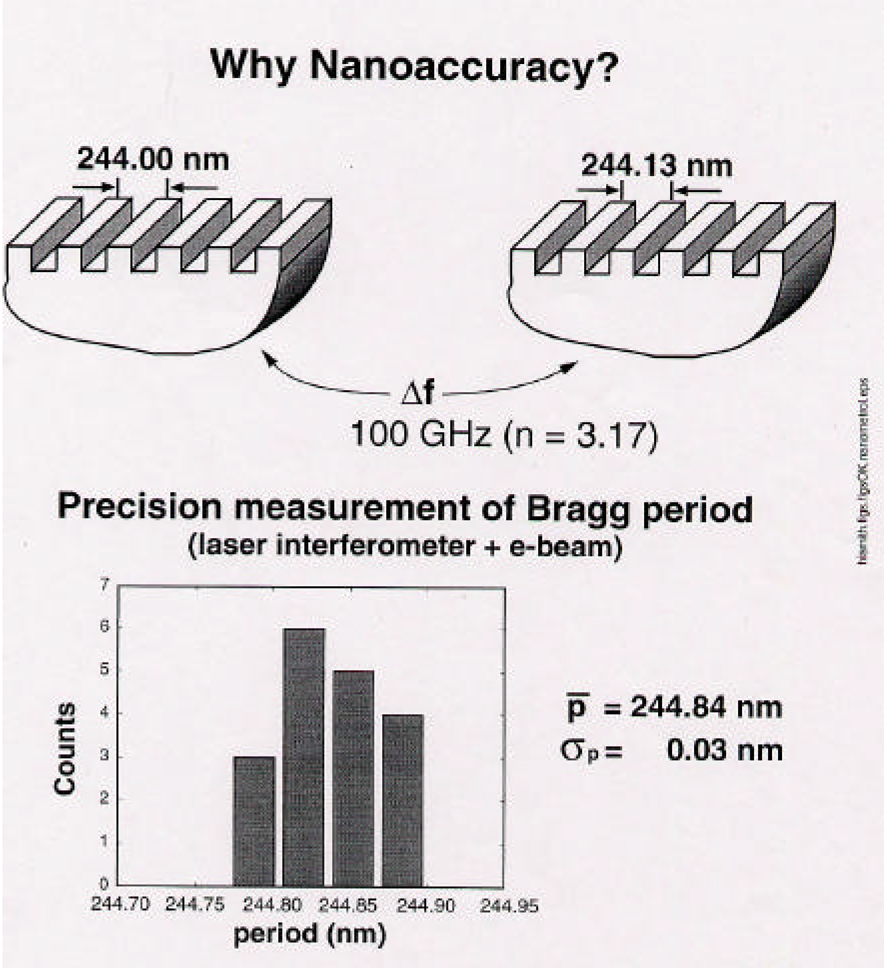

Quarter-Wave Shifted Bragg Grating Made with Dual-Layer Hardmask Process

Figure 7 is a micrograph of a portion of such a channel-dropping filter showing the waveguide and grating structure. Notice the quarter-wave phase step in the grating which makes it into a true resonant structure.

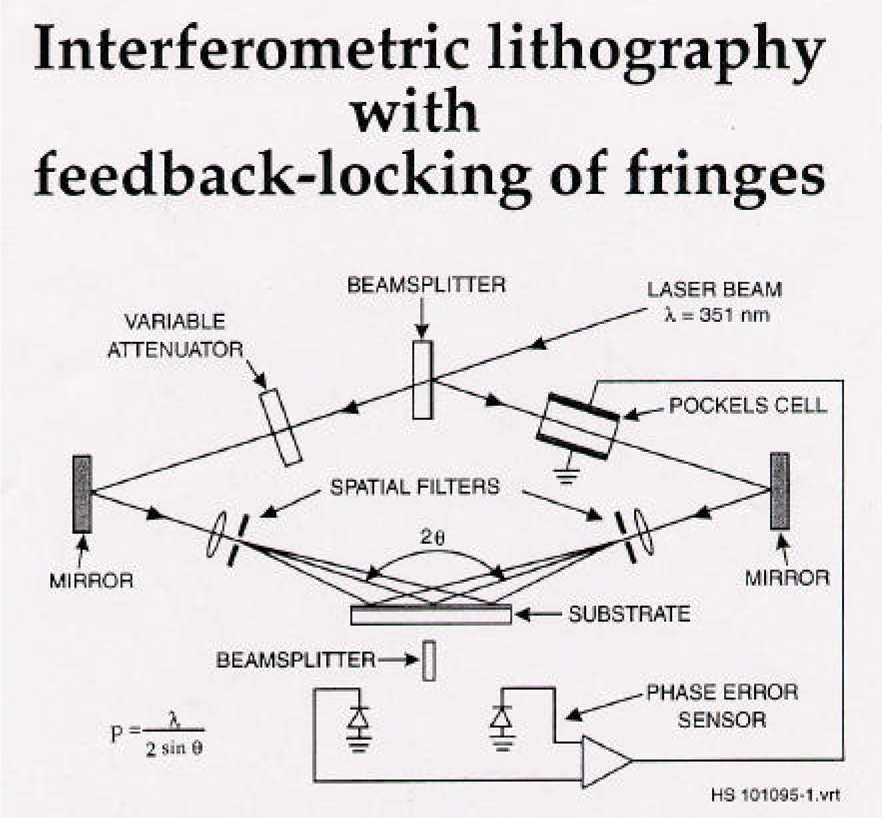
Figure 8 is an interesting way of demonstrating nanoaccuracy. If the medium of the waveguide has an index refraction of 3.17, which is not unusual, the spatial periodicity of the resonant structure is about 244.00nm. If one were to make another resonant structure with a spatial periodicity that differs from this by only 0.13 nm, the difference in resonant frequency would be 100 GHz. In order to apply nanotechnology to fabricate integrated-optical devices, we have to have this kind of control. The good news is that we know how to measure spatial periodicities. Actually we can measure them with standard deviations of 0.03 nm.

Figure 8



Achieving nanoaccuracy depends upon the technique called interferometric lithography. Figure 9 is a diagram of the system in our lab. Spherical waves of large radius are overlapped to produce a standing wave. Also shown is a feedback system to ensure absolute stability of the fringe pattern in time.

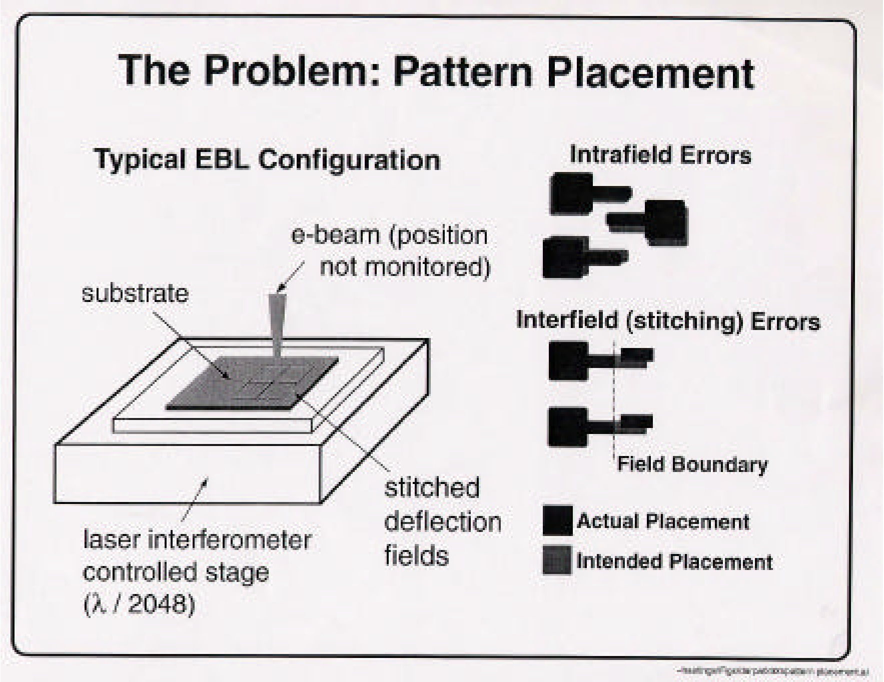
Figure 9



Over the past 25 years we have put in a great deal of effort perfecting the technology of interference lithography because we consider it an essential element of engineering in the nanometer domain. We have a variety of different types of systems. One important role of interference lithography is as a metrological tool, as illustrated in the next two graphics.

Figure 10 depicts a problem in the technique of scanning electron-beam lithography: the placement of features is often far removed from their intended positions. This is called pattern placement error. In the electron-beam systems, although the resolution is very high, the accuracy of placement is poor, often much worse than the resolution.

Figure 10



## The Problem: Pattern Placement

**Typical EBL Configuration**

**Intrafield Errors**

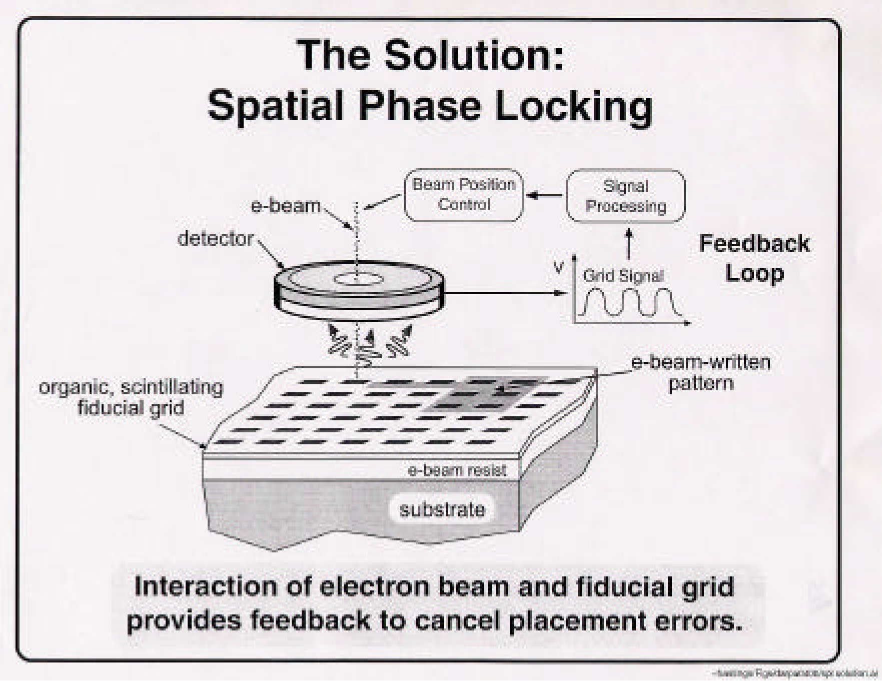
**Interfield (stitching) Errors**

■ **Actual Placement**

▨ **Intended Placement**

We are pursuing an idea we call spatial-phase-locking for solving this problem. The idea is depicted in Fig. 11. A substrate, coated with an electron beam resist, is additionally coated with a polymer film in which we have created a grid in a scintillating material. The grid is created by bleaching the material with UV interference lithography. This grid has the property of long-range spatial-phase coherence. In addition, we make the grid with accuracy and precision. The electron beam, scanning along, gives rise to an optical signal as it traverses the periodic scintillating grid. The periodic signal, in conjunction with appropriate signal processing, is used to control the position of the beam in a feedback loop. The feedback loop and the template produced by interferometric lithography ensures the accuracy of pattern placement.

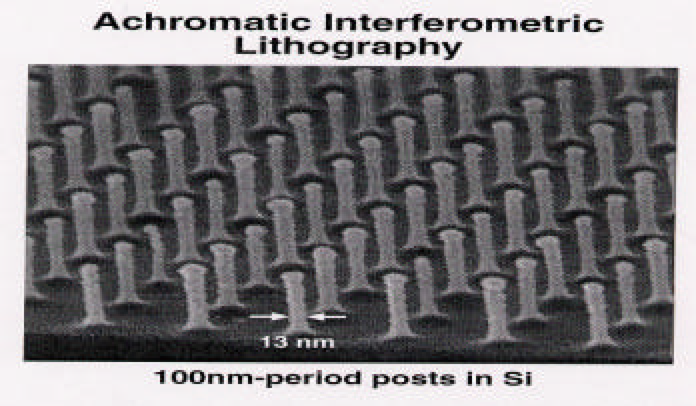
Figure 11


The Solution:
Spatial Phase Locking

Interaction of electron beam and fiducial grid provides feedback to cancel placement errors.

Dimensional control is an entirely different issue. Figure 12 shows a 100 nm pitch grating of 13 nm diameter Si posts. These structures were made with achromatic interference lithography and reactive-ion etching. Although these are very fine structures, they vary quite a bit in diameter. The control of the individual features is poor. I think that this is normal to the lithographic process. It represents an important limit to the lithographic process.

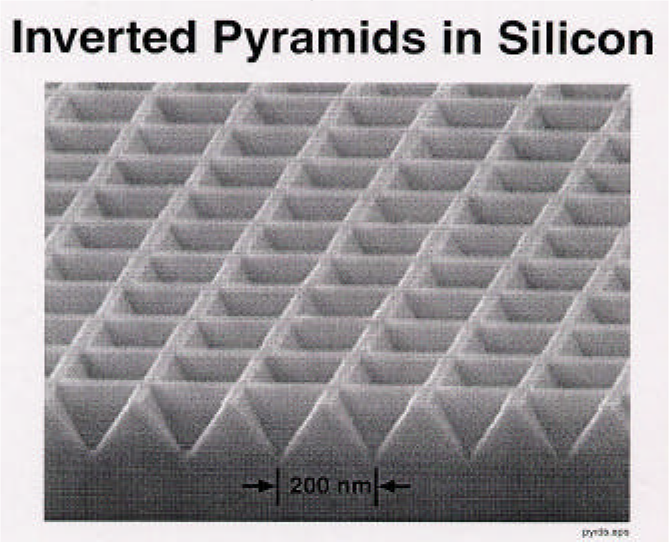
Figure 12


Achromatic Interferometric Lithography

100nm-period posts in Si

I am going to now discuss some incomplete ideas about how to approach and possibly solve the problem of dimensional control at the nanometer domain. Figure 13 shows a structure made in (100) Si with interference lithography and anisotropic etching. We see an array of inverted pyramids. The vast majority of the faces of these pyramids are atomically perfect. The apices of the pyramids are very close to atomically sharp. Thus, we have taken a process which is fundamentally limited—the lithography process—and achieved something that is atomically perfect.

Figure 13

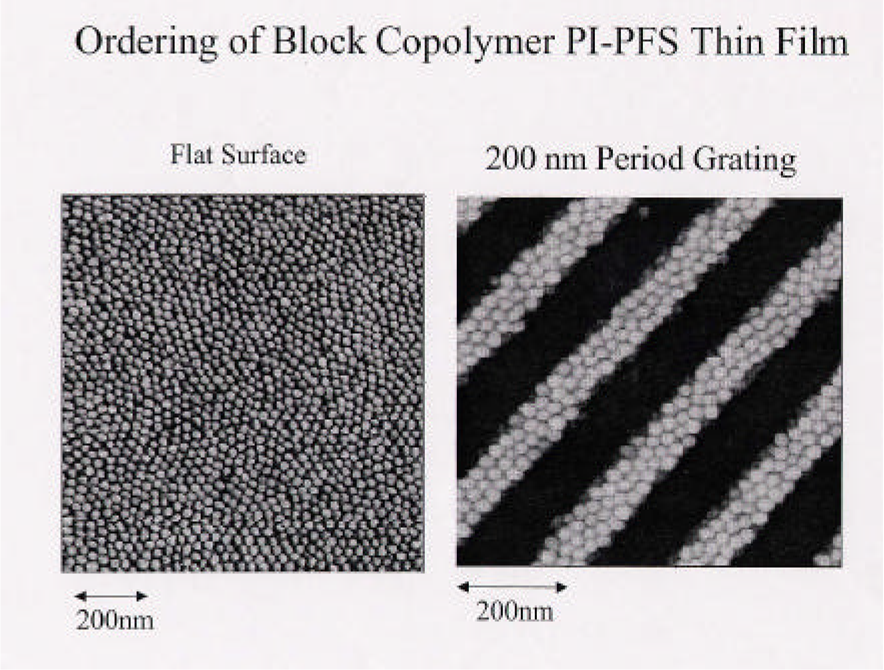


In the process we first etch circular holes in a silicon-nitride film. This always results in some edge roughness. Now we etch the Si in KOH. Because this solution etches hundreds of times faster in the <100> direction than in the <111> direction, we get enormous amplification. We can thereby produce structures which are approximately atomically perfect. I consider this a first step in the direction of making something atomically perfect. But, the bad news is that this is the only material, and the only geometry, in which we have figured out how to approach atomic perfection.

Figure 14 depicts a block copolymer which is self-assembled into an approximately regular pattern. However, it is far from perfect. By patterning the substrate surface with a 200 nm period grating, we improve the organization, and give it long-range spatial-phase coherence. This is a single experiment in what we expect will be an entirely new avenue of investigation: lithography-guided self assembly. In effect, the lithography provides a template. We expect that this will eliminate many of the defects that characterize self assembly.

This is an incomplete idea, and it is by no means a panacea or total solution. It is merely a step in the direction of making a bridge from lithography to the nano world.

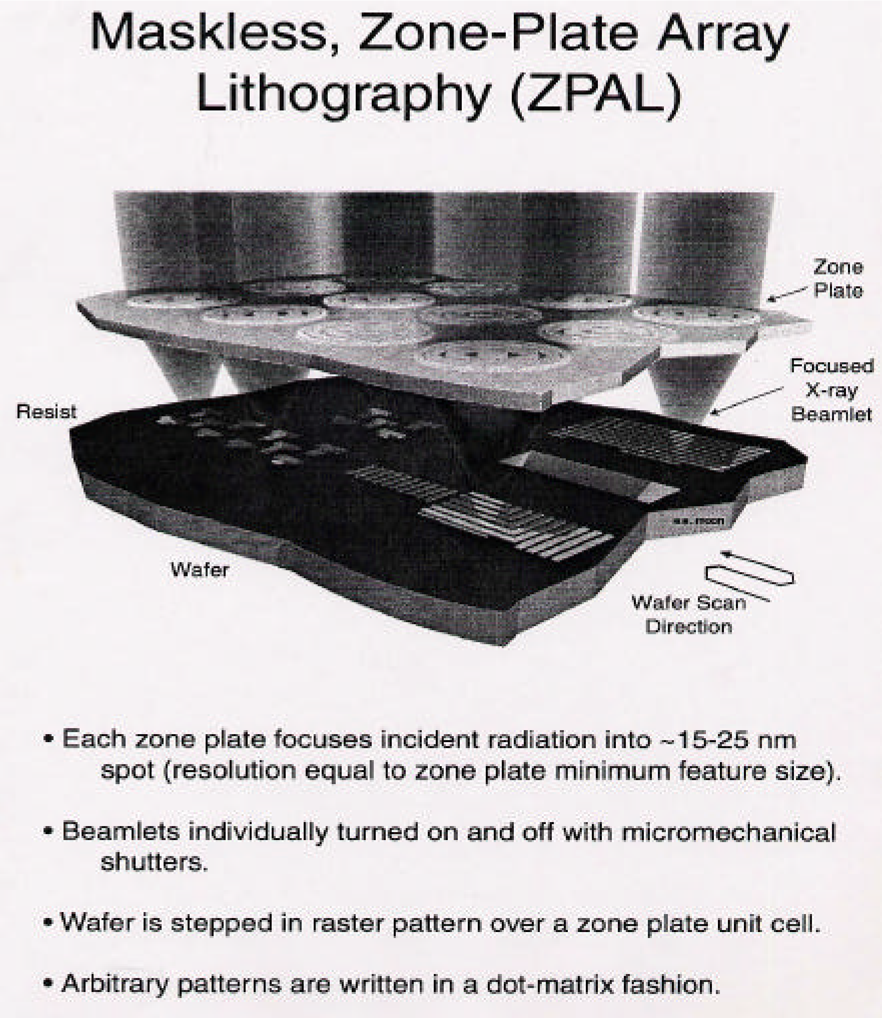
Figure 14



Lithography is a very powerful technique; it puts information onto a surface. This is the fundamental reason the semiconductor revolution has occurred. Lithography is a viable process down to 20 nm features. Its accuracy and precision can be below 1 nm. However, feature-size control is not so good. In fact, below 50 nm feature size control is a problem. Atomic-level perfection, such as we saw in the inverted pyramids, is possible only in selected materials and configurations. I would not give up hope that we could achieve this in other materials and through other clever ideas. Lithography-controlled self assembly is a possible bridge to the molecular domain. In fact, I believe it will prove to be an essential bridge.

In lithography one would like to have a maskless process, one that could operate with the ideal particle. Figure 15 depicts such a lithographic approach, called zone-plate array lithography (ZPAL). Zone plates can focus any radiation, including even neutral atoms. In addition to making an array of zone plates, one must be able to multiplex the beams to the individual zone plate, and to intelligently scan the substrate. By appropriately multiplexing the beams and moving the substrate, one can create patterns of arbitrary geometry in a manner similar to dot-matrix printing. For multplexing we currently use the TI micromirror array. Actually, the Daewoo micromirror array is even more attractive. We've demonstrated lithography at the theoretical limit using the 442 nm line of the HeCd laser. By going to 157 nm deep UV sources we should be able to get down to 90 nm features.

Figure 15



# Maskless, Zone-Plate Array Lithography (ZPAL)

- Each zone plate focuses incident radiation into ~15-25 nm spot (resolution equal to zone plate minimum feature size).
- Beamlets individually turned on and off with micromechanical shutters.
- Wafer is stepped in raster pattern over a zone plate unit cell.
- Arbitrary patterns are written in a dot-matrix fashion.

How far can this be extended? If we use the 4.5 nm carbon K photon, our simulations indicate that we can do 25 nm feature sizes. We believe that the combination of arrays of zone plates, micromechanical shutters, and computer based intelligence in the multiplexing and stage motion represents the lithographic process of the future.

Thank you.

# HAIWON LEE

## *HANYANG UNIVERSITY*

## SCANNING PROBE MICROSCOPE AND IMPRINT LITHOGRAPHYN FOR NANOMETER-SCALE FABRICATION

As President Clinton's FY 2001 budget request includes an 84% ($227 million) increase in the government's investment in nanotechnology research and development, the Administration is making this National Nanotechnology Initiative (NNI) a top priority. The emerging fields of nanoscience and nanoengineering are leading to unprecedented understanding of the fundamental building blocks of all physical things. The initiative will strengthen scientific disciplines and create critical interdisciplinary opportunities among scientists and engineers in the United States. At the U.S.-Korea science and technology cooperation forum, especially on nanotechnology, it is very worthwhile for both countries to find a way for new collaboration as long as the science and technology cooperation between our two countries rapidly grows, and this is why there is an important role for both the United States and Korea. In this presentation, the current status and trend of research on nanofabrication based on SPM and imprint lithographies at various Korean research institutes will be discussed.

The ongoing miniaturization of electronic and mechanical devices has led to an interest in the generation of nanometer-sized structures on surfaces. With the scale-down in dimensions of very large-scale integration devices to the nanometer region, there is currently great interest in the possible use of proximal probes as tools for the fabrication of nanoelectronic devices. To date, a number of attempts have been reported to fabricate nanometer-scale structures on the semiconductor or thin metal films surfaces using a scanning tunneling microscope (STM) and atomic force microscope (AFM). Those investigations have largely been motivated to evaluate the potential use of a STM and AFM in the fabrication of nanostructures in an atomic resolution.

Single electronics has recently attracted much attention for future electron device generations and strongly motivates investigations in the filed of lithography and pattern transfer in the nanometer regime. However, further downscaling of device dimensions rapidly points out the limitations of conventional optical and electron beam techniques. Alternatively, scanning probe microscopy (SPM) has demonstrated capabilities for atomic-level manipulation and also potential for local modification of a variety of surfaces using different approaches such as exposure of resists, decomposition of organometallic compounds, or selective anodic oxidation of silicon and metallic substrates. The nanometer scale lithography requires an optimum condition of nanolithographic processes with a reliable high-resolution resist. In case of resist the films must be prepared in a thin and uniform layer in order to attain high spatial resolution in nanometer scale. Organic thin films, e.g., self-assembled monolayers, Langmuir-Blodgett films, and spin-coated polymer films can be used as resists and patterned with nanometer precision. The resulting nanostructures exhibit promising applications in the development of nanometer-scale electronics devices, biochips, and sensors. The key to reach high spatial precision is to selectively break chemical bonds or direct chemical reactions using local tip-surface interactions during fabrication. These methods include AFM-based lithography such as tip-catalyzed surface reaction, tip-induced displacement, and STM-based lithography such as tip-assisted electrochemical etching, oxidation, and field-induced adsorption. However, SPM lithography should be further developed for practical use in manufacturing nanometer-scale devices. In the near future, it should become possible to employ large parallel arrays of STM/AFM tips in order to realize a practical nanolithography suitable for manufacture of ICs with vastly increased speed and function density.

Nanofabrication of self-assembled monolayers (SAMs) have attracted tremendous attention because of its scientific importance and potential application. STM-induced patterning of organomercaptan SAMs at biases arises from a faradaic electrochemical process. Organomercaptanes adsorb onto some metal and semiconductor surfaces to yield ultrahigh density monolayers. These monolyers can be viewed as resists for STM lithography since they effectively passivate surfaces against many mass- and electron-transfer processes but do not prevent electron tunneling from STM tips. Scanning probe anodization also can be carried out on organosilane-based SAM resists. Several resist processes have been developed to apply for nanofabricaton.

A single electron transistor (SET) is considered to be a candidate for an element of future low power, high density IC because of a possible ultra-low power operation with a few electrons. For the practical application it is indispensable for the SET to be operated at room temperature. For this purpose, the size of the island of SET must be as small as ~10 nm to reduce the total capacitance of SET and to overcome the problems of the thermal fluctuation. However, the size of ~10 nm is out of the range of the present conventional microfabrication process, so the fabrication of a SET using STM/AFM nano-oxidation process is one of very promising method. Recently, single-electron transport in ropes of carbon nanotubes has much attention. Their conducting properties are predicted to depend on the diameter and helicity of the tube.

Carbon nanotubes are attractive for many potential applications, including new electron field emitters in panel displays, single-molecular transistors in microelectronics, and molecular filtration membranes. The ability to controllably obtain aligned and/or patterned carbon nanotube architecture is of paramount importance to fundamental characterizations and potential applications. Controlled synthesis involving chemical vapor deposition has been an effective strategy to order multiwalled nonotube on surfaces. Single-walled nanotubes (SWNTs) have been proposed as an ideal system for the realization of molecular electronics. SWNTs are true molecular wires with their diameters in the range of ~1-5 nm such that a SWNT is either metallic, semiconducting, or semimetallic depending on their two-terminal conductances. Individual SWNT wires can be grown from controlled surface sites by catalyst patterning, however an approach for obtaining SWNTs in aligned orientations perpendicular or parallel to surfaces can open new possibilities in fundamental characterization and device applications of organized nanowire architectures on flat substrates. In particular, Dai and co-workers have produced patterns of perpendicularly aligned carbon nanotubes through growth of the nanotubes on a partially masked surface by pyrolysis of molecules containing both the metal catalyst and carbon source required for nanotube growth.

As hard disk recording densities increase, the grain size of the magnetic layer is being reduced in order to maintain a good signal/noise ration when reading data from the disk. However, if the grains become too small then a 'superparamagnetic' limit is reached in which the magnetization direction in the magnetic grains can be reversed by thermal energy, leading to loss of recorded data. One method for reducing media noise is to store data in periodic arrays of 'nanomagnets' lithographically defined magnetic particles, each of which has dimensions of less than 100 nm. Applying voltage between the AFM tip and ferroelectric thin films induces ferroelectric polarization switching, and this induced polarization can retain their entity even without the applying voltage. The bits can be read by piezo-response imaging in contact mode of AFM with high resolution (~100 Gbits/in$^2$), so the ultra-high information density can be achieved by using SPM lithography. An alternative way for fabricating nanomagnets is to use a method of self-assembly with organic monolayer. This approach combines soft lithography and the formation of nanoparticles onto self-assembled monolayers.

Application of SPM to information storage is also promising, because the size of a data bit will be from submicron to subnanometer and is much smaller than that in any present storage device. In most cases of SPM-based information storage, a bit is accompanied by a topographical change of the recording medium. The contact mode AFM gives a chance of detecting several interactions between tip and sample. For example, the force and the current can be detected simultaneously and independently with a conducting AFM probe, so the practical information storage system using contact mode AFM can be constructed without topographical modification in a recording medium. Recently a small bit of 10 nm in diameter was formed in a polyamide Langmuir-Blodgett film under the vias pulse with the SPM probe and the bit exhibits a change in conductance only with no change in topography.

The development of low-cost, high throughput lithography techniques with sub-50-nm linewidth resolution is essential for the future manufacturing of semiconductor ICs and the commercialization of electronics and magnetic nanodevices. Electron beam lithography has demonstrated 10-nm resolution; however, because it exposes point by point in a serial manner, the current throughput of the technique is too low to be economically practical for mass production of sub-50-nm structures. Imprint lithography based on compression molding and a pattern transfer process is also an alternative lithographic method as a low-cost and high-throughput manufacturing technology for fabricating ICs and other sub-50 nm structures. Imprint lithography can eliminate many factors that limit the resolution of conventional lithographies. Using this imprint lithography Chou and his co-workers already achieved a minimum feature size of 10 nm in a resist >100 nm thick. With further development of materials and alignment system, imprint lithography may allow fabrication of 10 nanometer structures and become one of potentially important lithographic technique for manufacturing ICs and other nanodevices.

# Plenary Session II

# SANG-IL PARK

## *CHAIRMAN AND CEO*
## *PSIA CORPORATION*

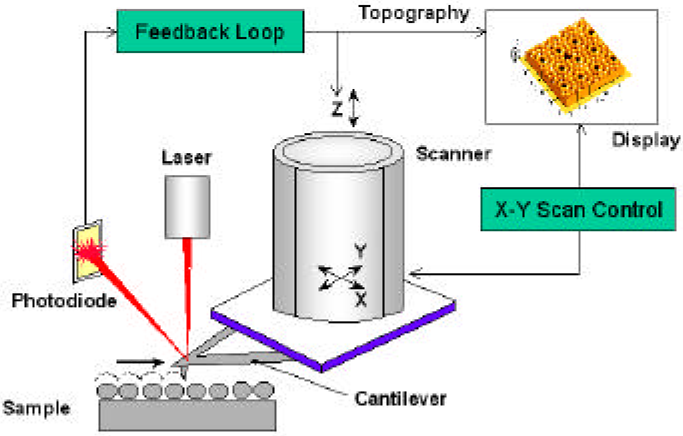
# ADVANCES OF SPM AS A CHARACTERIZATION TOOL FOR THE NANOTECHNOLOGY ERA

Good afternoon, ladies and gentlemen. It is my pleasure to present the work we have done in Korea on scanning probe microscopy (SPM).

### Introduction

We all know that modern high technology industries require smaller scale characterization beyond that which has been available through traditional methods. Fortunately, SPM was invented in the early 1980s. The first tool was the scanning tunneling microscope (STM), which was invented by G. Binning and H. Roher in 1981. They won the Nobel Prize for their work in 1986. The STM uses a small tungsten needle. It uses the quantum mechanical tunneling effect, which allows us to control the spacing between the probe and the sample to get images. The biggest limitation of STM is that we can only image conducting samples. Even these conducting samples cannot be imaged well if they are exposed to air, due to oxidation and contamination.

Figure 1



To remove this limitation, AFM was invented at Stanford University at Professor Quate's lab. The principle of AFM is very simple, but it is so powerful that it made a big impact on nano-scale science. Figure 1 depicts how AFM works. The key part is the probe, which is a very sharp tip that is attached to a small cantilever. As the probing tip approaches the sample, an inter-atomic force comes into effect. Due to this force, the cantilever will bend up or down, and we can measure this motion with a laser beam. By detecting the reflected beam, we are able to control the feedback in a way that the tip follows the sample surface. As we scan x and y, we can collect z data information and form AFM images.

There have been many instruments using the AFM technique. They are mostly for research purposes. Some of the latest products using AFM are the automated instruments for semiconductor fabrication.

SPM has several advantages over other techniques.

- High resolution
- Quantitative 3-D information
- Non conductors as well as conductors and semiconductors
- Operates in air, liquid, and vacuum
- Measures not only topography but also electrical, magnetic, and optical properties

SPM has the best resolution in lateral and vertical dimensions compared to other microscopy.

**Advanced Metrology for Higher Precision and Accuracy**

The typical metrology tool is CD-SEM, a matured technology having high throughput. But it has some disadvantages:

- it may produce sample damage and contamination,
- does not work on a non-conducting substrate,
- does not provide height information, and
- requires a vacuum chamber

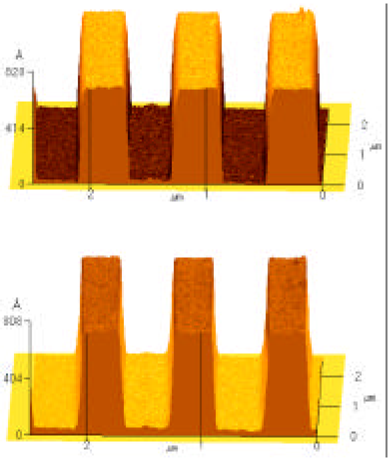
SPM does not have these drawbacks, but it does have some other weaknesses. Two of the most significant are tip-surface convolution effect and the throughput.

In every metrology method, there are measurement errors. In SPM, the first problem we encounter is finite tip shape. It is not possible to get the tip thin as is ideal. Therefore, the convolution effect is inevitable. Fortunately, tip technology has been continuously improving. Recently, we have acquired ion milled tips with a much higher aspect ratio, and carbon deposited tips are available. A good way to remove the tip convolution effect is by using a tip characterizer. By doing so, we can get SPM images of the tip. By collecting that information we can deduce what the tip looks like.

Once we know the tip shape, we can bypass the tip convolution effect. Surface topography is mixed with tip geometry, which causes convolution and produces a dilated image. With the known tip shape, we can correct the image by the erosion method to recover the original shape to a certain degree. There are ways to image how the tip will make the AFM image different from the original shape, then recovering how the surface should look by comparing the tip shape.

Figure 2 shows a measurement of a photomask metrology. The upper image is the raw data that we got with AFM. By going through this de-convolution process, we were able to reconstruct a corrected image in the below. At the upper edge we could recover almost 100 percent of the original shape, but at the bottom corner, we could not. This is because the bottom corner is an uncertain area, where the AFM image does not have sufficient information.

Figure 2



## Electrical Characterization

Figure 3 shows a basic diagram of an electrostatic force microscope (EFM). We applied DC and AC bias voltage between the conducting substrate and the tip. Due to the AC component, the tip would oscillate. Using lock-in amplifiers we can measure ω and 2ω components, from which we can obtain surface charge or surface potential, and capacitance information. We can also get topography at the same time, by employing standard non-contact mode or contact mode AFM feedback circuits.

Figure 3

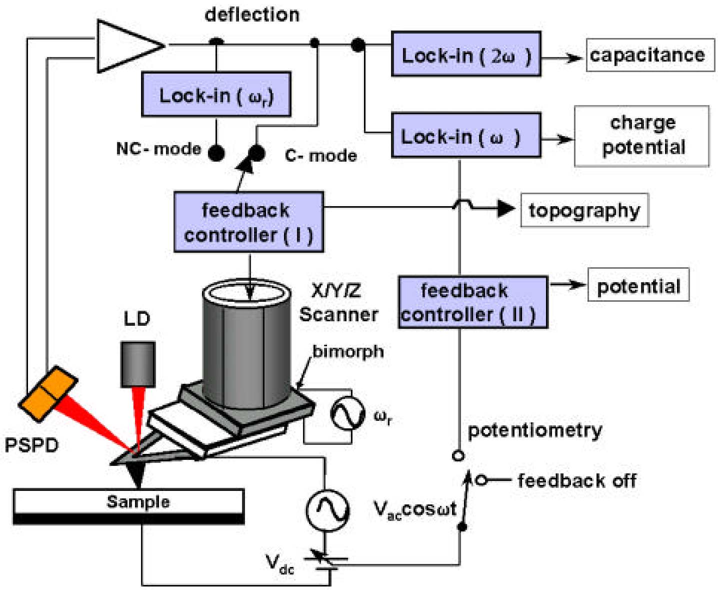
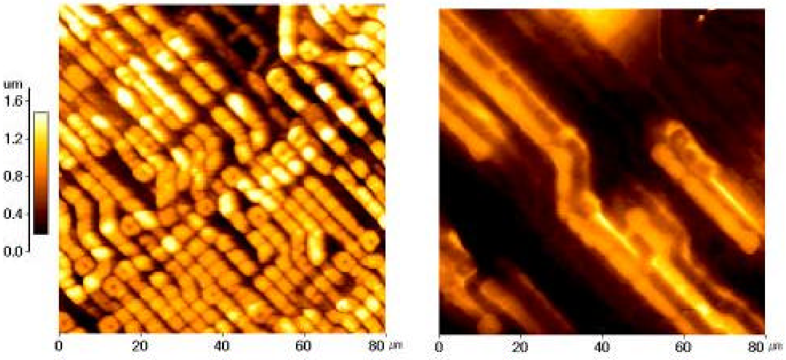


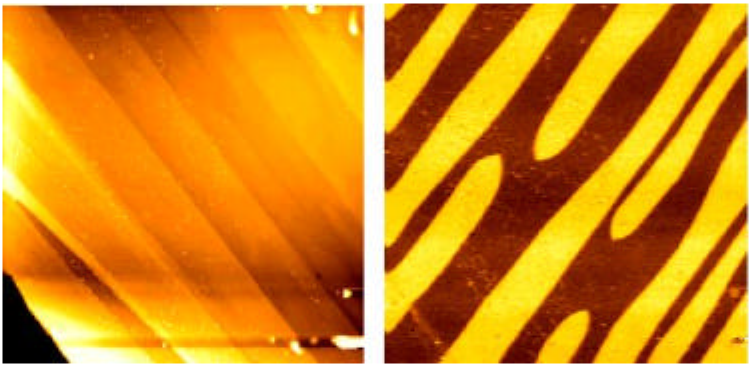
Figure 4 shows an example of EFM with an actual ASIC chip on which we obtained topography (left) and surface potential image (right). From the surface potential image, we can see where the circuit is logic one or zero. This image was taken without removing the passivation layer. It was possible since the electrostatic force can penetrate through an insulating layer.

Figure 4



There is a brand new method of electrical characterization called dynamic contact EFM (DC-EFM), which we invented at PSIA. The apparatus is similar to EFM, but we put the tip in contact with the sample. You would think the cantilever would oscillate in free space with AC-biased voltage, but once tip is in contact with sample it would stop oscillation. However, since the sample has a finite hardness, even though the tip is in contact, it goes into a compliance mode where the tip compresses the top layer of the surface and we can get certain information on the surface from the residual oscillation. If the surface has uniform hardness you get electrical information. If the surface is uniform electrically, you get hardness information. Figure 5 is an example of DC-EFM on ferroelectric TGS (triglycine sulphate) showing topography on the left and ferroelectric domains on the right.

Figure 5



## High Speed AFM

AFM has many advantages, but its weakest point is its speed. AFM cannot image fast enough because we have to mechanically move the probing head up and down following the surface. Mechanical scanners have only a few hundred Hz bandwidths. That means the cantilever cannot go up and down more than a few hundred times per second. The way to overcome this problem is to reduce the moving parts. So rather than making the whole head move up and down, we are developing a system where only the cantilever moves up and down by embedding actuating elements (zinc oxide) into the cantilever. Since the cantilever is so tiny and light, it can respond much faster. We estimate that this would be approximately 100 times faster than bulk piezo scanner and it can make almost real-time imaging, which is our goal.

The bulk piezo scanner has a resonance frequency at 500 to 600Hz, but the zinc oxide cantilever can respond up to 50 to 60kHz. We have not completed our system development yet, but our preliminary system can image at a much faster rate than conventional AFM. At this time, our imaging speed is not limited by the mechanical response, but rather by our electronics.

## Conclusion

SPM is a very powerful instrument for nanoscale surface characterization. It keeps on evolving and expanding its applications and capabilities. There are many activities in this field in Korea, and there is room for cooperation between Korean and American scientists.

Thank you very much.

# CHARLES M. LIEBER

***MARK HYMAN PROFESSOR OF CHEMISTRY***
***HARVARD UNIVERSITY***

## UNDERSTANDING AND EXPLOITING NANOSCALE BUILDING BLOCKS FOR NANOTECHNOLOGIES

I would like to thank everyone for the opportunity to speak at this timely Forum on Nanotechnology. I would like to share with you today in this session on characterization our group's interest in building up nanoscale tools and devices from well-defined nanoscale building blocks. The success of this process is governed by what we can do in understanding these materials at the outset.

I would like to talk about our vision for nanotechnology. Our approach is to try to exploit the exquisite sensitivity of chemistry to make building blocks such as nanoclusters and nanowires or nanotubes which can then be used as building blocks. If we understand them and build up from the bottom up as opposed to the top down, we hope to create the tools and devices of the future. Ultimately, this is going to involve some complex assembly. We are going to have a far-reaching goal to take these building blocks and actually make a computing device. Our goals, therefore, are to take building blocks, understanding their properties and build new tools and devices—new tools which can help further understand and ultimately enable the assembly of new devices. This is really a change. Nanotechnology to us means an enabling approach to overcome or change the paradigm of manufacturing. This vision is a long-term vision.

How is one going to achieve this vision? One needs to focus on a number of areas which are very interdisciplinary in nature. There is nanostructure synthesis which involves biology, chemistry, and material science. This is an area where I think there has been quite a bit known and developed but there is still a lot left to do.

There is, of course, characterization. This involves interests and skills from chemistry and physics. Here there is even more that is left to do, although we are certainly learning. Then, there is the issue of hierarchical assembly. How do we take these nanostructures and organize them into very complex functional devices? That is going to take the techniques of biology and chemistry. Lastly, when we think about making tools and devices, we can not short-change the importance of engineering, computer science, and physics. As we make electronic devices from these building blocks, we are going to have to think about new types of architectures and programming to be able to actually organize and address them in a rational manner.

So what makes this field so exciting to me is not only is there quite a bit of progress but also that it is very interdisciplinary in nature.

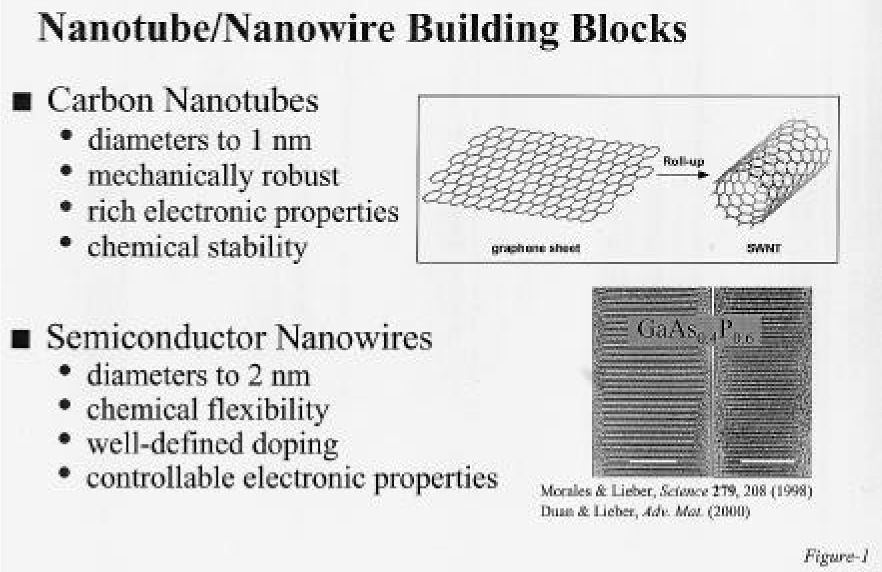
I want to focus this afternoon on one particular aspect of nanotechnology: one-dimensional nanostructures as building blocks for the future. This involves the synthesis of what we will term nanowires (NW) and nanotubes (NT) and understanding their fundamental properties through characterization. In so doing, one has the opportunity to assemble new electronic systems from which we hope ultimately to be will be able to make computing devices. We can today make new tools—probes and sensors—which allow us exquisite sensitivity for imaging, manipulation and detection down to a single molecule level in the hard nanometer scale regime. We can then take these building blocks and assemble them into solids which may have enhanced or novel properties such as in the case of mechanical materials.

The types of building blocks that I am going to be discussing in this talk are carbon nanotubes, and I will say a little bit about the challenges of characterizing these. These are materials have diameters down to 1 nanometer, which is really on the scale of a molecule. Therefore, it is a really beautiful example of a material which bridges from the molecular scale of chemistry up to the solid state world because it is periodic. It can have atomic periodicity over microns and up to millimeters in length. We know from measurements using scan-probe microscopies that it is mechanically very robust. It has very rich electronic properties and a lot of interesting chemistry.

There is also another class of materials of equal importance in our minds and these are semiconductor wires. They have a similar diameter—they are down to around 2 nanometers in diameter. They have chemical flexibility. They have well-defined doping—one can vary the electronic properties in a very controllable manner. We can take these materials which are not made on surfaces but which can be made in vapor phase and make what we call bottles of materials. We can then think about how to organize them in some useful ways.

I would like to start with the challenges of characterization. For nanotubes there are a number of tools which can be used. One of the common tools of characterization which is exceedingly important in nanoscale science is transmission electron microscopy. Figure 1 is an image of a single wall nanotube. It is about 1.5 nanometers in size. It is a tubular structure. We can learn something about its morphology, but we cannot learn its detailed atomic structure.

Figure 1



## Nanotube/Nanowire Building Blocks

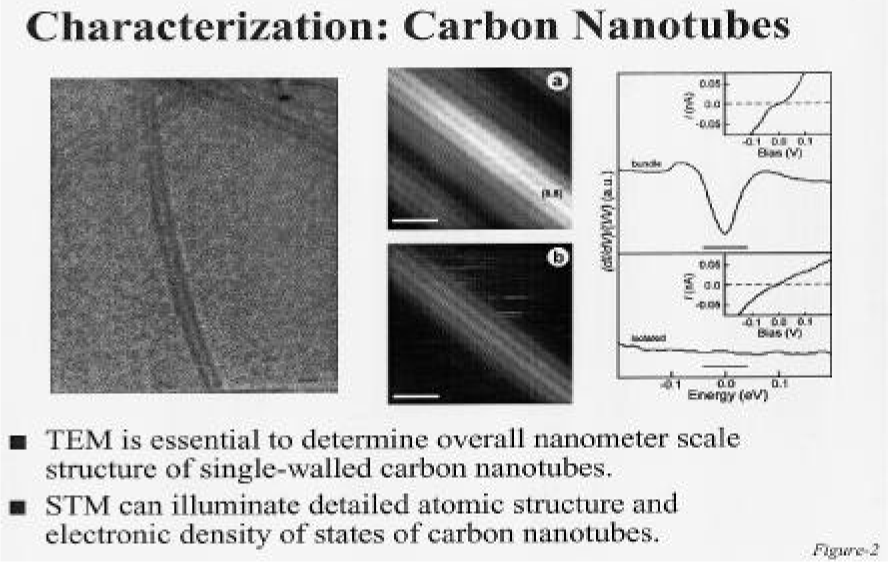
- Carbon Nanotubes
  - diameters to 1 nm
  - mechanically robust
  - rich electronic properties
  - chemical stability
- Semiconductor Nanowires
  - diameters to 2 nm
  - chemical flexibility
  - well-defined doping
  - controllable electronic properties

Morales & Lieber, *Science* **279**, 208 (1998)
Duan & Lieber, *Adv. Mat.* (2000)

*Figure-1*

We can use other techniques such as scanning tunneling microscopy, which is a very powerful technique that can illuminate the atomic structure and the electronic properties of nanotubes. Figure 2 is an example of why this is important in this nanomaterials area.

Figure 2



## Characterization: Carbon Nanotubes

- TEM is essential to determine overall nanometer scale structure of single-walled carbon nanotubes.
- STM can illuminate detailed atomic structure and electronic density of states of carbon nanotubes.

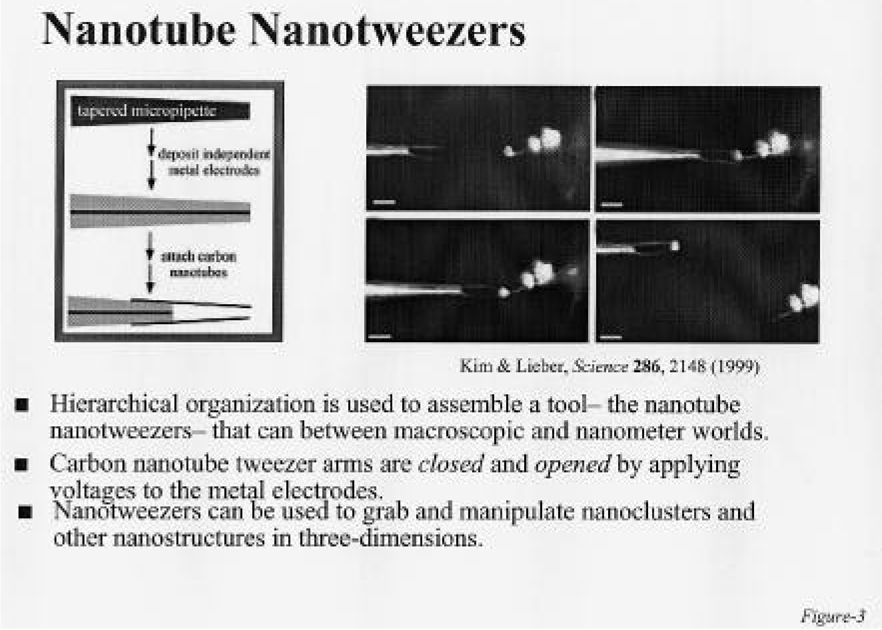
*Figure-2*

These are images of atomic structure which one can use to define the structure of a nanotube. Both of the nanotubes in figure 2 are the same. They have a particular symmetry which leads one to believe, based on work originally done by Millie Dresslehouse, that they should be metallic. One tube is actually part of a bundle—that is several tubes organized together and they have intratube interactions. The other tube is isolated. If one looks at the electronic properties of this, it is finite and it behaves as a metal. However, due to interactions with additional tubes in this bundle, a gap evolves. This is understood in terms of a broken symmetry in the system. It is a very interesting fundamental issue, but it also has exceedingly important practical implications when one thinks about using nanotubes as wires. If they have gaps and they are no longer metallic, that is certainly important and one needs to understand and develop the tools to characterize such effects.

Even with these uncertainties, can we use nanotubes to develop things? Electronics depends upon controlling the electronic properties, and we cannot control nanotube electronic properties between metals and semiconductors yet. But we can exploit their electromechanical properties or mechanical properties. There are two examples which I would like to share with you in which we are using these nanomaterials to build the new tools which enable further characterization. The first is nanotube nanotweezers. The idea behind this is to see if we can actually bridge from the macroscopic world through the nanometer scale material which has fairly high aspect ratio down to the nanometer scale and do something other than just scanning the tip around. We can actually create such structures through what I call a hierarchical organization where we have different levels of fabrication all the way down to attaching or fabricating nanotubes onto independent electrodes at a micron scale which will then take us down to the nanometer scale. What this enables is that one can now actuate these tubes if they are connected to independent electrodes electrostatically, much like other larger-scale tweezers. What that immediately suggests is that one has a tool for manipulation and grabbing in three-dimensional space.

Figure 3 illustrates that one can actually take the tweezers, come up to a nanometer scale cluster, close the tweezers on that cluster and move that around in three-dimensional space and deposit it somewhere at will. One not only has a tool that can move with a scanning probe microscope around on a surface, but by increasing the complexity and by taking advantage of the unique properties of this nanomaterial, one can create a more powerful tool. I wanted to bring this to your attention because the student who started this work and did all the work from its inception is Phillip Kim, a product of SNU and a former student of mine who is now a Miller Fellow at Berkley.

Figure 3



## Nanotube Nanotweezers

Kim & Lieber, *Science* **286**, 2148 (1999)

- Hierarchical organization is used to assemble a tool– the nanotube nanotweezers– that can between macroscopic and nanometer worlds.
- Carbon nanotube tweezer arms are *closed* and *opened* by applying voltages to the metal electrodes.
- Nanotweezers can be used to grab and manipulate nanoclusters and other nanostructures in three-dimensions.

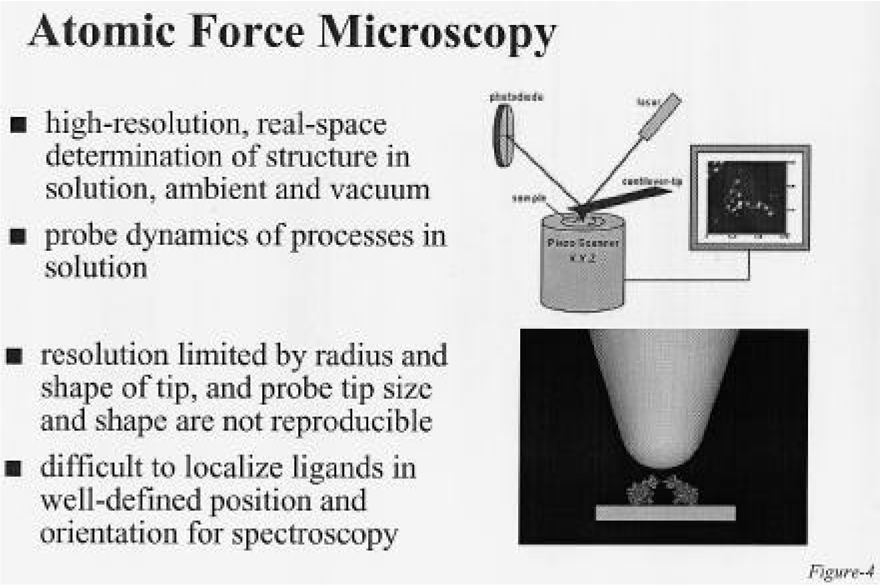
*Figure-3*

Where can one go with this? It actually enables new types of science and technology. One can use these nanotweezers to create two-tipped scanning probe microscopes in a fairly straightforward manner which allows manipulation down to truly a molecular scale. One can actually use these probes because they are conducting to characterize, grab something, put the probes down and measure a two-terminal transporter. One of the directions that we are most interested in terms of enabling new science and technology, allows one to move into biological systems and other soft-condensed matter systems. One can dream about, ultimately, cellular level surgery with such structures. We can also visualize this as serving as a basic unit for developing nanorobotics because you have something that can manipulate, and grab, and be actuated in a very well-defined manner but on a length scale which is different than in MEMS.

Let me turn briefly to the area of scanning probe microscopy. This is really taking a step back, but as Dr. Park indicated in the last talk, this is clearly one of the most critical tools today for nanoscale science and technology. It is used throughout biology, chemistry, physics and engineering. As he indicated, there are many types of information that one can get: topography, chemical information, molecular interactions, and magnetism. One of the key things is that the resolution is dependent largely on the probe tip.

Where can one go with this? We are thinking about what needs to be done to really push this a quantum step forward. We know that the AFM is a powerful technique. But if one wants to look at the problem from my perspective, not from microelectronics but from true nanoscale science, AFM is not powerful enough.

Figure 4

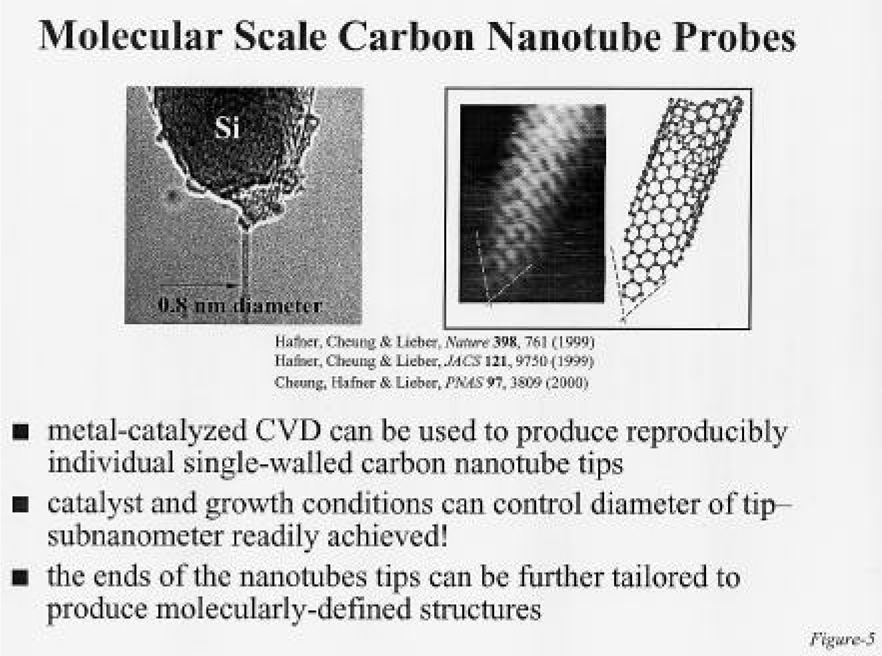


### Atomic Force Microscopy

- high-resolution, real-space determination of structure in solution, ambient and vacuum
- probe dynamics of processes in solution
- resolution limited by radius and shape of tip, and probe tip size and shape are not reproducible
- difficult to localize ligands in well-defined position and orientation for spectroscopy

For instance, looking at individual proteins, figure 4 illustrates as good as you are going to be able to get with silicon. It has a 5 nanometer radius, a curvature tip. But it is huge compared to a large protein, shown in figure 4. If one really wants to get additional true molecular scale information, if one wants to get away from these problems of fabrication of identical tips, how can one do that? What we need is a molecular type of probe which can be made identical every time. There is a way to do that. The way is using carbon nanotubes. Figure 5 is a very nice example of how one can bridge our conventional microbe to nanoscale materials world down to the molecular scale with one of these single carbon nanotube probes.

Figure 5



**Molecular Scale Carbon Nanotube Probes**

Hafner, Cheung & Lieber, *Nature* **398**, 761 (1999)
Hafner, Cheung & Lieber, *JACS* **121**, 9750 (1999)
Cheung, Hafner & Lieber, *PNAS* **97**, 3809 (2000)

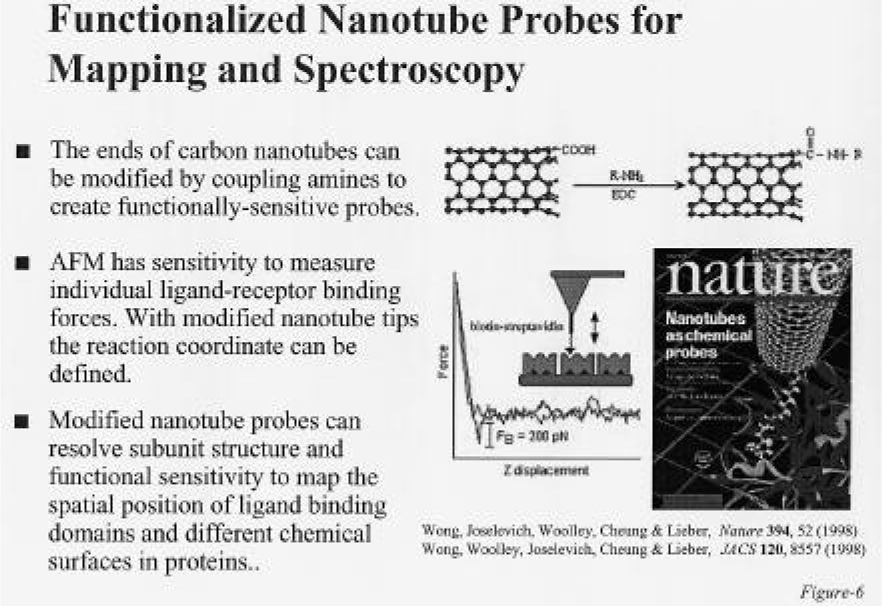
- metal-catalyzed CVD can be used to produce reproducibly individual single-walled carbon nanotube tips
- catalyst and growth conditions can control diameter of tip—subnanometer readily achieved!
- the ends of the nanotubes tips can be further tailored to produce molecularly-defined structures

*Figure-5*

The way one can make these is using chemical vapor deposition using a catalyst. The important point about that is that the catalyst defines the diameter of the nanotube. In a sense, if one prepares monodispersed catalysts for which there are a number of mechanisms, one can prepared monodispersed tips—monodispersed on a scale that will never be achieved in my mind using silicon. Despite the small scale, these tips are remarkably robust. One can grow these sub-nanometer or molecular resolution tips and, moreover, as one thinks to the future one can further tailor them to provide a molecularly defined tip.

Figure 6 shows an example of some emerging work in this area. One can etch the end of the tip. What we find using tunneling microscopy, which is the only available technique to image at the atomic scale, is a well-defined molecular entity at the end of the probe. This gives unique power in terms of future

Figure 6



## Functionalized Nanotube Probes for Mapping and Spectroscopy

- The ends of carbon nanotubes can be modified by coupling amines to create functionally-sensitive probes.
- AFM has sensitivity to measure individual ligand-receptor binding forces. With modified nanotube tips the reaction coordinate can be defined.
- Modified nanotube probes can resolve subunit structure and functional sensitivity to map the spatial position of ligand binding domains and different chemical surfaces in proteins..

Wong, Joselevich, Woolley, Cheung & Lieber, *Nature* 394, 52 (1998)
Wong, Woolley, Joselevich, Cheung & Lieber, *JACS* 120, 8557 (1998)

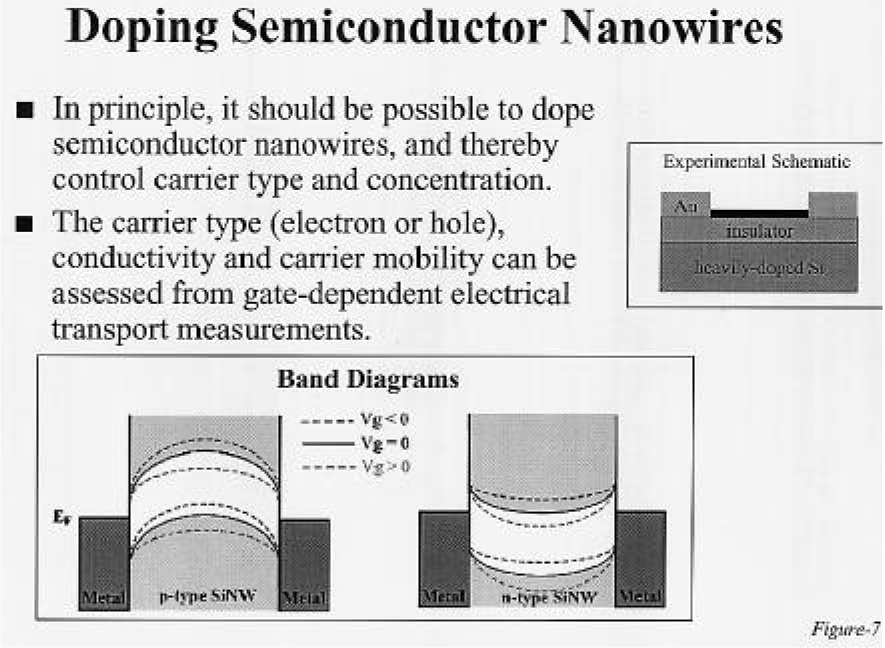
*Figure-6*

One of the things that one can think about is elaborating the probe. That is taking the end of the probe and modifying it with specific molecules—increasing its flexibility to get additional information. This is very important in the areas of biology and soft condensed matter. We can think about actually taking advantage of AFM's ability to measure single molecule interactions and our ability now to create these single tubes to map, with essentially molecular resolution, binding sites on proteins. I think the implication of the results coming out of nanoscale science and technology to adjoining areas such as biology are going to become more and more important in the future in developing tools.

To finish up, I would like to turn to the futuristic idea of actually assembling electronic devices from these building blocks. We have been able to make free-standing nanowires in virtually any chemical composition. We can make single crystal wires with virtually any semiconductor material, and we know how to do that in a predictable way. This is done with a method which allows one to prepare bulk quantities—quantities which can be manipulated like molecules in solution. Once one can do that, one can think about assembling. They have nanometer scale diameters and length, and they can be relatively well controlled at this scale down to the two nanometer scale. There are a lot of materials here, and if one can dope these materials, one can think about assembling P&N type materials to make devices.

This leads to an important issue. How does one characterize doping in a single wire which is only a couple nanometers in diameter? You can count the number of dopings. It is a very small number. It is, therefore, a difficult characterization problem. The way one can do it is indirectly through electrical characterization. Figures 7 and 8 show a traditional semiconductor device structure where one has a nanowire, a source and a drain. This is prepared using nanofabrication to put electrodes onto this very small wire and then using a gate to change the electrostatic potential. Through the conductivity dependence versus gate, one can determine whether one has a p-type or n-type wire unambiguously. One can use this approach to demonstrate that silicon nanowires can be reproducibly doped with boron and phosphorous to create p-type and n–type materials. You might say that should be obvious, but it is never obvious when you are working at this small scale because of the segregation effects or different chemistry that might occur when one gets to very small scale structures.

Figure 7

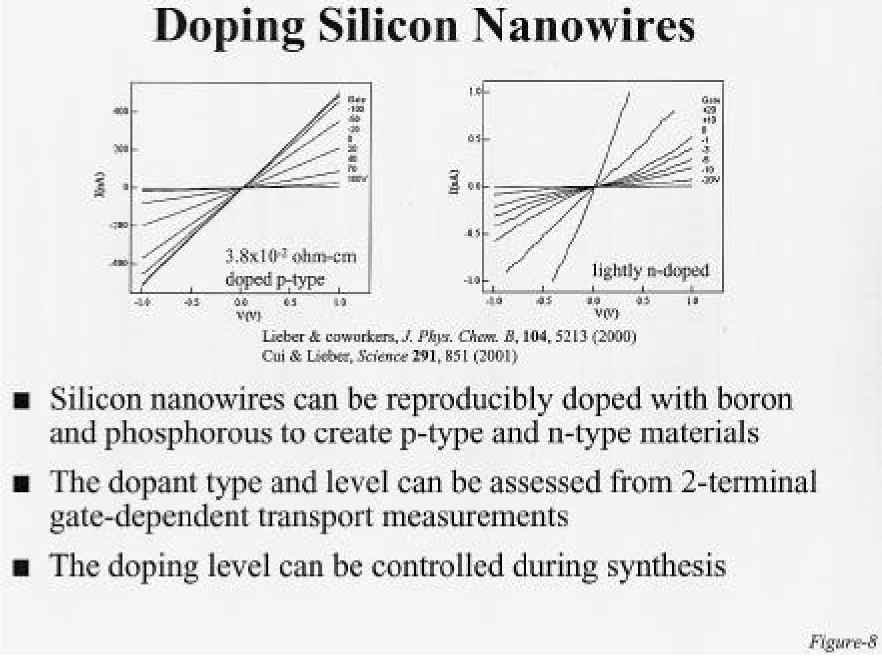


**Doping Semiconductor Nanowires**

- In principle, it should be possible to dope semiconductor nanowires, and thereby control carrier type and concentration.
- The carrier type (electron or hole), conductivity and carrier mobility can be assessed from gate-dependent electrical transport measurements.

*Figure-7*

Figure 8



## Doping Silicon Nanowires

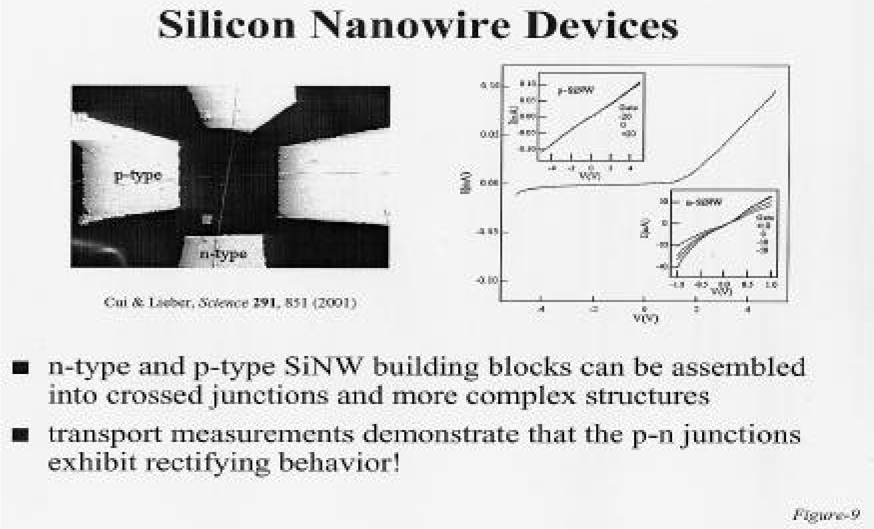
Lieber & coworkers, *J. Phys. Chem. B*, **104**, 5213 (2000)
Cui & Lieber, *Science* **291**, 851 (2001)

- Silicon nanowires can be reproducibly doped with boron and phosphorous to create p-type and n-type materials
- The dopant type and level can be assessed from 2-terminal gate-dependent transport measurements
- The doping level can be controlled during synthesis

*Figure-8*

So, one can make n- and p-type structures. These are, in fact, field-effect transistors. I do not think that is the direction to push this. The dopent level can be controlled as well so we can control the conductivity over many orders of magnitude. We have an opportunity now to change the paradigm of making devices. Instead of doing complex lithography and growth, one can simply think about taking beakers of differently doped wire and assembling them and actually making devices. That is the idea.

Figure 9



## Silicon Nanowire Devices

Cui & Lieber, *Science* **291**, 851 (2001)

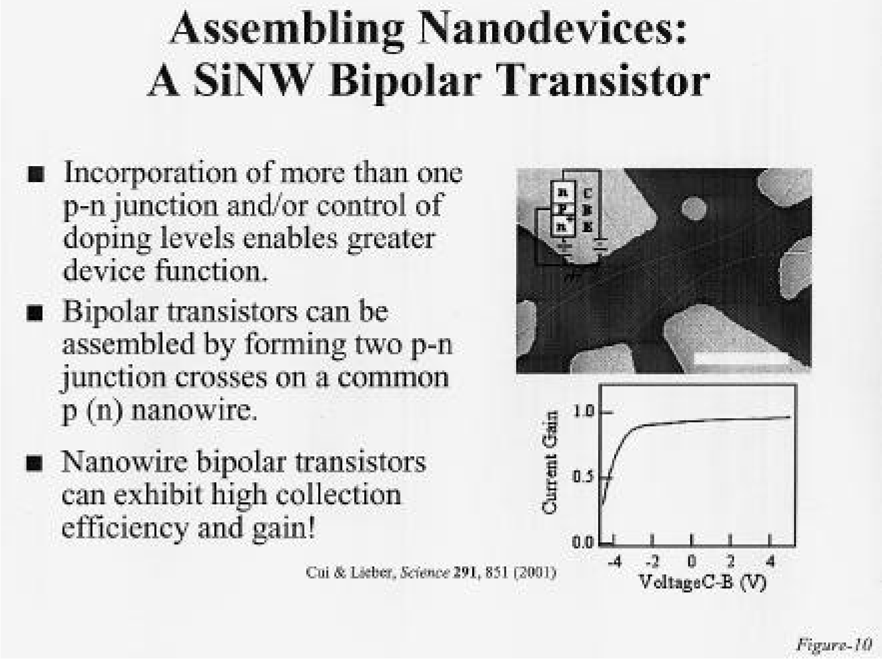
- n-type and p-type SiNW building blocks can be assembled into crossed junctions and more complex structures
- transport measurements demonstrate that the p-n junctions exhibit rectifying behavior!

*Figure-9*

To test that idea, figure 9 shows an n-type wire, and we assembled this sequentially. Shown also is a p-type wire, and the hardest part is putting electrodes on that. We can characterize the properties of this p and n junction. We know we can assemble these. We know that they are p- and n-type wires and transport measurements demonstrate that these are, in fact, rectifying—they form nice thyodes. Here is the transport behavior across the junction. We know that the individual wires are nearly omically contacted and rectification is not due to the metal semiconductor contact here. What we have is the ability in a very simple form to organize p and n type materials into a very simple or basic building block of semiconductor devices. Can one go beyond that in complexity?

It is actually possible. Let me share with you some results about our thinking on making bipolar transistors. We need additional complexity in the sense that it would be nice to have a heavily doped material as your emitter, have a base which has some lower doping level and a low-doped collector, and assemble these sequentially so that we know which are which. One can actually do that. Figure 10 illustrates a device, in the sense that we have a p base wire here and we crossed that with an n+ and an n wire where we can again control the doping levels through synthesis. We can assemble these in arbitrarily complex ways, and we need to learn how to do more complex assembly. If one looks at the transport in this bipolar transistor, one can actually show that one has quite high collection efficiency and reasonable gain—not as good as a state of the art semiconductor devices, but pretty reasonable based on the simplicity of this process at this stage.

Figure 10



## Assembling Nanodevices: A SiNW Bipolar Transistor

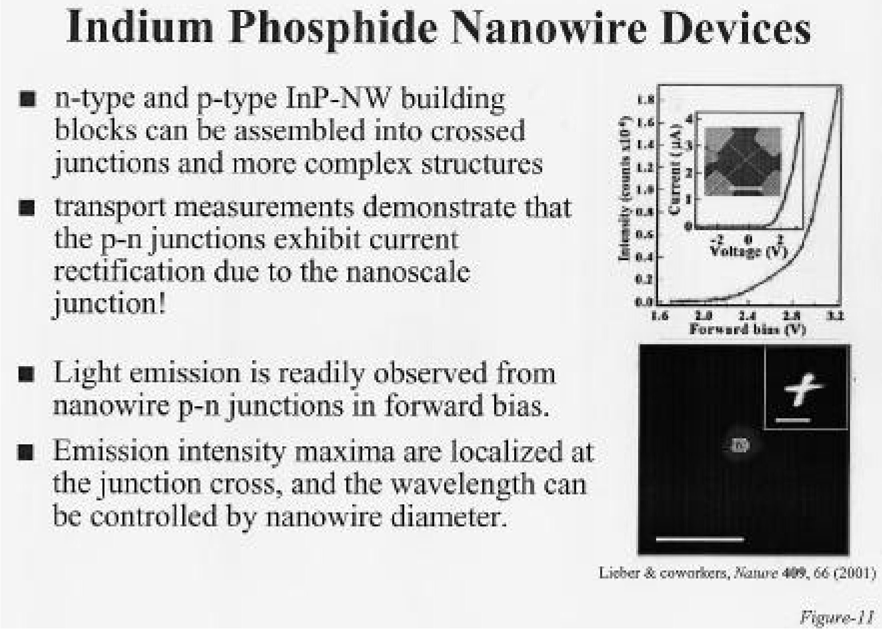
- Incorporation of more than one p-n junction and/or control of doping levels enables greater device function.
- Bipolar transistors can be assembled by forming two p-n junction crosses on a common p (n) nanowire.
- Nanowire bipolar transistors can exhibit high collection efficiency and gain!

Cui & Lieber, *Science* **291**, 851 (2001)

*Figure-10*

This concept is not only limited to silicon. It is not clear how important optoelectronics is going to be in the nanofuture, but one can certainly look at direct gap materials as well. We have looked at Indian phosphide. We can also make these building blocks in n- and p-type Indian phosphide. And they can be assembled into cross structures as well. These materials also exhibit diode structure. Figure 11 shows a p, n junction and with current voltage behavior. It is rectifying in reverse. It has no current flow in reverse bias, and it has a sharp onset in forward bias. The really remarkable thing is at this nanometer scale junction in forward bias, when one does the right characterization technique, you can actually see light being emitted from this diode. We actually have, in essence, what is a nanometer-scale LED—where the light is only emitted in forward bias and where the intensity is dependent on the forward current. We can demonstrate that we have light emission from this junction. It is the beginning of optoelectronics from a new approach. We can control the wave-length—not only by the material but by the well known quantum confinement effect—by varying the wire diameter as well.

Figure 11



## Indium Phosphide Nanowire Devices

- n-type and p-type InP-NW building blocks can be assembled into crossed junctions and more complex structures
- transport measurements demonstrate that the p-n junctions exhibit current rectification due to the nanoscale junction!
- Light emission is readily observed from nanowire p-n junctions in forward bias.
- Emission intensity maxima are localized at the junction cross, and the wavelength can be controlled by nanowire diameter.

Lieber & coworkers, *Nature* 409, 66 (2001)

*Figure-11*

So one is at the point of being able to start to think about building up electronic devices—electronic functionality—in a very different way from how we have thought about of doing it. This is not just saying that we are going to do bottom-up assembly, we can actually start to do it. There is still a lot of work to do in the future.

Let me just indicate what I think are some of the current and future needs in this area from the standpoint of characterization. What kind of information do we need? We need tools and continued development of techniques to give us a common structure as we work at smaller and smaller length scales. As I indicated from these doping studies where we could only indirectly determine this, we need better methods to determine chemical composition. One needs approaches to determine electronic structure—the electrical properties which can change due to changes in dimensionality; that is, the transport of materials, optical properties, mechanical properties etc. The key thing is that we really want this information down at the single molecule scale which places very strong constraints on how one gets it. The reason for requiring that the information be generated on an individual nanostructure is due to heterogeneity—nanostructure-to-nanostructure variation. If one really wants to understand fundamentals, we need those types of techniques.

What kind of tools and facilities can give us this technique? Electron microscopy is clearly an important tool and it is going to remain important. We have to acknowledge the fact that all of our electron microscopy work has been done almost exclusively at MIT, and I think MIT recognizes the importance of this technology. There are scan probe microscopies and there are many guises. They continue to be important and as people continue to make creative variations of these techniques to get additional information, they will play an increasingly important role. I consider nanofabrication facilities absolutely essential as a tool or facility for characterization in this area. If you can't connect to materials, you can't understand them. There have been tremendous advances in optical microscopies that allow one to get at the single nanostructure but this continues to be important.

The thing to keep is we need to improve the resolution and we need to improve the type and detail of information that we can get out of these techniques. If you are thinking about facilities or organizations for the future, you need to bring together this type of instrumentation in an interactive environment, not only just physicists and engineers, but involving chemists and biologists. The multidisciplinary interactions are going to enable great things in the future.

# EDWIN L.THOMAS

## *MORRIS COHEN PROFESSOR OF MATERIAL SCIENCE AND ENGINEERING AND*

## *DEPUTY DIRECTOR OF THE MICROPHOTONICS CENTER*

## *MASSACHUSSETTS INSTITUTE OF TECHNOLOGY*

## NANO MATERIALS AND DEVICES

Thank you. It is a pleasure to be here.

Instead of talking about a single research program, I am going to talk about the Microphotonics Center's efforts and give you some highlights of our work.

I think what you will take away is that a hierarchical structure is a good description. A lot of the people working in microphotonics and thus are working from the nano scale upward and integrating things. We believe very strongly about using microphotonics as a platform for the next revolution in information. My talk will touch on the work of a number of other people and some of my own.

Computer power is very available and very cheap; the scarce quantity now is bandwidth. Currently Tb/s capacity is in the fiber backbone, but in fact people work with a lot slower speeds in the overall network. Therefore, there are lots of opportunities to improve things by taking the network from electrical to electro-optical to perhaps even an all-optical network. Along the way, there are plenty of materials characterization issues, materials processing issues and nano scale and micro scale phenomena and structures.

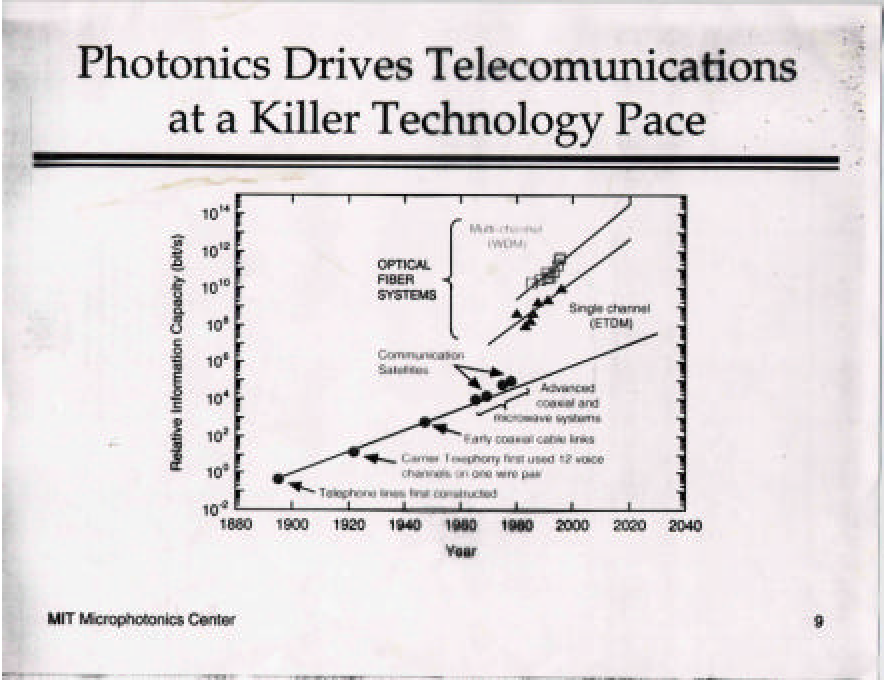
So, I would like to talk a bit about the next "killer" technology: microphotonics. We have the Microphotonics Center at MIT that actually grew out of the NSF materials research lab and now involves about 20 faculty. Some of the activities focus on using high-dielectric contrast materials—that is a high refractive index and a low index material. This affords opportunities for smaller size components. One can confine light and bend it and turn it and route it in smaller dimensions. You are able to concentrate and make higher optical fields.

The Center has a mission statement and at the heart of it is "new materials, structures and architectures." The focus is to take this scientific base and attack the problems of integrating photonic systems.

The Center has several themes. One is to keep track of things using an optical clock. If you are going to do communications over fiber networks, certainly wavelength division multiplexing is a challenge and there is a lot of activity there. Other aspects include things like displays, modulators, and the whole business of being able to measure things with precision—the metrology that has been mentioned before in Professor Smith's presentation.

Figure 1 is a semilog plot that has information capacity in bits per second on the vertical axis and time on the horizontal axis. Just before 1900 the telephone came along and two people could talk to one another. About 1920 or so there are 12 voices going over a single twisted pair of telephone lines. Then something revolutionary happened in the early 1980s: the first optical fibers come along. Lionel Kimerling, Director of the MIT Microphotonics Center, then was at Bell Labs and people were working on microwave power and coaxial cables and they thought these were the optimum in capacity. Then optical fibers came along and then came the Internet, and now every one wants the capacity to take off. It is a whole new paradigm to go into optical transmission, and we are up into the 10 to the 12 Terabits per second range at the present and needing more all the time.

Figure 1



Photonics Drives Telecomunications
at a Killer Technology Pace

MIT Microphotonics Center

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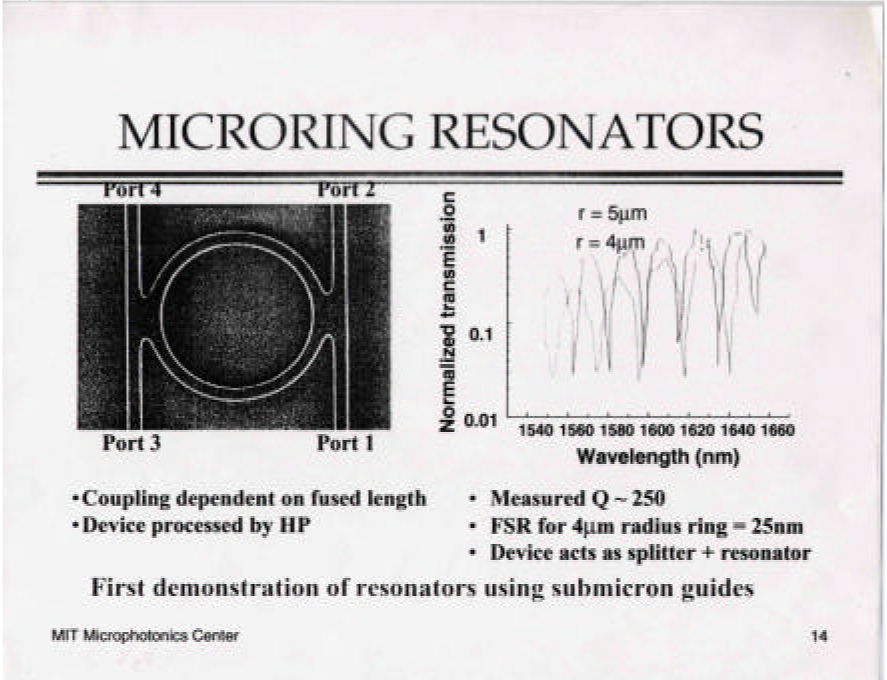
Telecommunications activity covers a whole range. There is everything from wide area networks where you are sending signals from one metropolitan area to another or across the ocean, to the whole field called “fiber to the home.” Right now you have telephone lines coming in. Usually there is a cable line to your house for your TV or your computer. In the future this may be a single fiber which brings all the information you need in and also takes all your signals and responses out. To do that, we need to integrate, which is a big challenge. A lot of signals that are transmitted optically get converted into electrons which are processed and then resent on. That interconversion presents a bottleneck in the network. One of the things to do is to develop materials that allow us to keep everything all optical. Integrated optical circuits is another main theme within the Center.

Figure 2



MICRORING RESONATORS

- Coupling dependent on fused length
- Device processed by HP

- Measured Q ~ 250
- FSR for 4µm radius ring = 25nm
- Device acts as splitter + resonator

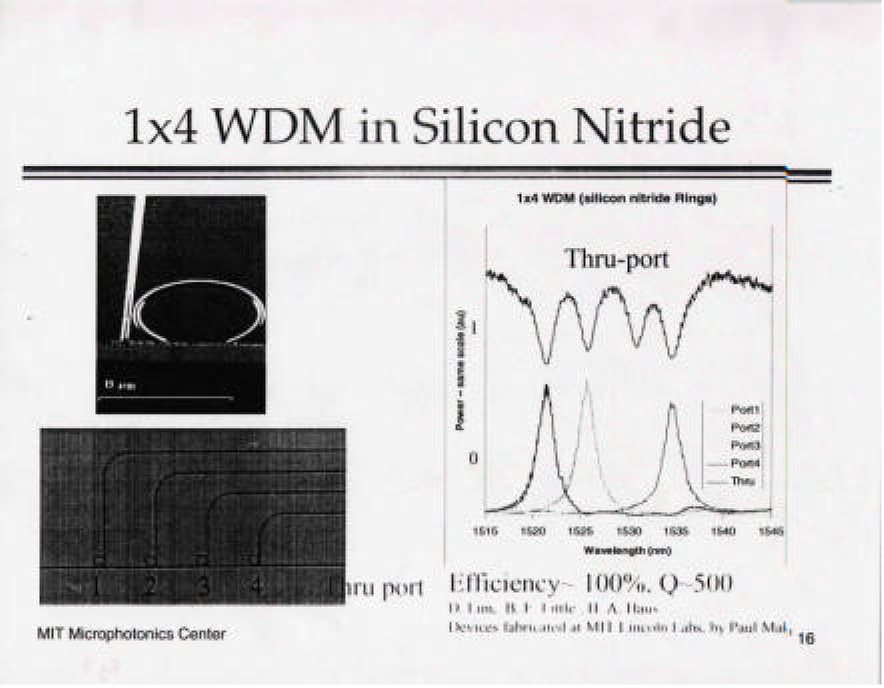
**First demonstration of resonators using submicron guides**

MIT Microphotonics Center 14

Figure 2 depicts a microring resonator. Photons moving along the waveguide could be coupled into another waveguide through a ring resonator. Shown here is a response for two different radii of the ring and the design wavelength is 1.5 microns, the telecommunication wavelength. These are very small devices that allow coupling and transfer of information without converting photons to electrons and back to photons.

Figure 3 is another router. The bottom picture shows a throughport—a fiber that is carrying four different wavelengths—and you want to pick off each of the wavelengths and send it to some other place. The side view of one of these resonators is shown with the fibers coming along with the multiple wavelengths on it. The actual characterization—not only structural characterization but also optical performance characterization—of these different ports is known. Ports 1to 4 have power going through them at very precise wavelengths that were designed in the telecommunications regime where the separation in wavelength is 5 nm. Here is the signal that was sent down the pipe, and the figure shows the losses that occur as each of the different signals drops off into the separate fibers that carry it off to another destination.

Figure 3



1x4 WDM in Silicon Nitride

Efficiency~ 100%, Q~500

D. Lim, B. E. Little, H. A. Haus

Devices fabricated at MIT Lincoln Labs. by Paul Mai,

MIT Microphotonics Center

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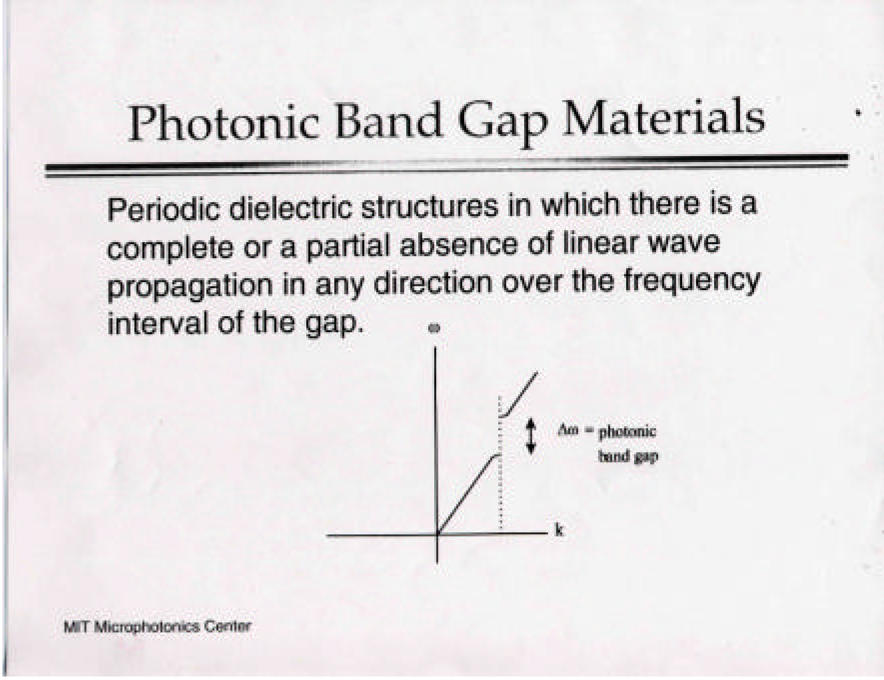
An important part of photonics is photonic crystals. Moropho butterflies are beautiful blue butterflies which have no blue pigment whatsoever. Their color is made by an optical effect of selected reflection of blue light. If you look at a SEM picture of the upper wing of the butterfly, you see very detailed structures that nature built. Likewise, a natural opal is made out of silica spheres that are stacked together in a close packed array. It is the index difference between the silica and the air that gives opal its nice colors.

People are working hard trying to build photonic crystals, that is crystals that interact with light. A special type of photonic crystal is a photonic band gap material. We have just heard a lot in the previous talk about electronic band gaps. I want to introduce you to an analogous concept for photons and that is photonic band gaps. Figure 4 depicts a dispersion relationship with frequency versus K vector where there is a gap where certain frequencies are not allowed to propagate inside the crystal. If you have a periodic dielectric and you have a photon, the solutions are block waves, and, depending upon the structure of the crystal, some of the waves may be diffracted and not allowed to propagate. This phenomena can be used in neat ways to make materials called photonic band gap materials.

Figure 4



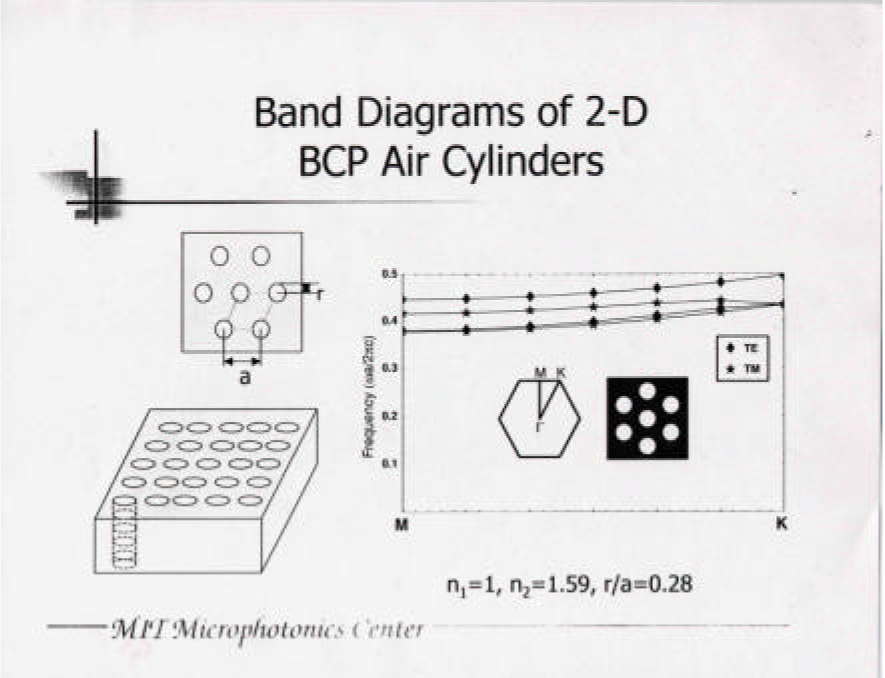
Photonic Band Gap Materials

Periodic dielectric structures in which there is a complete or a partial absence of linear wave propagation in any direction over the frequency interval of the gap.

MIT Microphotonics Center

If you want to design photonic band gap materials, there is a design criteria which highlights the letter “D”. You must consider the necessary Dielectric contrast, the right Distances, low Dissipation, and good control of Defects. Defects in general are not good, but defects can be very valuable if you can control them and put them exactly where you want.

Figure 5



Band Diagrams of 2-D
BCP Air Cylinders

$n_1=1$, $n_2=1.59$, r/a=0.28

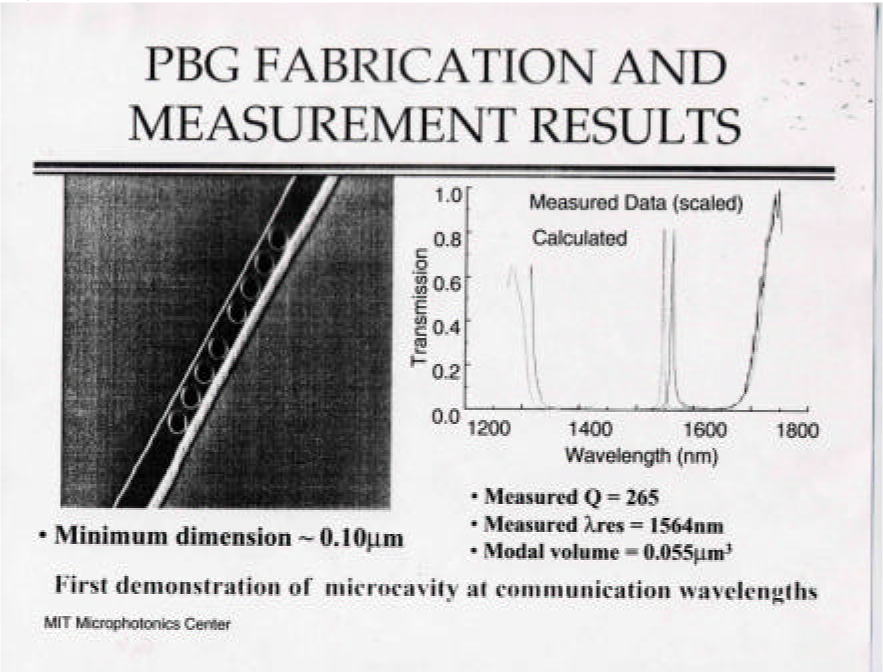
MIT Microphotonics Center

Figure 5 depicts a two dimensional example of a band structure for cylinders of air in a high dielectric. For wave vectors incident normal to the cylinders, there is a set of frequencies which are forbidden. No allowed propagating states are there, so light propagating perpendicular to those cylinders would be completely reflected. This is an omnidirectional, two-dimensional band gap which allows us to control photons.

Professor Joannopoulos, a theorist in our Microphotonics Center and one of the experts in the world, wrote a book called *Photonic Crystals: Molding the Flow of Light*. That is a very interesting concept to think about—being able to make light go where you want it to go. You forbid it to go inside a photonic crystal unless there is a purposefully made defect in the crystal in which case it can follow the defect or be trapped on the defect.

Figure 6 shows the use of a defect in a device. The device is called an air bridge. Lithography has been used to produce a structure in Si in which you see a waveguide which has a series of holes periodically spaced, except in one place where one hole is missing. On purpose, a set of various wavelengths would be propagating down the waveguide and they would see this periodic dielectric and the various waves would be reflected back, except for a narrow set of certain wavelengths which would be able to go unopposed right through this defect. You can think of the defect as putting a state in the gap, just like when you dope a semiconductor. There is a state within the band gap which allows a particular wavelength to pass unimpeded along this particular waveguide. It is, in fact, a filter: a bunch of different frequencies come along, but only one is allowed to traverse this bridge.

Figure 6



PBG FABRICATION AND MEASUREMENT RESULTS

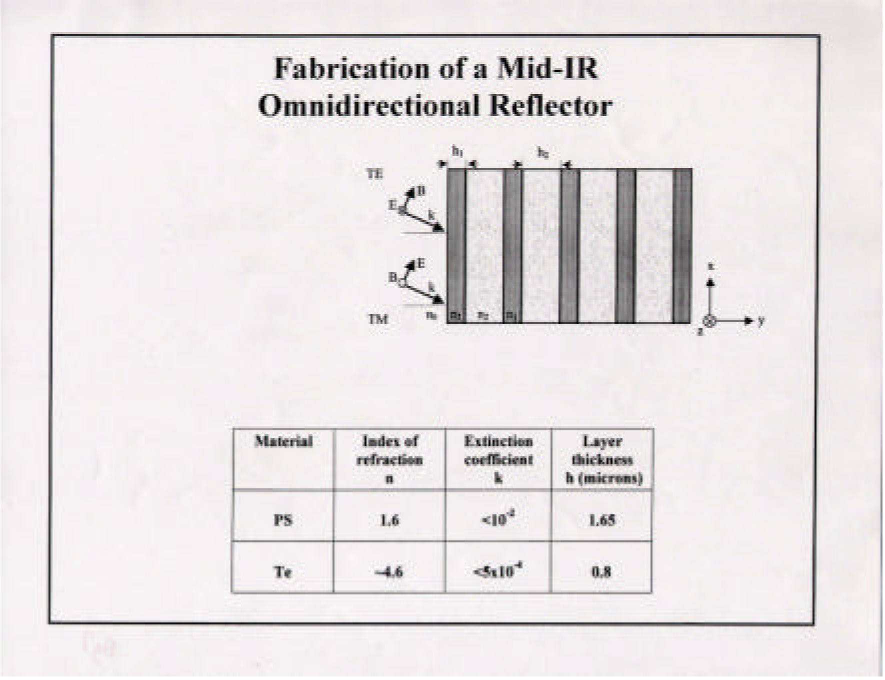
- Measured Q = 265
- Measured λres = 1564nm
- Modal volume = 0.055μm³
- Minimum dimension ~ 0.10μm

First demonstration of microcavity at communication wavelengths

MIT Microphotonics Center

We have done some work on mirrors—simple one dimensional devices. Figure 7 depicts the MIT MIROR (Mid-IR mirror). It is a simple one-dimensional dielectric stack with alternating layers of a high index and a low index. It is made out of simple materials. The idea here is that if you have a high enough index contrast you can actually make the band gaps open up.

Figure 7

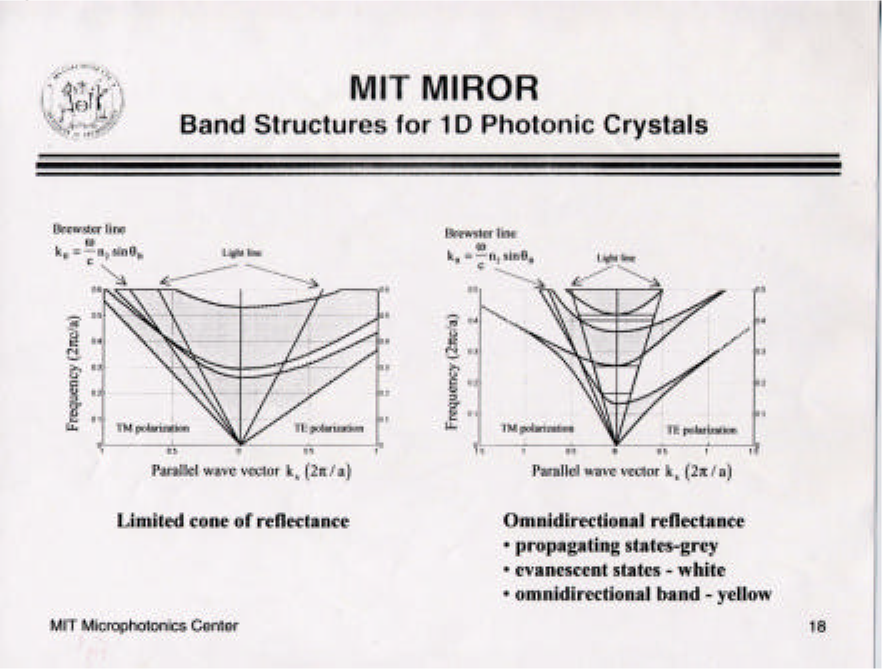


Fabrication of a Mid-IR Omnidirectional Reflector

| Material | Index of refraction n | Extinction coefficient k | Layer thickness h (microns) |
|---|---|---|---|
| PS | 1.6 | $<10^{-2}$ | 1.65 |
| Te | ~4.6 | $<5\times10^{-4}$ | 0.8 |

Figure 8 shows two band diagrams with frequency plotted versus the parallel component of the wave vector. In the left diagram, the white band is the set of forbidden states where frequencies and certain wave vector combinations are not allowed to propagate in the material. On the right is the same kind of diagram, except instead of having a relatively low dielectric contrast, we used very large dielectric contrast. The band gaps increased in width. In fact, in the second band, a higher harmonic band gap opens up. This is a very simple one-dimensional design. The light line is also shown on the diagram. If an incident wave from outside the material enters the material, Snell's Law causes it to refract so the angles that light can enter the material are limited to be over the cone of angles contained between the two straight lines. It turns out that if you have frequencies which are forbidden all the way to the light cone, then basically you have an omnidimensional reflector.

Figure 8



**MIT MIROR**

**Band Structures for 1D Photonic Crystals**

**Limited cone of reflectance**

**Omnidirectional reflectance**
- **propagating states-grey**
- **evanescent states - white**
- **omnidirectional band - yellow**

MIT Microphotonics Center

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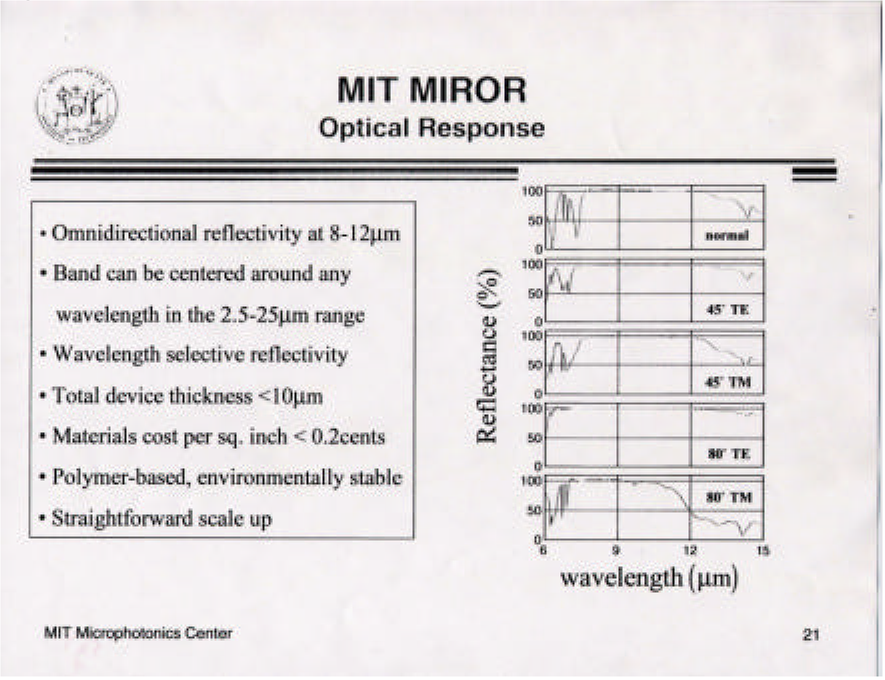
Figure 9 shows a series of experiments where we measured reflectance versus wavelength. We designed a device to have a band gap between 8 and 12 microns, and reflectivity is shown at normal incidence, at $45^o$ and at $80^o$. One sees there is complete reflectivity throughout the 8-12 micron wavelength regime. With these you do not have to specify an angle of optimization for the mirror because these mirrors are good reflectors at all angles. One other thing you can do with the MIROR is roll it up and make a tube out of it. Now you have a one-dimensional stack which has a hollow center. We call this the omniguide. The center of the device is empty and can guide light in the low-density air surrounded by an alternating layer structure of high and low dielectrics. It confines the light in the tube. Because the light is not guided by total internal reflection but guided by a photonic effect, you can bend this tube in any direction and any radius you want, and the light can't leak out of it. There is not much absorption of light in the middle of the tube because it is s hollow tube. Therefore, there is very low loss so you can transmit very high power. It also guides a very wide band width because you can control the stop band by the choice of the dielectric materials you use.

Figure 9



## MIT MIROR

### Optical Response

- Omnidirectional reflectivity at 8-12µm
- Band can be centered around any wavelength in the 2.5-25µm range
- Wavelength selective reflectivity
- Total device thickness <10µm
- Materials cost per sq. inch < 0.2cents
- Polymer-based, environmentally stable
- Straightforward scale up

MIT Microphotonics Center

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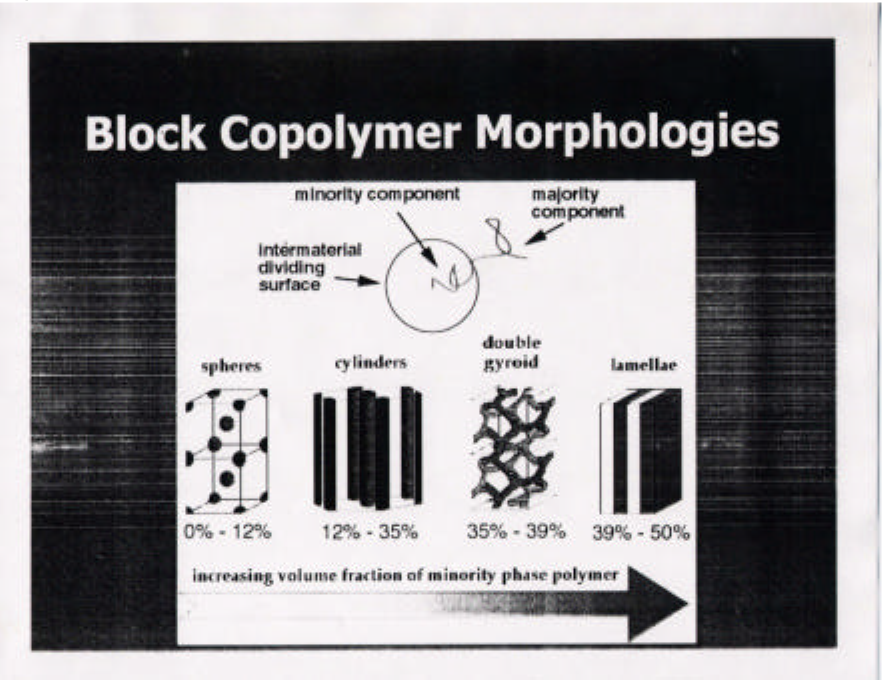
Let me finish up with a little bit about self assembly and how that can actually be used for photonics. Block copolymers are simple materials that are comprised of covalently linked blocks. Figure 10 shows polystyrene linked with polyisoprene. The styrene and isoprene repel one another, so you have self assembly of the styrene and the self assembly of the isoprene avoiding one another, and these molecules form various periodic structures. Figure 10 shows some of the kinds of structures that are possible. The particular periodicity you get depends on the ratio of the volumes of the two blocks. If they are about the same ratio, you get flat interfaces and what we call lamellae. If you have very asymmetrical ratios, let us say a short blue block and a very large white block, you would have blue spheres in a matrix comprised of the other block. Two-dimensional cylinders come in at a different composition. And there are interesting interconnected cubic networks between the lamellae and the cylindrical states. The length scale of block copolymers is controlled by the molecular weight. In fact, one of the challenges is in order to interact with visible and maybe even telecommunications wavelengths, we need to go very large molecular weights.

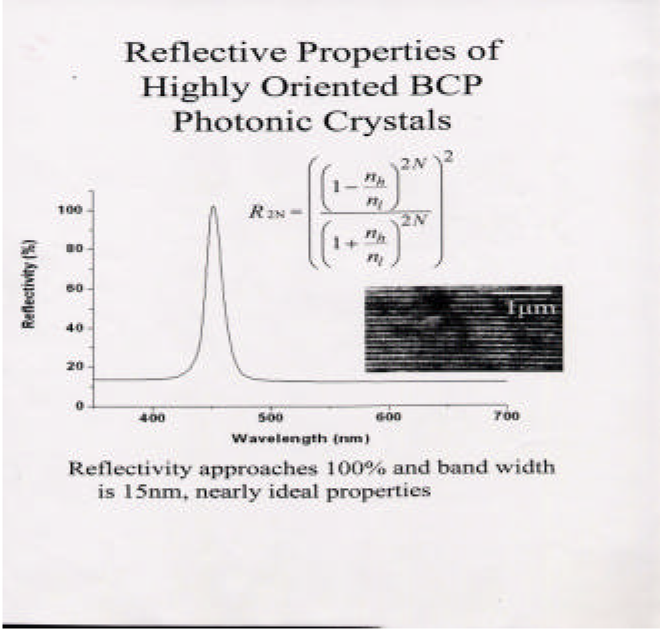
Figure 10


Block Copolymer Morphologies

increasing volume fraction of minority phase polymer

Figure 11 depicts a reflector that displays 90% reflectivity with a very narrow band width which is nearly ideal for this material. The material down on a surface causes it to self-assemble into layers—you can see this in cross sectional microscopy as a beautiful periodic one-dimensional array which acts as a selective mirror. This material was made with a 400,000 molecular weight polystyrene block and a hydrogenated 400,000 molecular weight polyisoprene. So molecular weights have to be made very large to get large length scales to interact with visible light.

Figure 11



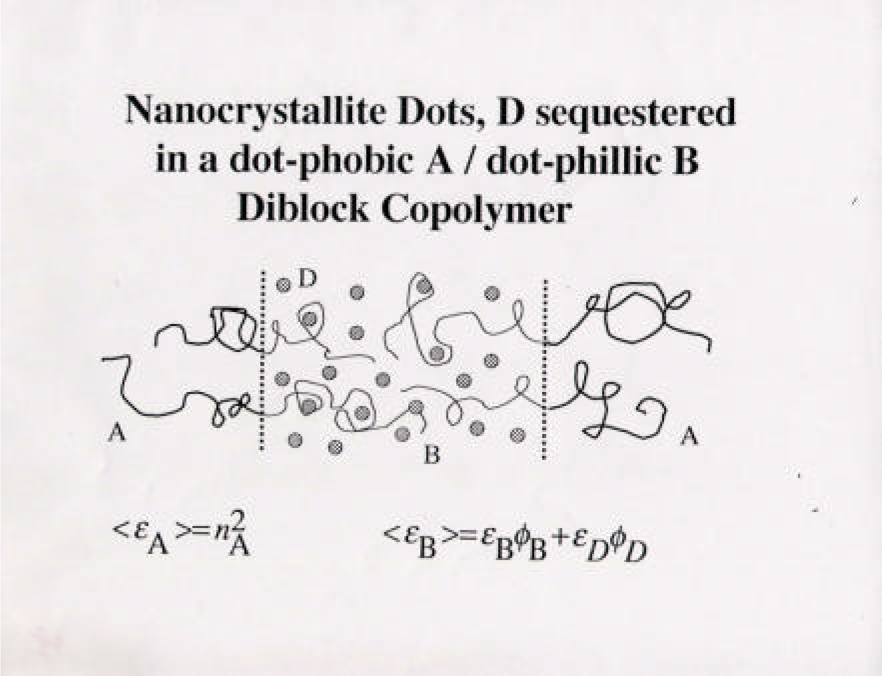
Reflective Properties of
Highly Oriented BCP
Photonic Crystals

$$R_{2N} = \left( \frac{\left(1 - \frac{n_h}{n_l}\right)^{2N}}{\left(1 + \frac{n_h}{n_l}\right)^{2N}} \right)^2$$

Reflectivity approaches 100% and band width
is 15nm, nearly ideal properties

The other thing we mentioned in one of the design criteria was dielectric contrast. Polymers inherently do not have very different dielectric indices. One of the things we can do at the nanoscale is put particles inside the material to build index. The concept here is to use quantum dots which can be used also as an active light emitting material. If you make something which dots are attracted to—such in figure 12—where there is a dot-phillic block and a dot-phobic block, the A block would have its index unchanged by the addition of the particles while the B block would have an index based on rule of mixtures additivity. The dielectric contrast in this self-assembled system of nanoparticles and block copolymer would be much higher and this enhances the applications of these kinds of materials.

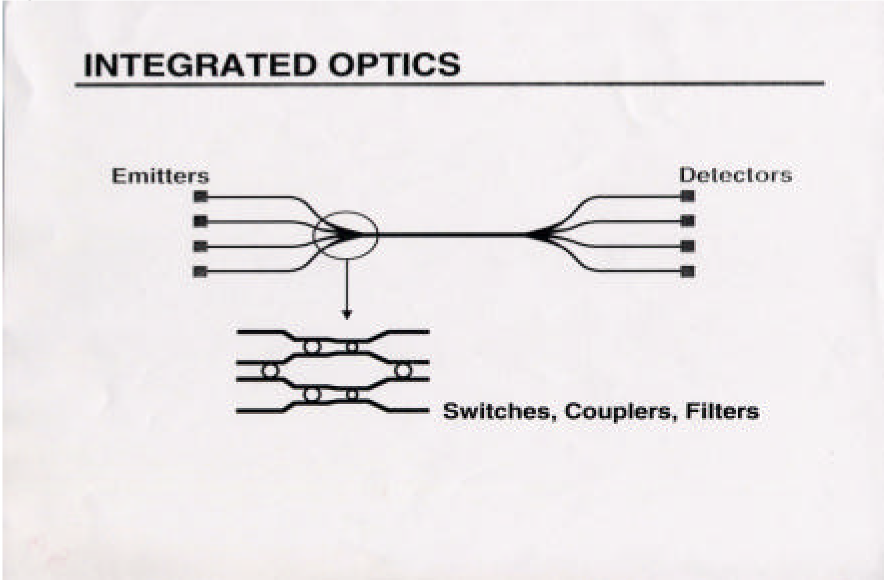
Figure 12



Nanocrystallite Dots, D sequestered in a dot-phobic A / dot-phillic B Diblock Copolymer

$<\varepsilon_{\mathrm{A}}>=n_{\mathrm{A}}^2$ $<\varepsilon_{\mathrm{B}}>=\varepsilon_{\mathrm{B}}\phi_{\mathrm{B}}+\varepsilon_D\phi_D$

Figure 13



INTEGRATED OPTICS

In closing, let me say a little about the future. There are lots of opportunities and research that needs to be done. Figure 13 is a ten-year outlook where optical networks have become all-optical so the bottleneck is removed. That is, signals do not have to be converted from photons to electrons and then back to photons. Right now there are a lot of parts of the network that are doing that and those are slow parts. Perhaps in a few years we will start to see some of this nano technology coming in where everything will be miniaturized. One of the drivers for microphotonics is to put optical devices on silicon chips that normally are centimeters or so pieces of equipment. If you can make light bend and route it around and do your wavelength division multiplexing and modulate and you can do it on micron scale rather than on centimeter scale, there will be much better efficiency and price. As things tend to shrink over time in all fields and they tend to integrate over time in all fields, we may be seeing in 20 years some really astounding nanoscale structures coming into photonics.

Thank you for your attention.

# DOH-YEON KIM

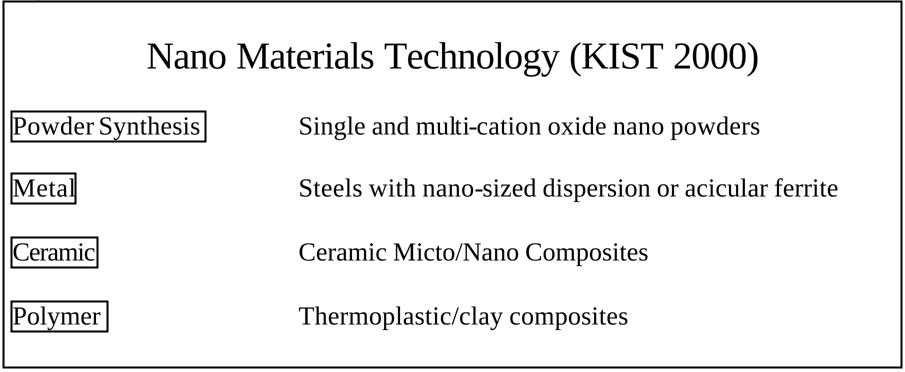
***DIRECTOR***
***CENTER FOR MICROSTURCUTRE SCIENCE OF MATERIALS***
***SEOUL NATIONAL UNIVERSITY***

## NANOSTRUCTURE MATERIALS: SCIENTIFIC AND TECHNOLOGICAL RESEARCH ACTIVITIES IN KOREA

My presentation today is going to focus on materials research, not the devices. I am going to review the scientific and technological research activities on nanostructure materials in Korea.

The fifth International Conference on Nanostructure materials was held last August in Sendai, Japan. There were many papers submitted by Koreans indicating that research in this field is very active in Korea. I will introduce today the work of several Koreans in this field.

Figure 1



Nano Materials Technology (KIST 2000)

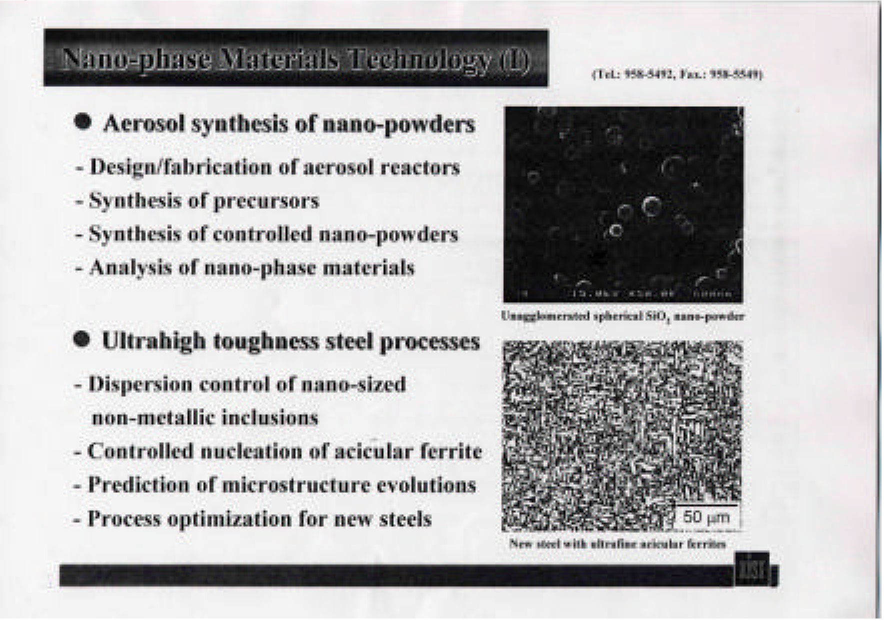
| | |
|---|---|
| Powder Synthesis | Single and multi-cation oxide nano powders |
| Metal | Steels with nano-sized dispersion or acicular ferrite |
| Ceramic | Ceramic Micto/Nano Composites |
| Polymer | Thermoplastic/clay composites |

Dr. Huesap Song, hssong@kistmail.kist.re.kr

The first is research being conducted in the Korea Institute of Science and Technology (KIST) which is the highest ranking research institute in Korea. They have their own funding program called KIST 2000 and the research on nanomaterials is supported by KIST 2000. The project leader is Dr. Song. Figure 1 shows the areas of their work.

Figure 2 illustrates spherical nanopowder made in KIST by using an aerosol technique. They are working from design of aerosol reactors to the analysis of obtained powders. On the other hand, this shows the micro-structure of a new scale which are defined as acicular ferrite. The toughness of this material is known to be better than any other steel product. They are controlling the nucleation of acicular ferrites and they are optimizing the process.

Figure 2



## Nano-phase Materials Technology (I)

(Tel.: 958-5492, Fax.: 958-5549)

- **Aerosol synthesis of nano-powders**
  - Design/fabrication of aerosol reactors
  - Synthesis of precursors
  - Synthesis of controlled nano-powders
  - Analysis of nano-phase materials

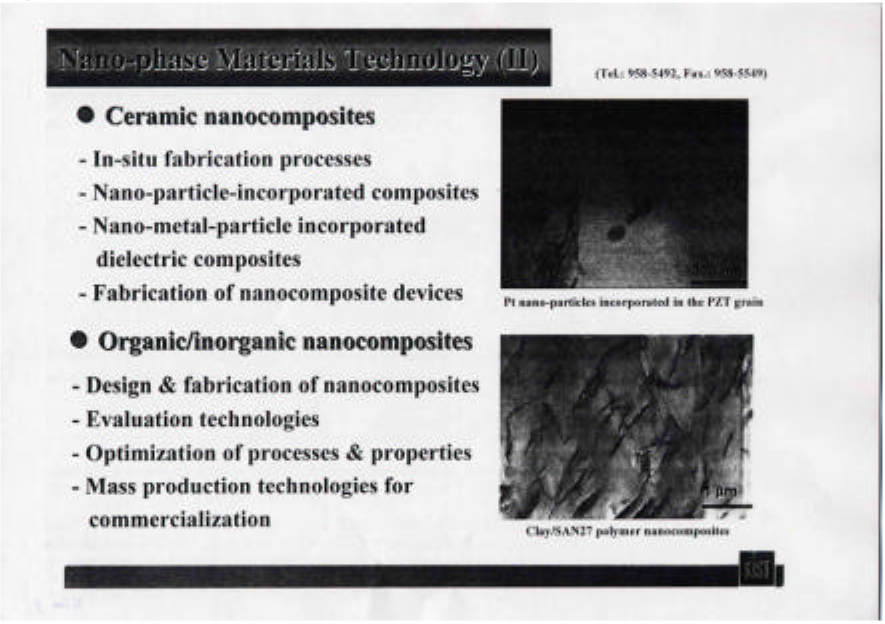
Unagglomerated spherical $SiO_2$ nano-powder

- **Ultrahigh toughness steel processes**
  - Dispersion control of nano-sized non-metallic inclusions
  - Controlled nucleation of acicular ferrite
  - Prediction of microstructure evolutions
  - Process optimization for new steels

New steel with ultrafine acicular ferrites

For ceramic nanocomposites, nano-particles are usually incorporated in various materials. Figure 3 shows Pt nano-particles incorporated in PZT grain. Also at KIST, they are developing high-strength polymer nanocomposites by dispersion of very fine clay powders. They are now in the technology transfer stage for mass production.

Figure 3



Nano-phase Materials Technology (II)

(Tel.: 958-5492, Fax.: 958-5549)

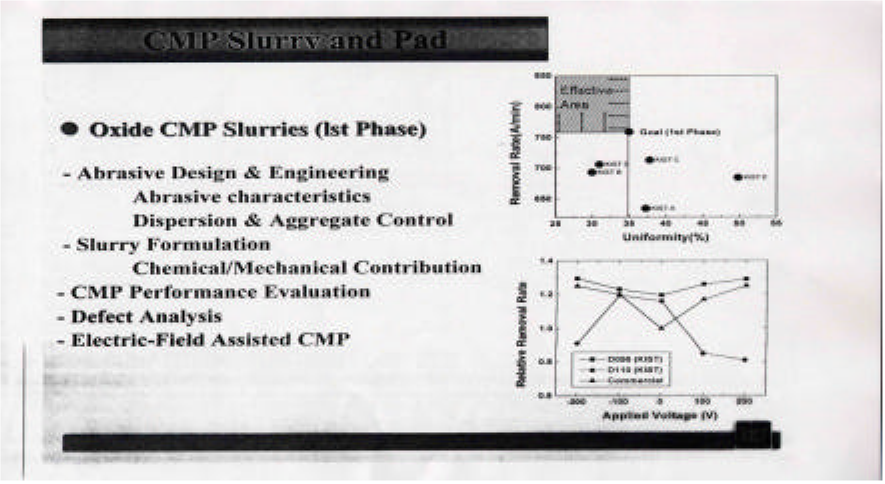
- **Ceramic nanocomposites**
  - In-situ fabrication processes
  - Nano-particle-incorporated composites
  - Nano-metal-particle incorporated dielectric composites
  - Fabrication of nanocomposite devices
- **Organic/inorganic nanocomposites**
  - Design & fabrication of nanocomposites
  - Evaluation technologies
  - Optimization of processes & properties
  - Mass production technologies for commercialization

Pt nano-particles incorporated in the PZT grain

Clay/SAN27 polymer nanocomposites

Through this research, they have developed many things. The first example is a chemical/mechanical/polishing (CMP) slurry. Figure 4 shows its properties. The removal rate of the CMP slurry is much better than any commercial product.

Figure 4



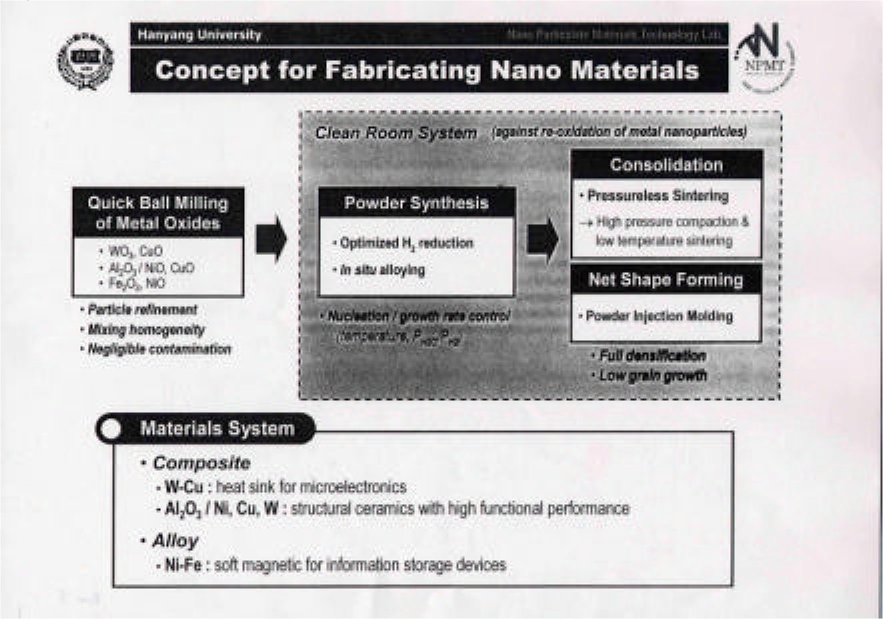
CMP Slurry and Pad

- **Oxide CMP Slurries (lst Phase)**
  - Abrasive Design & Engineering
    - Abrasive characteristics
    - Dispersion & Aggregate Control
  - Slurry Formulation
    - Chemical/Mechanical Contribution
  - CMP Performance Evaluation
  - Defect Analysis
  - Electric-Field Assisted CMP

Now I will discuss the research work of Professor Lee of Hanyang University. His research subject is bulk nanostructure materials. At Hanyang University they are making nanopowders by using mechano-chemical process. Bulk materials are obtained by pressureless sintering and powder injection molding. They are also working for in situ characterization of nanoparticals.

Figure 5 illustrates their overall processing route for nanomaterials using various oxide powders such as $WO_3$. These powders are reduced in a controlled hydrogen atmosphere and the bulk materials are obtained by sintering. Full densification and minimum grain growth is most important during this process. The materials they have developed are tungsten copper composite for microelectronics and aluminum copper composite for high-strength ceramic materials and Ni-Fe alloy for information storage devices.

Figure 5



Hanyang University    Nano Particulate Materials Technology Lab.

**Concept for Fabricating Nano Materials**

NPMT

**Quick Ball Milling of Metal Oxides**
- $WO_3$, CuO
- $Al_2O_3$ / NiO, CuO
- $Fe_2O_3$, NiO

- *Particle refinement*
- *Mixing homogeneity*
- *Negligible contamination*

*Clean Room System* *(against re-oxidation of metal nanoparticles)*

**Powder Synthesis**
- Optimized $H_2$ reduction
- *In situ alloying*

- *Nucleation / growth rate control* (temperature, $P_{H2O}/P_{H2}$)

**Consolidation**
- Pressureless Sintering
  → High pressure compaction & low temperature sintering

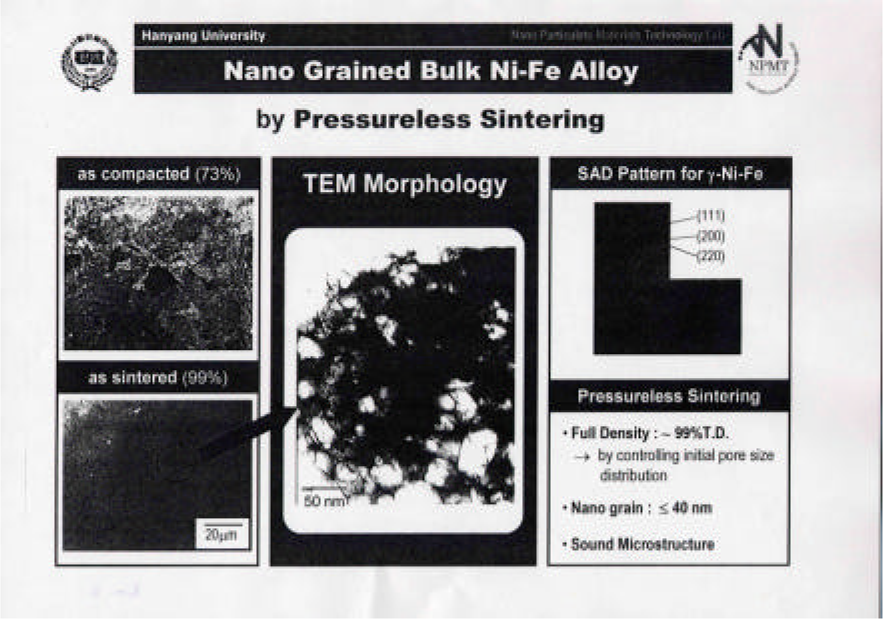
**Net Shape Forming**
- Powder Injection Molding

- *Full densification*
- *Low grain growth*

**Materials System**
- *Composite*
  - **W-Cu** : heat sink for microelectronics
  - **$Al_2O_3$ / Ni, Cu, W** : structural ceramics with high functional performance
- *Alloy*
  - **Ni-Fe** : soft magnetic for information storage devices

Figure 6 shows nano grained bulk nickel alloy that they have developed by pressureless sintering. Before sintering the composite has only 73% of theoretical density, but after sintering full density was obtained. The average grain size of material is less than 40nm. This material is known to have very excellent magnetic properties.

Figure 6



Hanyang University

## Nano Grained Bulk Ni-Fe Alloy

by **Pressureless Sintering**

as compacted (73%)

as sintered (99%)

20μm

TEM Morphology

50 nm

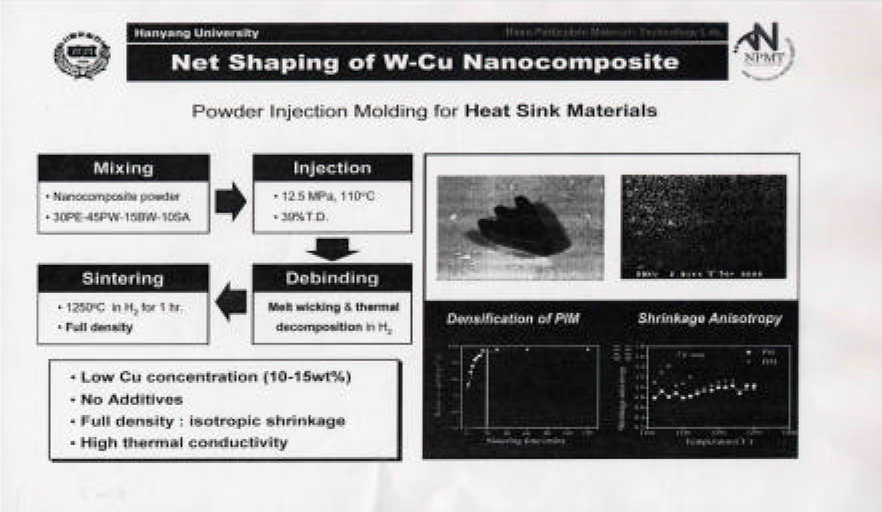
SAD Pattern for γ-Ni-Fe

Pressureless Sintering

- **Full Density : ~ 99%T.D.**
  → by controlling initial pore size distribution
- **Nano grain : ≤ 40 nm**
- **Sound Microstructure**

Figure 7 illustrates a tungsten copper component they have made by powder injection modeling. After sintering at 1250 degrees for one hour in hydrogen atmosphere they reached full density with isotropic shrinkage. This material is also known to have various advantages such as high thermal conductivity.

Figure 7



Hanyang University

## Net Shaping of W-Cu Nanocomposite

Powder Injection Molding for **Heat Sink Materials**

**Mixing**
- Nanocomposite powder
- 30PE-45PW-15BW-10SA

**Injection**
- 12.5 MPa, 110°C
- 39%T.D.

**Debinding**
Melt wicking & thermal decomposition in $H_2$

**Sintering**
- 1250°C in $H_2$ for 1 hr.
- Full density

- **Low Cu concentration (10-15wt%)**
- **No Additives**
- **Full density : isotropic shrinkage**
- **High thermal conductivity**

*Densification of PIM*

*Shrinkage Anisotropy*

Let me now move to the work of professor Choi who is working at the Seoul National University as a professor in the school of mechanical and aerospace engineering. He is the head of the Creative Research Initiative (CRI) Center. Around 3 years ago the Korean government decided to stimulate creative research and began funding a new program called CRI. Since then, around 40 to 50 new research centers under this umbrella have been established. The Center for Nanopartical Control is one of them. The research objectives are to:

- Establish methods to control size, morphology, crystalline of nanoparticles of various materials
- Establish measuring and modeling technique for growth of nanoparticles, and
- Understanding the fundamentals of the evolution of nano aggregates.

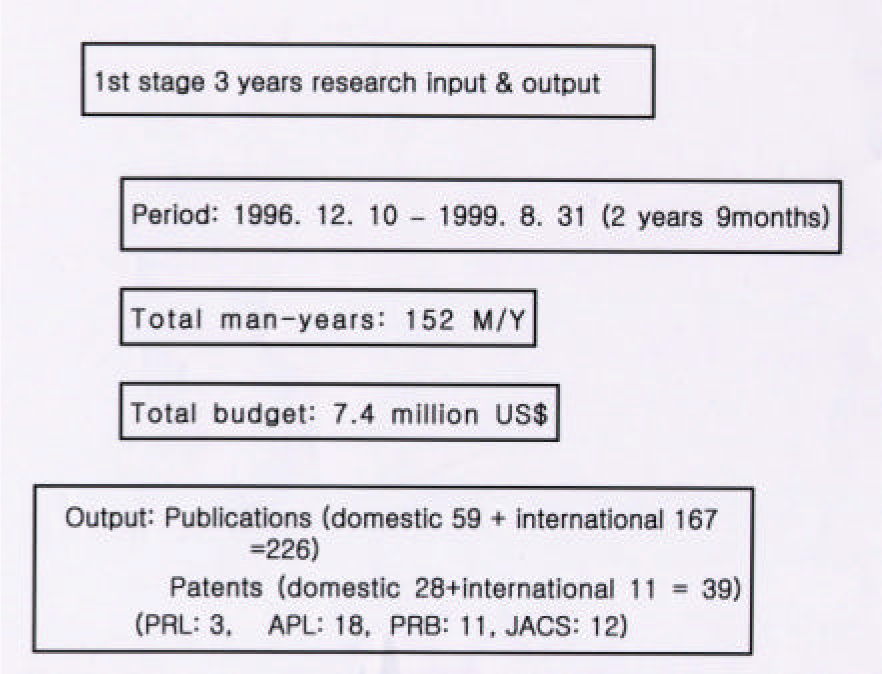
They are mainly using flame aerosol technique. They are investigating formation process and the composition of multicomponent nanoparticles.

Another important research group in Korea on nano structures and materials is in the Korean Institute of Machinery and Materials (KIMM). This projected is supported by the High-level Advanced National (HAN) project, which is for the application of research. The project leader is Dr. Kim. They are developing nanostructures: WC-Co and W-Cu by using the chemical vapor condensation (CVC) process.

I would finally like to introduce the work of Dr. Moon who is working at the Korean Institute of Standards and Science (KRISS). He has a nanostructures technology project which is a nine-year project aiming for the development of nanodevices such as single electrons transistors and quantum dots. “From atoms through devices to materials” is their catch phrase. This project is quite unique in terms of interdisciplinary studies. It brings together physics, material science and electronics. Many different research organizations such as KRISS, KIST, etc. are participating. Their main research objective is to develop a room-temperature SET device and high-density magnetic media. They are now in the second stage. The project began in 1996. They have completed their first three-year stage.

Figure 8 shows the input and output of the first three-year phase. During that time they used $7.4 million research funds. They have published more than 200 papers and they have 40 patents.

Figure 8



1st stage 3 years research input & output

Period: 1996. 12. 10 – 1999. 8. 31 (2 years 9months)

Total man-years: 152 M/Y

Total budget: 7.4 million US$

Output: Publications (domestic 59 + international 167 =226)
Patents (domestic 28+international 11 = 39)
(PRL: 3, APL: 18, PRB: 11, JACS: 12)

While it is true that the research activities on nanostructure materials in Korea is quite limited compared to that of the United States, in certain areas, Korean researchers are quite active. I hope mutual cooperation will be enhanced in the future.

# POLICY AND TECHNICAL ROUNDTABLE

## *SUMMARY REPORT*

Dr. Robert Trew, Director of Research, U.S. Department of Defense and Min-Koo Han, Secretary General, Korea Research Foundation, presided over the roundtable discussion.

A panel of experts facilitated the discussion by presenting brief opening remarks. The panel included: Dr. Seth Lloyd, Associate Professor of Mechanical Engineering, Massachusetts Institute of Technology; Mihail C. Roco, Senior Advisor on Nanotechnology, U.S. National Science Foundation; Stephen Chou, Professor, Department of Electrical Engineering, Princeton University; Jo-Won Lee, Director, the National Program for Tera-level Nanodevices Development; Jong-Oh Park, Director, the National Program for Intelligent Microsystem Development; and Kyoungwan Park, Leader and Project Manager, Nano Electronic Devices Research Team, the Electronics and Telecommunications Research Institute.

Dr. Trew provided some issues to inspire questions and discussion. He asked whether or not nanotechnology is truly a broad spectrum applicable to a wide range of research disciplines, or are certain areas like electronics, material science, or biotechnology more likely to profit. He asked what are the major barriers to nanotechnology as well as whether or not resource sharing through regional, national and/or international centers is a good or viable approach. He also laid out some policy issues such as whether or not the concept of nanotechnology is being oversold. Is nanotechnology true long-range basic research? If so, will or why should industry invest in it? Will the issue of intellectual property rights be a stumbling block to industry participation and international collaboration? Finally there is the issue of ethics. Are there areas of research that should be avoided?

Seth Lloyd explained his work which is to design and build quantum computers. The kind of research that he does is often sub-nanoscale engineering, but his goal is to design larger and larger quantum computers which will extend upward into the nanoscale. He noted that he is interested in trying to explore the ways that quantum mechanics affects engineering at the nanoscale.

Kyoungwan Park suggested that Korean and U.S. scientists engage in collaboration in the field of nano science. He suggested that it is better to exchange young researchers in core technology areas. He noted that there are still many problems in using the AFM and STM technique that could benefit from collaboration. He stated that there is no reliable nanolithography technique right now with resolution of 15nm or less. Therefore, he recommended the exchange of young scientists in the field of nanolithography. Since the cost of developing a nanolithography system is very great, he proposed that it is a good candidate for collaboration through a large-scale research project.

Stephen Chou opined that the biggest barrier in realizing the potential of nanotechnology is developing the manufacturing technology. He said there are three factors affecting the increased interest in nanotechnology. First, some of the devices being made right now are being shrunk so small that the new theory in the nanoscale has become significant. Second, sophisticated instrumentation has been developed which allow us to look at things at the nanoscale. And third, there are a number of new fabrication technologies being developed. Suddenly, nanotechnology is no longer just a theoretical science, it can have a real impact on society. Prof. Chou also asked the question: how do we develop the manufacturing technology. He defined the top-down approach and the bottom-up approach. He suggested that we need a new direction which combines the top-down and bottom-up approach called "lithographically-guided or induced self-assembly."

Dr. Jo Won Lee noted that projections for the future indicate that at about 2010 the world market for semiconductors will be $1 trillion. If we can't overcome the technological limit, he suggests that the global economy will be in big trouble. He suggests that international collaboration is necessary. He indicated that there are potential partners in both countries for collaboration. In Korea the National Program for Tera-level Nanodevices and Intelligent Microsystem Program could be partners. He suggested that collaboration should be open to nanotechnology-related national programs of both the United States and Korea. He hopes that such collaboration will make a contribution to the advancement of nano science and technology by providing cooperate research between Korea and the U.S.

Dr. Jong-Oh Park mentioned the need for an international symposium between Korea and the United States on nano science and technology. More specifically he proposed that the two countries hold joint workshops on specific topics on a regular basis. The topics need to be very concrete and generate more specific collaboration proposals.

Dr. Mike Rocco noted that it is an exciting time for nano science and technology. The fact that we can manipulate things at the nanoscale has raised the level of interest in the United States. He suggested that there are a number of mechanisms for collaboration. NSF sponsored more than 600 projects in nano science and technology in 2000. The best way to increase collaboration is through investigator-to-investigator contact. A second way is through centers. For example the NNUN is open to foreign participants (50 percent or more are foreign). However, since the centers do not have program money they are not the best way to stimulate collaboration. But the centers do have long-term programs and facilities and therefore, over the long-term may provide a good opportunity for collaboration.

Suk Han Lee has experience in developing commercialized MEMs devices. He noted that there is large gap between basic and applied research and that at this point he emphasized that collaboration should focus on basic knowledge.

During the general comment period, it was agreed that setting up joint workshops on specific topics which could lead to increased collaboration would be a useful way to proceed. There was also a discussion of the differences between collaboration at the commercialization level and at the basic level. Mike Rocco indicated that the government funds a lot of collaboration between foreign and U.S. investigators in countries all over the world. It was agreed that nano science and technology is really small science as opposed to big science with need for large government-to-government intervention. If investigators in one country want to collaborate with investigators in another country and they have the means to do so; the institutions are open.

Several participants noted that there is a strong flow of Koreans to the United States, but not as many from the United States to Korea. A suggestion was made that we should hold workshops on specific areas of nanotechnology where U.S. researchers may be willing to invest time and money to work in Korea on Korean initiatives.

Dr. Han concluded the session by proposing some recommendations. In addition, many participants felt very strongly that there should be specific workshops held in the near future to lay out research agendas in the various fields.

# Appendices

# APPENDIX I

## *RECOMMENDATIONS OF THE KOREA-U.S. FORUM ON NANO SCIENCE AND TECHNOLOGY*

Adopted on September 22, 2000

The Forum,

Recognizing that nano science and technology, together with information technology and biotechnology, will lead the world in the 21st century, characterized as the knowledge-based society;

Noting that as both countries recognized the growing importance of nano science and technology, the Korean government recently launched two nanotechnology-related national R&D programs and the U.S. government announced national initiatives in nano science and technology early this year; and

Convinced that mutual cooperation and partnership is crucial to ensuring the success, as in other areas, in the nano science and technology R&D programs of both countries;

Recommends that the following courses of action to the sponsoring and interested institutions:

1. Nano science & technology-related national programs of Korea and the United States be open to the scientists and engineers of both countries under the principle of mutuality and reciprocity. Scientists of the United States be invited to the Tera-level Nanodevices Development Program and the Intelligent Microsystem Development Program of Korea, and means will be explored to permit Korean counterparts access to the National Nanofabrication Users Network (NNUN) as well as other programs implemented under the umbrella of the national initiatives in nano science and technology of the United States.

2. both countries jointly hold a workshop on nano science & technology on a regular basis. As the first step, a workshop is scheduled to be held in Seoul in April 2001, in which ten experts in nanoelectronics from each country are scheduled to participate.

3. The governments of both countries build, and share the use of databases on national R&D programs and projects as well as experts in nano science and technology in their respective countries.

4. To promote exchange of information and facilitate cooperation in the area of nano science & technology, scientists and engineers of both countries establish a “Cyber Nano Science and Technology Society.”

5. Since the exchange of young scientists is considered to be the most effective means for cooperation, both countries encourage exchange of young scientists in nano science and technology by expanding or strengthening the existing scientists exchange programs between the two countries.

Signed on behalf of the Korean Participants
Min Koo Han
Secretary General
Korea Research Foundation

Signed on behalf of the U.S. Participants
Robert J. Trew
Director of Research
U.S. Department of Defense

# APPENDIX II

## *BIOGRAPHIES*

**Moon Ho Chang** is *president of the Korea Institute of Science & Technology Evaluation and Planning (KISTEP).* His career began as a chemist with Miwon Co., Ltd. in Korea. After his Ph.D., Dr. Chang joined California Institute of Technology (Caltech) as a research fellow. He returned to Korea to lead the Organic and Pharmaceutical Synthesis Lab at the Korea Institute of Science and Technology (KIST). He was also an adjunct professor in the Department of Chemistry at the Korea Advanced Institute of Science and Technology (KAIST). Dr. Chang left KIST to serve as R&D program director for the Highly Advanced National (HAN) Project ('G7 Project') at the Korean Science & Technology Policy Institute (STEPI). He also served as chairman of the Advisory Committee for the National Science & Technology Development Plan Toward 2010. Dr. Chang then moved to the Ministry of Science & Technology (MOST) to serve as director general for R&D Coordination on Chemical Technology and Life Science. After returning to KIST, Dr. Chang was appointed by MOST to serve as chairman of the Planning and Steering Committee for the Creative Research Initiative (CRI) National Project. He was also an adjunct professor in the Department of Chemistry at Hanyang University. He left KIST to serve as president of STEPI before assuming his current position. Dr. Chang is a member of the Steering Committee of the National Science and Technology Council (NSTC). He received a B.S. from Seoul National University, and a Ph.D. in Chemistry from the University of Alberta.

**Jung-Hoon Chun** is associate professor of mechanical engineering and co-director of the Manufacturing Institute at the Massachusetts Institute of Technology (MIT). He has been a member of the MIT Mechanical Engineering faculty since 1989, and is involved in several research projects in the area of materials processing and manufacturing. Currently, he is using his uniform droplet spray (UDS) apparatus in the study of droplet-based manufacturing (DBM) processes, and in the transfer of this technology to industry. His high-energy x-ray tomographic system images the solidication front in real time for the metal casting industry. This technology is then applied to develop an understanding of formation defects in lost-foam casting. His splashless resistance spot welding control system ensures the formation of required weld nuggets, while providing safe and cost-effective welding conditions for the automotive industry. He is also involved in the development of next-generation processes and equipment for lithography and chemical-mechanical planarization (CMP). His teaching focuses on these research areas and on management in engineering.

**Howard Ho Chung** is the *current president of the Korean-American Scientists and Engineers Association (KSEA), and president and CEO of MITEC International of Naperville, IL.* Prior to his current position at MITEC, Dr. Chung was director of corporate technology development at the Chicago Manufacturing Center. He began his professional career in 1966 as a first lieutenant in the Republic of Korea Army. From 1968-1969, he was a staff scientist in the Systems Engineering Research Center of the Korea Advanced Institute of Science and Technology (KIST). Following that position, he served as a teaching assistant in the Mechanical Engineering Department at Tufts University, staff scientist in the Electro-Mechanical Systems Engineering Department of the Lincoln Laboratory at the Massachusetts Institute of Technology (MIT), mechanical engineer (principal investigator) in the Materials and Components Technology Division and then project manager in the Reactor Engineering Division of Argonne National Laboratory. Dr. Chung has published over fifty publication in archival journals and conference proceedings and over sixty technical reports. He is a fellow of the American Society of Mechanical Engineers (ASME), where he is chairman-elect. At ASME, he has held various committee positions. He is also a member of the American Institute of Steel Construction (AISC) and the American National Standard Institute (ANSI). Dr. Chung received a B.S. in naval architecture and aeronautical engineering from Seoul National University; an M.S. in mechanical engineering from Tufts University; an M.B.A. in finance from the University of Chicago; and a Ph.D. in mechanical engineering from Tufts University.

**Alex d'Arbeloff** is *chairman of the MIT Corporation, Massachusetts Institute of Technology (MIT).* He was named to that position on July 1, 1997. He has been a member of the MIT Corporation since 1989, and has served on MIT's Corporation Development Committee and on visiting committees for the Departments of Economics, Electrical Engineering and Computer Science, and Mechanical Engineering. In addition, Mr. d'Arbeloff has taught classes at the Sloan School of Management, and developed and teaches a course on management and entrepreneurship for mechanical engineering graduate students. In 1960, he co-founded Teradyne, Inc., now a leading manufacturer of automatic test equipment and interconnection systems for the electronics and telecommunications industries. He served as president and chief executive officer until May 1997, and chairman of the board until June 2000. Teradyne is world's largest producer of automatic test equipment for the semi-conductor industry. Mr. d'Arbeloff serves on the boards of several private and non-profit institutions. He is a co-founder of Sparkventures, an early stage fund focused on investments in the New England area. Born in France, Mr. d'Arbeloff lived in Paris and in South America before his family moved to the United States. He spent his adolescence in the New York area, then came to Massachusetts to attend MIT, where he earned an SB in management.

**Min-Koo Han** is *secretary general of the Korea Research Foundation.* The Korea Research Foundation is responsible for university research support under the Korea Ministry of Education. Prior to his current position, Prof. Han was associate dean of the College of Engineering at Seoul National University. He began his career in 1970 as assistant professor in the Department of Electrical and Computer Engineering at the State University of New York at Buffalo. He returned to Korea in 1984 to serve in the School of Electrical Engineering at Seoul National University, where he currently is a professor of electrical and computer engineering. From 1995 to 1997, he was a program director of information and electronics technology at the Korea Science and Technology Policy Institute, which is responsible for planning and evaluating research funding within the Korean Ministry of Science and Technology. He has published more than 150 international journals papers and has been issued more than thirty patents in the area of poly-silicon thin films transistors for LCD and high-voltage integrated circuits. Prof. Han received a B.S. from Seoul National University, an M.S. from the University of Michigan, and a Ph.D. from Johns Hopkins University, all in electrical engineering.

**Doh-Yeon Kim** is the *director of the Center for Microstructure Science of Materials in Korea.* He also holds an appointment with the School of Materials Science and Engineering at Seoul National University. His research fields are grain growth, interface migration, sintering, and microstructure-property relationship in ceramics. Prior to joining Seoul National University in 1982, Prof. Kim was an assistant professor in the Department of Mechanical Engineering at Ajou University. From 1976 to 1979, he served as a researcher in the Research Center of Renault Automobile Company. Prof. Kim received a bachelor's degree from Seoul National University, an M.S. from the Korea Advanced Institute of Science and Technology, and a Ph.D. from Blaise-Pascal University.

**Lionel Kimerling** is the *Thomas Lord Professor of Materials Science and Engineering, director of the Materials Processing Center, and chairman of the Electronic Materials Degree Program at the Massachusetts Institute of Technology (MIT).* He conducts an active research program in the structure, properties and processing semiconductor materials. Prior to joining MIT, he was head of the Materials Physics Research Department at AT&T Bell Laboratories. He has served as adjunct professor of physics at Lehigh University. Before AT&T, he served as captain, United States Air Force at the Solid State Sciences Laboratory of the Air Force Cambridge Research Laboratories. He has authored over 200 technical articles. Prof. Kimerling was the 1994 president of TMS/AIME (The Minerals, Metals and Materials Society). He is chairman of the editorial board of the *Journal of Electronic Materials*, a fellow of the American Physical Society, a fellow of the American Association for the Advancement of Science; a member of the National Material Advisory Board of the National Research Council, the National Center for Photovoltaics Advisory Board of the National Renewable Energy Laboratory, the editorial board of *Applied Physics*

*Reviews*; and president of the TMS Foundation Board of Trustees. He is the recipient of the 1995 Electronics Division Award of the Electrochemical Society, the 1997 Humboldt Senior Scientist Research Award, the 1999 John Bardeen Award of TMS, and the TMS Fellow honor awarded in 2000. Prof. Kimerling received a bachelor's degree in metallurgical engineering and a doctorate in materials science from MIT.

**Haiwon Lee** is *professor in the Department of Chemistry at Hanyang University*. Prior to his current position, he was associate professor in Hanyang University's Department of Chemistry from 1993 to 1997. From 1988 to 1993, he served as principal research scientist at the Korea Research Institute of Chemical Technology. He was a research associate in the Department of Chemistry at the University of Texas from 1986 to 1988. Prof. Lee's fields of major interest are organic/polymer thin films, nanofabrication, and polymeric materials for light-emitting diodes and semiconductor integrated circuits. His honors include head of the Organic Thin Films Laboratory (national research laboratory), secretary general of the Division of Molecular Electronics of KPS, president of the Korea Research Group of Organized Molecular Assemblies, organizer of the Asian Symposium on Organized Molecular Films, and organizer of the Molecular Electronics and Devices Symposium Prof. Lee received a B.S. in chemistry from Sogang University and a Ph.D. in physical chemistry from the University of Houston.

**Jo-Won Lee** is *director of the National Program for Tera-Level Nanodevices in the Korea Institute of Science and Technology (KIST).* His fields of research are magnetic recording media/head, high Tc superconducting films and devices, diamond thin films and devices, and nanoelectronics (single electron memory). Prior to his current position, Dr. Lee was a general manager and then a project manager at the Samsung Advanced Institute of Technology. Earlier he was a visiting scientist at the IBM T.J. Watson Research Center, a research associate at Carnegie Mellon University, and a researcher at the Korean Agency for Defense Development. He authored and co-authored 77 papers and holds 31 patents. He was listed in *Who's Who in the World* (1994/1995 edition). Dr. Lee received a B.S. in metallurgical engineering from Hanyang University, and an M.S. and Ph.D. in metals science from Penn State University.

**Sukhan Lee** is a *senior executive director of Samsung Advanced Institute of Technology (SAIT),* the corporate R&D center for Samsung. He is heading the Systems and Control Sector consisting of the Micro Electro Mechanical Systems (MEMS) Laboratory, Nano Systems Laboratory, and Mobile Systems Laboratory. Prior to joining SAIT, Dr. Lee was a professor of Electrical Engineering and Computer Science at the University of Southern California. He has held a joint appointment with the Jet Propulsion Laboratory (JPL) of the California Institute of Technology as a senior member of the technical staff since 1990. In 1995, he held an invited professorship at the Korea Advanced Institute of Technology (KAIST).

He has authored and co-authored more than 250 technical papers in the professional journals and the proceedings of major conferences. He published a book, *Computer Aided Mechanical Assembly*, and contributed Chapters to more than fifteen books. He has been awarded and has filed more than a dozen U.S. patents. Dr. Lee has made significant contributions to the advancement of robotics and automation, especially in the areas of human-machine systems, sensors and machine perception, intelligent systems, dexterous robotic manipulation, neural information processing, and computer integrated manufacturing. He was elected as a fellow of the Institute of Electrical and Electronics Engineers (IEEE) and as a member of the Korean National Academy of Science. His IEEE activities include serving as a member of the editorial boards and as a guest editor for the *IEEE Transactions on Robotics and Automation* and for the *IEEE Transactions on Neural Networks*, chairing the IEEE Technical Committees on Assembly and Task Planning and on Computational Intelligence in Robotics, and being founder of the IEEE International Symposium on Assembly Planning and the Symposium on Computational Intelligence in Robotics. He is currently a vice president of the Korean Sensor Society, and is serving as a member of the Board of Directors for the Korean Systems, Control, and Automation Society as well as for the Korean Institute of Electronics Engineers. Dr. Lee served as the President of the Korean American Scientists and Engineers Association (KSEA) Southern California Chapter in 1996, and was elected as Councilor of KSEA in 1999. Dr. Lee received B.S. and M.S. degrees in electrical engineering from Seoul National University and a Ph.D. in electrical engineering from Purdue University. His held a post doctoral fellowship in biomedical engineering at the Rensselaer Polytechnic Institute.

**Charles Lieber** is the *Mark Hyman Professor of Chemistry at Harvard University*. Prof. Lieber began his postdoctoral career in 1985 conducting research at the California Institute of Technology. As an NIH Fellowship awardee, he investigated factors determining thermal and photo induced electron transfer rates in ruthenium-modified myoglobin. In the summer of 1987, he assumed an associate professorship at Columbia University. At Columbia, Prof. Lieber embarked upon a new research program addressing the synthesis and properties of low-dimensional materials. His early work at Columbia was recognized by several prizes, including a Presidential Young Investigator Award, David and Lucile Packard Fellowship in Science and Engineering, Camille and Henry Dreyfus Teacher-Scholar Award, and an Alfred P. Sloan Fellowship. In 1981, he moved to Harvard University as a professor of chemistry and now holds a joint appointment in the Department of Chemistry and Chemical Biology, and the Division of Engineering and Applied Sciences. His work at Harvard has focused on understanding complex materials from a chemical perspective, including the chemistry and physics of low-dimensional and nanoscale materials, and the development of new synthetic approaches for rationally assembling inorganic nanostructures and nonstructured materials. He has also pioneered the creation and application of new chemically sensitive microscopies for probing organic and biological materials at nanometer to molecular scales. This work has been recognized by a number of awards and lectureships, including the American Chemical Society Pure Chemistry Award (1992), the MRS Young Investigator Award (1993), the George Ledlie Prize (1994), and the Leo Hendrik Baekeland Award (1995). He is a fellow of the American Association for the Advancement of Science and the American Physical Society. Prof. Lieber received a B.A., with honors, in chemistry from Franklin and Marshall College, and a Ph.D. from Stanford University.

**Seth Lloyd** is *Finmeccanica Career Development associate professor in the Department of Mechanical Engineering at the Massachusetts Institute of Technology (MIT).* His research focuses on how physical systems process information. He was the first person to develop a realizable model for quantum computation and is currently working with a variety of groups to construct and operate quantum computers and quantum communication systems. Prior to joining MIT, Prof. Lloyd was at the California Institute of Technology and Los Alamos National Laboratory with Nobel Prize winner Murray Gell-Mann as a postdoctoral fellow. Prof. Lloyd received a B.A. in physics from Harvard University, an M.Phil. in philosophy of science from Cambridge University, and a Ph.D. in physics from Rockefeller University.

**Thomas Magnanti** is *dean of the School of Engineering and one of the twelve Institute professors at the Massachusetts Institute of Technology (MIT)*, where he has been a faculty member since 1971. He has devoted much of his professional career to education that combines engineering and management and to teaching and research in applied and theoretical aspects of large-scale optimization. His research and teaching interests focus on the theory and application of large-scale optimization, particularly in the areas of network flows and combinatorial optimization. Prof. Magnanti was a founding co-director of MIT's industry-university collaborative research and educational program, Leaders for Manufacturing, and has served as head of the Management Science Area (about one-third) of the Sloan School. He previously has co-directed MIT's interdepartmental Operations Research Center as well as an on-campus/off-campus graduate program called System Design and Management. He is a former president of the Operations Research Society of America (ORSA) and has been editor-in-chief of this Society's flagship journal, *Operations Research*. He is past president of the Institute of Operations Research and the Management Sciences (INFORMS). Prof. Magnanti currently serves on several university advisory boards: the International School of Management and Industrial Administration of Linköping University in Sweden, the Harvard Business School, the Stanford School of Engineering, the Ford Design Institute, and the Institute for Mathematics and its Applications. He has previously served as a member of the National Research Council's Manufacturing Studies Board and on the board of the Lemelson-MIT Prize Committee. His publications include co-authorship of two textbooks, *Applied Mathematical Programming* and *Network Flows: Theory, Algorithms and Applications*, and the co-editorship of two other books. Prof. Magnanti received an undergraduate degree in chemical engineering from

Syracuse University, and masters degrees in both statistics and mathematics from Stanford University, where he also received his doctorate in operations research.

**Duncan Moore** was confirmed by the U.S. Senate in the fall of 1997 for the position of *associate director for technology in The White House Office of Science and Technology Policy*. In this position he works with Dr. Neal Lane, President Clinton's Science Advisor, to advise the President on U.S. technology policy, including the Next Generation Internet, Clean Car Initiative, new construction materials, and NASA. Dr. Moore is on leave from his position as the Rudolf and Hilda Kingslake Professor of Optical Engineering at the University of Rochester. Previously, from 1995 until the end of 1997, he served as dean of engineering and applied sciences at the University. He also served as president of the Optical Society of America, a professional organization with 12,000 members worldwide, in 1996. Dr. Moore has extensive experience in the academic, research, business, and governmental arenas of science and technology. He is an expert in gradient-index optics, computer-aided design, and the manufacture of optical systems. He has advised nearly fifty graduate thesis students. In 1993, Dr. Moore began a one-year appointment as science advisor to Senator John D. Rockefeller IV of West Virginia. He also chaired the successful Hubble Independent Optical Review Panel organized in 1990 to determine the correct prescription of the Hubble Space Telescope. In addition, Dr. Moore is the founder and former president of Gradient Lens Corporation of Rochester, NY, a company which manufactures the high-quality, low-cost Hawkeye boroscope. Dr. Moore was elected to the National Academy of Engineering in February 1998. He has been the recipient of the Science and Technology Award of the Greater Rochester Metro Chamber of Commerce (1992), the Distinguished Inventor of the Year Award of the Rochester Intellectual Property Law Association (1993), and the Gradient-Index Award of the Japanese Applied Physics Society (1993). Dr. Moore received a Ph.D. in optics from the University of Rochester. He had previously earned a master's degree in optics at Rochester and a bachelor's degree in physics from the University of Maine. He also received an honorary doctor of science degree from the University of Maine in 1995.

**Jong-Oh Park** is *director of the Intelligent Microsystem Program (IMP) in Korea*. Prior to his current position, Dr. Park was principal researcher at the Korea Institute of Science and Technology. He has also served as guest researcher at the Fraunhofer Institute of Manufacturing Technology and Automation in Germany, and researcher at the Korea Institute of Science and Technology. He has published forty papers, and hold nineteen patents. He is the recipient of the Golden Robot Award from the International Federation of Robotics (1997), the grand prize in the Science and Technology Division from Chung JinKi Mass Media Culture Prize (1992), and the IR 52 Inventor’s Prize (1991). Dr. Park received a B.S. in mechanical design from Yonsei University, an M.S. in optimization from the Korea Advanced Institute of Science and Technology, and a Ph.D. in robotics from Stuttgart University, Germany.

**Kyoungwan Park** is *leader and project manager of the Nano Electronic Devices Research Team in the Telecommunication Basic Research Laboratories at the Electronics & Telecommunications Research Institute of Korea.* Prior to his current position, Dr. Park performed postdoctoral research in the Department of Material Science and Engineering at North Carolina State University (NCSU). He was a research assistant and later an instructor in the Department of Physics at NCSU. Dr. Park also served as a researcher in the Optical Standards Laboratory of the Korea Standards Research Institute, and a lecturer in the Department of Physics at Chungnam National University. He is co-author of 63 publications and one book, and has four patents. Dr. Park received a B.S. in physics from Seoul National University, an M.S. in physics from the Korea Advanced Institute of Science and Technology, and a Ph.D. in physics from North Carolina State University.

**Sang-il Park** is the Chairman and CEO of PSIA, a leading manufacturer of industrial Scanning Probe Microscope (SPM) in Korea. Earlier, Dr. Park founded Park Scientific Instruments (PSI) in California, where he served as the Chairman and CEO for 9 years. Prior to founding PSI, he worked with Prof. Quate at Stanford University as a Research Associate. Dr. Park authored and co-authored numerous research papers, a text book on SPM, and nine U.S. patents. He received his Ph.D. in applied physics from Stanford University and his B.S. in physics from Seoul National University. Dr. Park is a member of Korean Physical Society, Korean Vacuum Society, and American Physical Society.

**Yoon-Soo Park** is *executive director of the Korea-U.S. Science Cooperation Center and a program director at the Office of Naval Research (ONR).* At ONR, he is responsible for initiating, planning, directing and coordinating broad basic and applied research and exploratory and advanced development projects in the areas of electronic and optoelectronic devices and materials, and optical sensors. In addition to ONR-funded research programs, he manages large research programs funded by the Advanced Research Projects Agency (ARPA), and the Ballistic Missile Defense Organization (BMDO). Prior to ONR, Dr. Park served as director of the Air Force Scientific Research Liaison Office in Tokyo. He has also served as group leader at the Air Force Avionics Laboratory and Aerospace Research Laboratory. He received the Decoration for Air Force Exceptional Civilian Service from the Secretary of the Air Force for exceptional performance and contributions during his tenure in Tokyo, and Air Force Scientific Achievement Awards as group leader. He has approximately 150 publications to his credit and holds three patents on electronic devices. Dr. Park's academic career includes serving as a visiting professor in the Department of Physics at Seoul National University under the sponsorship of Seoul National University and the U.S. Agency for International Development (USAID), the University of Dayton, adjunct professor of physics at Marquette University and Wright State University, and adjunct professor of electrical engineering at George Mason University. He served as a consultant for the United Nations Industrial

Development Organization (UNIDO) regarding research in the area of III-V compound semiconductors at the Korean Advanced Institute of Science and Technology. He is a fellow of the American Physical Society (APS) and the Korean Physical Society (KPS), and is a senior member of the Institute of Electrical and Electronics Engineers (IEEE). He is currently serving as chairman of the Executive Committee of the Korea-U.S. Science Cooperation Center. On April 21, 1997, Science Day of the Republic of Korea, he was awarded the National Medal of Honor by the President of Korea for his contribution to the advancement of science and technology in Korea. Dr. Park received a B.S. in physics from Seoul National University, a masters in physics from the University of Alberta, Canada, and a Ph.D. from the University of Cincinnati. He pursued post-doctoral studies at the Technical University of Berlin, serving concurrently as guest lecturer. He received an honorary degree of science from Cheonbuk National University.

**J. Thomas Ratchford** is *distinguished visiting professor in the National Center for Technology and Law at the George Mason University (GMU) School of Law's Tech Center*. He directs the Tech Center's Science and Trade Policy Program. Prior to joining GMU in 1993, Prof. Ratchford served as associate director for policy and international affairs at The White House Office of Science and Technology Policy (OSTP). Prior to confirmation by the Senate to his OSTP position in 1989, he was the associate executive officer of the American Association for the Advancement of Science (AAAS). Prof. Ratchford is also CEO of STTA, LC. A condensed matter physicist, Prof. Ratchford has served on university faculties and research staffs of private and governmental laboratories. As a subcommittee staff director of the U.S. House of Representatives' Committee on Science in the 1970s, he was one of the first scientists to serve the Congress full-time. He was selected as a Congressional fellow of the American Political Science Association, a fellow of the AAAS and the American Physical Society (APS), and a member of the Council on Foreign Relations. He is active in international science and technology programs in the U.S., Asia, and Europe, and chairs the U.S. side of the U.S.-China Science Policy Initiative for the National Science Foundation. He has published extensively on U.S. and global trade and technology trends and policies. Prof. Ratchford received a B.S. in mathematics and physics from Davidson College, and an M.A. and Ph.D. in physics from the University of Virginia.

**Jung Uck Seo** is *minister of the Ministry of Science and Technology, Republic of Korea (ROK)*. Prior to accepting his current appointment in March 1999, Minister Seo served as President of ChoDang University. He began his career in 1957 as chairman of the Electronics Department in the ROK Air Force Academy. He followed that position with service at the Agency for Defense Development from 1970 to 1983, where he began as a division head and moved up to vice president and finally president of that agency. From 1971 to 1984 he was a lecturer at Seoul National University and a visiting professor at Korea University. From 1984 to 1990 he was at Korea Telecom, where he began as TDX and

TICOM project manager, and moved up to senior executive vice president. He was vice minister of the Ministry of Science and Technology from 1990-1992. Minister Seo has also served as president of the Korea Institute of Telematics and Electronics, CDMA and KOREASAT DBS project manager and later chairman at the Commission for Radio Communications Development in the Ministry of Information and Communications, chairman of the Commission for IMT-2000 System II Development, and vice chairman of SK Telecom. His honors and awards include the Iron Tower Order of Industrial Service Merit Award (1978), IEEE Fellow (1982), the Camellia Order of Civil Merit (1986), the Yellow Stripes of Service Merit (1992), Texas A&M Outstanding International Alumnus Award (1996), The Gold Tower Order of Industrial Service Merit (1996), the Woon Kyung Prizes (1998), and IEE Fellow (U.K.) (1999). Prof. Seo received a B.S. in electrical engineering from Seoul National University, and a Ph.D. in electrical engineering from Texas A&M University. He also attended the Global CEO Program at Seoul National University.

**Henry Smith** is the *Joseph F. and Nancy P. Keithley Professor of Electrical Engineering in the Department of Electrical Engineering and Computer Science and director of the Nanostructures Laboratory at the Massachusetts Institute of Technology (MIT).* From 1968–1980, Prof. Smith was at MIT's Lincoln Laboratory where he worked on surface-acoustic-wave devices and pioneered the development of techniques for fabricating nanometer structures. In 1980 he was appointed a professor of electrical engineering at MIT, and was appointed to his current position in 1990. Prof. Smith and his co-workers are responsible for a number of innovations in nanostructures technology and applications, including: conformable photomask lithography, x-ray lithography, the phase-shift mask, the attenuating phase shifter, spatial-phase-locked electron-beam lithography, interferometric alignment, graphoepitaxy, surface-energy-driven grain growth, achromatic interferometric lithography, zone-plate-array lithography and a variety of short-channel, quantum-effect and microphotonic structures and devices. He is a fellow of the Institute of Electrical and Electronics Engineers (IEEE) and a member of the National Academy of Engineering, the American Physical Society, the American Vacuum Society, the Materials Research Society, the Optical Society of America, and Sigma Xi. He is the recipient of the Cledo Brunetti Award of the IEEE, and has been a visiting scientist at University College in London, Thompson CSF in Paris, the Norwegian Institute of Technology, the Nippon Telegraph and Telephone Corporation, the University of Glasgow, the University of Goettingen, the Max Planck Institute under a Humbold Research Award for Senior U.S. Scientists.

**Nam Suh** is the *Ralph E. and Eloise F. Cross Professor, head of the Department of Mechanical Engineering, and the director of the Manufacturing Institute at the Massachusetts Institute of Technology (MIT).* Prof. Suh has been on the MIT faculty since 1970. During this period, he was the founding director of the MIT Laboratory for Manufacturing and Productivity. He was also the founder and director of the MIT-Industry Polymer Processing Program, head of the Mechanics and Material Division of the Mechanical Engineering Department, and a member of the Engineering Council of MIT. In October 1984, Prof. Suh took a leave of absence from MIT to serve as the head of engineering at the National Science Foundation, a Senate-confirmed, Presidential appointment. He returned to MIT in January 1988. Prior to joining the MIT faculty, Prof. Suh was with the University of South Carolina, USM Corporation, and Guild Plastics, Inc. He was also a visiting professor at Tokyo University. He has received many awards and honors, including the KBS Korean Compatriot Award for Scholarly Achievements. He is also the winner of the 1997 Ho-Am Prize for Engineering. He is a fellow of the American Society of Mechanical Engineers (ASME), and is a member of several scientific societies and associations, including the Korean Academy of Science and Technology. He serves on editorial boards of many journals and is a series editor for the Advanced Manufacturing Series of Oxford University Press. Prof. Suh was also the founding co-editor-in-chief of the International Journal, *Robotics and Computer-Integrated Manufacturing.* He was the key architect of the Five-Year (1980-85) Economic Development Plan of the Republic of Korea. Prof. Suh received his S.B. and S.M. degrees from MIT, and his Ph.D. from Carnegie-Mellon University. He also holds honorary doctorate degrees from the University of Massachusetts-Lowell, Worcester Polytechnic Institute, and the Royal Institute of Technology, Stockholm, Sweden.

**Robert Trew** is director of research for the U.S. Department of Defense (DoD). He has management oversight responsibility for the $1.2 billion yearly basic research programs of the Military Services and Defense Agencies. Dr. Trew is serving as vice-chair of the Interagency Working Group on Nanotechnology and is leading the formulation and implementation of the DoD nanotechnology program. Dr. Trew has extensive experience in industry, academia, and government. His industrial experience includes employment at General Motors Corporation in Michigan and Watkins-Johnson Company in California. In addition to his present DoD assignment, he worked for the U.S. Army Research Office as a program manager for five years. From 1976 to 1993 Dr. Trew was on the faculty of North Carolina State University, where he served as professor of electrical and computer engineering, and from 1993 to 1997 he was George S. Dively Professor of Engineering and chair of the Department of Electrical Engineering and Applied Physics at Case Western Reserve University. He was a visiting professor at the University of Duisburg in Germany in 1985. Dr. Trew is a fellow of the Institute of Electrical and Electronics Engineers (IEEE) and serves on the Microwave Theory and Techniques Society ADCOM. He is currently serving as chair of the Publications Committee and was the editor-in-chief of the *IEEE Transactions on Microwave Theory and Techniques* from 1995 to 1997. He is currently co-editor of the new *IEEE Microwave Magazine*. Dr. Trew was the recipient of the 1998 IEEE MTT Society Distinguished Educator Award. He received the 1992 Alcoa Foundation Distinguished Engineering Research Award and a 1991 Distinguished Scholarly Achievement Award from NCSU. He was a recipient of an IEEE Third Millennium Medal award, and is currently an IEEE Microwave Distinguished Lecturer. Dr. Trew has three patents and has published more than 140 technical articles, 13 book chapters, and given over 250 scientific and technical presentations. He received the Ph.D. degree in electrical engineering from the University of Michigan.

**Kensall Wise** is the *J. Reid and Polly Anderson Professor of Manufacturing Technology and director of the National Science Foundation (NSF) Engineering Research Center for Wireless Integrated MicroSystems at the University of Michigan*. From 1963 to 1965 and from 1972 to 1974, Prof. Wise was a member of the technical staff at Bell Telephone Laboratories. In 1974 he joined the Department of Electrical Engineering and Computer Science at the University of Michigan. He is a fellow of the Institute of Electrical and Electronics Engineers (IEEE) and the American Institute for Medical and Biological Engineering (AIMBE), and a member of the U.S. National Academy of Engineering. Prof. Wise received a B.S.E.E. from Purdue University, and an M.S. and Ph.D. in electrical engineering from Stanford University.

# APPENDIX III

## *ORGANIZING COMMITTEE*

Moon Ho Chang
President
Korea Institute of Science and Technology Evaluation and Planning

Young-Ho Cho
Associate Professor
Department of Mechanical Engineering
Korea Advanced Institute of Science and Technology

Stephen Y. Chou
Professor
Department of Electrical Engineering
School of Engineering and Applied Science
Princeton University

Jung-Hoon Chun
Associate Professor of Mechanical Engineering
Massachusetts Institute of Technology

Kukjin Chun
Professor
School of Electrical Engineering
College of Engineering
Seoul National University

Jae Hee Ha
Manager
Memory R&D Division SRAM Process Team
Hyundai Electronics Industries Co., Ltd.

Yong Taek Im
Mechanical Engineering Program Director
Division of National R&D Management
Korea Institute of Science and Technology Evaluation and Planning

Bon Jae Koo
Director
Technology Cooperation Policy Division
Science and Technology Cooperation Bureau
Ministry of Science and Technology

Jae Young Lee
Head, Department of International Science and Technology Cooperation
Korea Institute of Science and Technology Evaluation and Planning

Jo-Won Lee
Member of the Research Staff
Microelectronics Lab
Materials Device Sector
Samsung Advanced Institute of Technology

Seth Lloyd
Associate Professor
Department of Mechanical Engineering
Massachusetts Institute of Technology

Jong-Oh Park
Director
Intelligent Microsystem Center
Korea Institute of Science and Technology

Sang-Il Park
Chairman and CEO
PSIA Corporation

Yoon-Soo Park
Chairman, Executive Committee
Korea-U.S. Science Cooperation Center and
Program Director Optoelectronics
U.S. Office of Naval Research

J. Thomas Ratchford
Distinguished Visiting Professor
National Center for Technology and Law
George Mason University School of Law