Microsystems Research and Development in Japan
Site Reports

R. Howe (chair)
M. Allen
A. Berlin
E. Hui
D. Monk
K. Najafi
M. Yamakawa

January 14, 2002
WTEC PANEL ON MICROSYSTEMS

Sponsored by the National Science Foundation, the Defense Advanced Research Projects Agency, the Office of Naval Research, and the National Institute of Standards and Technology of the United States Government.

Roger T. Howe (Panel Chair)
Professor, EECS and ME Departments
Director, Berkeley Sensor and Actuator Center
The University of California
497 Cory Hall, #1774
Berkeley, CA 94720-1774

Mark Allen
Joseph M. Pettit Professor
Microelectronics Group
Electrical and Computer Engineering
MiRC 120
Georgia Institute of Technology
Atlanta, GA 30332-0250

Andrew A. Berlin
Manager, Biotechnology Research Group
Intel Corporation
Microsystems Technology Department
TMG/Intel Capital
SC9-09
2200 Mission College Blvd.
Santa Clara, CA 95054

Elliot E. Hui
Doctoral Candidate
Electrical Engineering and Computer Science
Berkeley Sensor and Actuator Center
The University of California
497 Cory Hall
Berkeley, CA 94720-1770

David J. Monk
Chief Engineering Manager
Sensor Development Engineering
Sensor Products Division
Motorola
2100 East Elliot Rd.
Tempe, AZ 85284

Khalil Najafi
Deputy Director
Center for Wireless Integrated Microsystems (WIMS)
University of Michigan
Electrical Engineering and Computer Science
2402 EECS Building
1301 Beal Ave.
Ann Arbor, MI 4810

Mineo Yamakawa
Staff Research Scientist
Intel Corporation
Biotechnology Research Group
TMG/Intel Research
SC9-09
2200 Mission College Blvd.
Santa Clara, CA 95054

WTEC, Inc.

WTEC provides assessments of foreign research and development in selected technologies under awards from the National Science Foundation (NSF), the Office of Naval Research (ONR), and other agencies. Formerly part of Loyola College’s International Technology Research Institute, WTEC is now a separate non-profit research institute. Elbert Marsh, Deputy Assistant Director for Engineering, is NSF Program Director for WTEC. Sponsors interested in international technology assessments and related studies can provide support for the program through NSF or directly through separate grants to WTEC.

WTEC’s mission is to inform U.S. scientists, engineers, and policymakers of global trends in science and technology. WTEC assessments cover basic research, advanced development, and applications. Panels of typically six technical experts conduct WTEC assessments. Panelists are leading authorities in their field, technically active, and knowledgeable about U.S. and foreign research programs. As part of the assessment process, panels visit and carry out extensive discussions with foreign scientists and engineers in their labs.

The WTEC staff helps select topics, recruits expert panelists, arranges study visits to foreign laboratories, organizes workshop presentations, and finally, edits and disseminates the final reports.

Dr. R. D. Shelton
President
WTEC, Inc.
2809 Boston St., Suite 441
Baltimore, MD 21224-4851

Mr. Geoff Holdridge
Vice President
WTEC, Inc.
2809 Boston St., Suite 441
Baltimore, MD 21224-4851

Dr. George Gamota
Senior Advisor to WTEC
17 Solomon Pierce Road
Lexington, MA 02173
WTEC Panel on

MICROSYSTEMS RESEARCH AND DEVELOPMENT IN JAPAN

SITE REPORTS

January 14, 2002

R. Howe (chair)
M. Allen
A. Berlin
E. Hui
D. Monk
K. Najafi
M. Yamakawa

NOTE: CONTENTS OF THIS DOCUMENT WILL BE AN APPENDIX TO THE FINAL REPORT, EXPECTED IN SPRING OF 2002
ABSTRACT

This volume contains preliminary site reports prepared by the members of the WTEC Panel on Microsystems based on their November 2001 visit to Japan. The reports have been reviewed by the panel’s Japanese hosts, and all changes requested by the hosts as of January 14, 2002 have been incorporated into these revised versions. The site reports will be included later as an appendix to the WTEC panel’s formal final report comparing MEMS and microsystems research and development in Japan with that in the United States. The entire report, including these site reports, will be reviewed by the Japanese hosts again prior to publication. Therefore the material in this volume should be considered preliminary information and subject to revision.

World Technology Evaluation Center (WTEC), Inc.

R. Duane Shelton, President

Staff Involved in this Study:

Geoffrey M. Holdridge, Vice-President for Operations
Y.T. Chien, Vice President for Research
Bobby A. Williams, Financial Officer
Roan E. Horning, Head of Information Technologies Section
Galina Paikouch, Administrative Assistant

Gerald Whitman, EnSTec, Inc., Japan Advance Contractor
Hiroshi Morishita, WTEC Japan Representative

Copyright 2002 by WTEC Inc. except as elsewhere noted. The U.S. government retains a nonexclusive and nontransferable license to exercise all exclusive rights provided by copyright. WTEC reports are distributed by the National Technical Information Service (NTIS) of the U.S. Department of Commerce. A list of available JTEC/WTEC reports and information on ordering them from NTIS is included on the inside back cover of this report.
# TABLE OF CONTENTS

**Table of Contents**

**Site Reports**

- Hitachi, Ltd. ................................................................. 1
- National Institute of Advanced Industrial Science and Technology (AIST), .............................................. 4
- Kagawa Academy of Science and Technology Integrated Chemistry Project ........................................ 6
- Micro Machine Center .................................................. 9
- Murata Manufacturing Company ................................ 17
- Olympus Optical Co., LTD ............................................. 20
- Omron ................................................................. 29
- Osaka University, Professor Okuyama’s Laboratory .......................................................... 36
- Osaka University, Professor Takeda’s Laboratory ........................................................ 39
- Ritsumeikan University ................................................. 41
- SONY Corporation ........................................................ 44
- Tohoku University .......................................................... 47
- Toyota Central R&D Laboratories, Inc. .......................... 53
- Wacoh ................................................................. 57
- Waseda University .......................................................... 61
- University of Tokyo, Professor Ando’s Laboratory ................................................................ 64
- University of Tokyo, Center for International Research on MicroMechatronics ..................... 67
SITE REPORTS

Site: Hitachi, Ltd.
Mechanical Engineering Reserch Laboratory
502, Kandatsu, Tsuchiura
Ibaraki, 300-013, Japan
http://www.hitachi.co.jp/Div/merl/index-e.html

Date visited: 16 November 2001

WTEC Attendees: M.G. Allen (report author); Y.T. Chien*; R.. Howe; E. Hui; and H. Morishita*
*denotes WTEC Representatives

Hosts:
Makato Hayashi, Head of R&D Planning Office, Hitachi, LTD., Mechanical Engineering Research Laboratory, 502, Kandatsu, Tsuchiura, Ibaraki, 300-013, Japan; Tel: +81-298-32-4111 (ext 6020); Direct: +81-298-32-8200; Fax: +81-298-32-8250; E-mail: hayashi@merl.hitachi.co.jp

Kenji Mori, Senior Researcher, R&D Planning Office, Hitachi, LTD., Mechanical Engineering Research Laboratory, 502, Kandatsu, Tsuchiura, Ibaraki, 300-013, Japan; Tel. Direct: +81-298-32-8200; Fax: +81-298-32-8250; E-mail: kjmori@merl.hitachi.co.jp

BACKGROUND AND GROUP OVERVIEW

The research laboratories of Hitachi are the major internal research arm of Hitachi, Ltd. The laboratories are organized into a Central Research Laboratory and a number of specialized laboratories (of which the Mechanical Engineering Research Laboratory, or MERL, is one.) There are several laboratories outside of Japan as well, including four in the U.S., several in Europe, and a new MERL in China. In the U.S., the research activities are concentrated in San Jose (semiconductor design), Santa Clara (Information/Networks); Detroit (Automotive Products), and Princeton (Digital Multimedia).

The Mechanical Engineering Research Laboratory houses approximately 400 researchers. The laboratory is performing research in a broad range of primarily-mechanical-engineering-related areas. Examples of products developed in the Laboratory include: magnetic disk devices; automated teller machines (especially for handling extremely complex or worn currency, Chinese currency was given as an explicit example); color laser printers; plasma etchers for large-scale integration; optical communications modules incorporating laser welding; semiconductor packages and devices; mechanical photonic switches; thin-type compact escalators; and many other electronic and non-electronic applications.

As an example of some of the non-MEMS capabilities of the Laboratory, a presentation on fluid mechanics analysis capabilities (on the large scale) was given by Dr. Shigenori Togashi, Senior Researcher. The facilities for computational fluid mechanics analyses were extensive. Both 80 gigaflop and 200 gigaflop facilities are available to perform unsteady flow field analyses around an entire product. Smaller 16 gigaflop and 3 gigaflop clusters are also available for partial analysis. Examples of products that have been successfully modeled range from instability of impeller pumps and flow in a two-phase pump-suction channel to the complete flow field around a high-speed (nozomi) shinkansen (bullet train).
MEMS R&D ACTIVITIES

Microfluidics (Dr. Ryo Miyake, Senior Researcher)

Hitachi's microfluidics work is motivated by both environmental issues as well as rapid medical diagnostics applications. A key technology that addresses these areas is to realize a simple sensing method for chemical substances. Hitachi's approach is to utilize a MEMS component as a key, high-value-added, and potentially replaceable portion of a larger, more valuable system.

As an example of this approach, Hitachi showed one of their MEMS-based commercial products: a compact water analysis system (Type AN-530). The basic idea is to have multipoint monitoring of water quality, as opposed to a single-point monitor at the city water distribution plant. If such monitoring devices could be made small enough and sufficiently low cost, they could be distributed along multiple branch pipes and interconnected by a data network to pinpoint contamination of the water supply. The core of this analysis system is a microfluidic chip that can measure residual chlorine content, turbidity, and chromaticity. Measurement is performed by bringing together reagents and sample water in a mixing chip, and passed through an optical absorptiometer to perform spectroscopic analysis.

MERL efforts are now moving toward micro total analysis systems and microfluidic devices for chemical processes. Part of this is motivated by MERL's potential participation in the (smaller-scale) successor project to the MITI Micromachine Project, which will focus on biosystems. A variety of fabrication technologies for these approaches are under investigation, including pneumatically-actuated silicone diaphragms, micropumps based on piezoelectric disks, multistack laminated flow channels with check valves, and siloxane-based separation microchannels. Examples of chemical process systems under consideration include microabsorption modules, microextraction modules, and microconcentration modules. Future application areas include proteomics (i.e., protein analysis), and point-of-care systems.

Disk Drive Actuators (Dr. Masahito Kobayashi, Senior Researcher)

As track densities on magnetic disk drives increase, individual track widths shrink, and the requirements on head tracking and stability increase. One MEMS application to address head stability pursued by Hitachi (as well as groups in the U.S. such as IBM) is to place MEMS-based micropositioners at the tip of the head positioner to allow fine control over the head position on the scale of the track width. The work performed by Hitachi utilizes PZT (lead-zirconate-titanate) piezoelectric actuators to perform the micropositioning.

Contactor Probes (Dr. Tatsuya Nagata, Senior Researcher)

In the assembly of multichip modules, the problem of Known Good Die (i.e., pre-testing of semiconductor die prior to assembly on the module to assure high yield) is of great importance. An important issue is to determine how to test these die prior to packaging while simultaneously preserving their ability to be packaged (e.g., testing without rendering the probing pads unsuitable for subsequent bonding). Examples of chips that fall into this category are memory chips. MEMS technology has been used to create an array of high density probe tips that match geometrically the pads on typical Hitachi memory chips. Requirements for this device include fine pitch probing (85 microns), high positioning accuracy (5 micron), small marks on the LSI pad (15 microns), stable probing load (50 mN), and low contact resistance (less than 1 ohm). The device is laid directly on the test chip using chip-to-chip pressure. These devices were designed for 64 MB DRAMS, but now these are obsolete, so they are redesigning the device for the next generation of DRAMS.

Optical Devices (Dr. Tatsuya Nagata, Senior Researcher)

The final presentation described MERL's efforts in optical devices. The technology is based on V-grooves anisotropically wet etched in silicon followed by installation of optical fibers and ball lenses. Thin film metal solders are used to fasten the components together. These devices were introduced several years ago and are currently in production in another division within Hitachi.
PARADIGM SHIFTS AND OUTLOOK

MERL plans to increase its efforts in microfluidics and bioanalysis, and perhaps decrease emphasis on more traditional physical sensors. As one example, they are interested in appropriate methods for DNA analysis and sequencing. Even though the human genome has been sequenced, Hitachi feels that there are needs for other sequencing approaches such as rice, plants, and other foodstuffs. They also mentioned that Hitachi used to manufacture airbag sensors, but ceased this activity since they felt that their fabrication costs were higher than that of other companies in the same market. Hitachi did acknowledge that they were planning new non-bio-related projects, but the details of these projects (including potential application areas) were proprietary. In general, the projects that were observed were consistent with the theme that the MEMS components were considered as crucial, value-added pieces of larger, more expensive (and potentially more profitable) systems.

REFERENCES


BACKGROUND

In the recent reorganization of the national laboratories, the name of the Mechanical Engineering Laboratory has been changed to the Institute of Mechanical Systems Engineering. Dr. Maeda leads a research group that is called ISEMI, an acronym that honors the late Dr. Isemi Igarashi, the founder of silicon MEMS in Japan. He provided a frank assessment of the ten-year Micromachine Project, which recently ended. This project’s focus was to develop a range of technologies needed to demonstrate microrobots for machine maintenance. The commercial market for these microrobots is too far in the future for it to have served as the project’s goal, in the view of Dr. Maeda. The mix of research projects supported by the Micromachine Project was weighted too heavily toward large companies. The new strategy, which is the direction his own group is pursuing, is to focus on developing low-cost technologies for MEMS and then creating the foundry or distributed fabrication network infrastructure that will allow access to them by a large number of users in small companies and academic instructions.

RESEARCH ENVIRONMENT

The presentation by Dr. Maeda provided a vision for a new strategy for MEMS research and development in Japan. He feels that AIST can be a catalyst in pursuing commercially relevant MEMS technologies, by partnering with the large number of small, specialized Japanese manufacturing companies. The latter have recently become less dependent on the large corporations, due in part to the economic downturn and the trend to move manufacturing offshore. In order to make these collaborations work, more than one small company may need to be involved and access to specialized fabrication services, such as LIGA, is needed. Dr. Maeda is engaged in gaining AIST funding for “jump-starting” these partnerships. The network of micro and milli-machining capabilities that would result from a series of cooperative projects could lead to a powerful, low-cost manufacturing capability for MEMS in Japan.

He provided two examples of how this new style of research partnership works: ISEMI is involved in developing a low-cost 8 x 8 MEMS optical switch using plastic microforming and “pop-up” mirrors. Embossing and injection molding is done at small companies, whereas possibly mold fabrication could be done using the LIGA process line at Ritsumeikian University. An Esco hot embossing machine is used with a
silicon master stamp for forming microstructures in PMMA and polycarbonate substrates. Some of these processes are being done in ISEMI’s own laboratory. Alignment of optical fibers to the mirror array, a critical step if the project is to achieve low manufacturing cost, is the task of a small start-up company. A second example was a multi-layer silicon circuit board that would be suitable for multi-chip modules or a dense probe card. In this case, ISEMI researchers use deep reactive ion etching to form channels, which are later filled by injected metal using a vacuum casting process at a small company called Optnics Precision. The vacuum casting process required one hour, which is much faster than the many electroplating steps that would be needed to form the structures conventionally.

Dr. Maeda pointed out that there are many high-valued-added applications for MEMS, even some that might qualify as “killer applications.” Examples given were high-resolution printer heads, high-density data storage, micro chemical reactors, and medical devices for the elderly or handicapped. By tackling the challenge of developing new low-cost, plastic microforming and metal-based micromachining processes in collaboration with small companies, ISEMI can catalyze a distributed MEMS manufacturing capability in Japan. Specific needs are the use of carbon dies for microforming glass, improved PZT piezoelectrics, and micro chemical reactors.

A final point on the research environment is the significant number of researchers from other Asian countries at the AIST, which is a Japanese national laboratory. We met visitors from China, Korea, and Singapore. The closer ties between Japanese and Asian institutions are a trend over the past few years.

RESEARCH PROJECTS

Dr. Maeda and his research group introduced several on-going research projects. The first was an ultrasonic micromixing chamber for integrated chemistry chips by Dr. Yang Zhen. The second was an interesting application of microfluidics to improving the performance and reducing the size of dialysis machines. In order to de-gas the dialyte, a seal between the liquid and the ambient was achieved using hydrophobic surface coatings. A piezoelectric two-dimensional scanning micromirror has also been developed, which has a resonant frequency of 8 kHz. With relatively low actuation voltages, the mirror achieved 40 degrees of deflection at resonance.

During the 1990s, Dr. Maeda and his colleagues developed processes for room-temperature bonding of silicon to silicon or other materials. He feels that the need for high vacuum during the bonding process makes it impractical in the short term. The project is now under the direction of Dr. Tagaki at ISEMI.

LABORATORY FACILITIES

In touring the ISEMI fabrication and test laboratories, we saw a good example of a “drop-in” clean room built within their existing building. Although we didn’t have time for a complete tour, the ISEMI lab has a reasonably complete set of fabrications tools for MEMS.
BACKGROUND

Prof. Kitamori is a member of the faculty of the University of Tokyo, but has his main research laboratory for applied integrated chemistry at the Kanagawa Academy of Science and Technology (KAST). Prof. Kitamori began his work in analytical chemistry during his ten-year career as a researcher at Hitachi, following an undergraduate education in physics and graduate work in chemistry. He is leading a five-year project on integrated chemistry at KAST. Microfluidics and integrated chemistry will be the focus of a major METI program that will start next year. Prof. Kitamori will play a leadership role in this initiative. Another potential initiative is in microfluidic systems for cell-based biochemistry, which could be the focus of a Ministry of Agriculture program starting 2003.

Research Environment

The laboratory at KAST is where Prof. Kitamori’s group works on applications-oriented research. His two laboratories at the University of Tokyo campus are used for more fundamental research. He spends the majority of his time at the campus, with one or two visits per week to KAST. The laboratory facilities at KAST include a well-equipped clean room for microfabrication and test labs; we ran short of time and couldn’t visit the latter.

Recently, Prof. Kitamori founded the Institute of Microchemical Technology (IMT), a start-up company that is initially located on a separate floor of the same building at KAST. This company will market both the thermal lens microscope and the microfluidic chips. The company has licensed patents belonging to KAST and is backed by both Kanagawa Prefecture and some private investors. The main purpose of the company is to facilitate technology transfer, rather than to develop into a manufacturer. A goal for the company is to return profits to the Prefecture to pay back some of its investment at KAST. Formation of the company required a significant amount of paperwork, according to Prof. Kitamori, due to his being affiliated with a national university. Five other companies have been spun out of KAST research groups recently.

Research Projects

Prof. Kitamori outlined his group’s research themes in a very effective, animated presentation. His approach is to use standard microfabrication techniques to form microfluidic platforms, in which he does highly sophisticated, innovative chemistry. He sees a wide range of applications for integrated chemistry in the life
The latter area is focused on chemical synthesis using the multiplexing capabilities of microflow systems. A major goal of his research is to extend the domain of integrated chemistry beyond the limitations of state-of-the-art capillary electrophoresis-based approaches, which are limited to aqueous solutions, ionic species, and fluorescence-based detection.

The substrate of choice is glass, with vertically stacked, interconnected chips being used for increasing the number of inputs and outputs. Much of his work is based on flow in channels that are 10-200 µm in diameter. However, his group is interested in the possibilities of “nanocapillaries” in which the behavior of water is unconventional. He hypothesizes that the water clusters are constrained by the capillary walls, resulting in different chemical behavior – such as a much longer decay constant for fluorescence. These capillaries are filled from the microchannels by surface tension. In order to connect the microflow chips to conventional microtubing, very small, precisely machined reusable plastic connectors are used. A small local company machines these connectors for Prof. Kitamori’s laboratory.

His first project is an integrated chemistry chip for cancer detection for detecting the marker “CEA.” The assay uses coated microparticles that are held in place in the microchannel using a dam structure. Using a microfluidic chip, the assay time is reduced from 2-3 days to 30 minutes. A heavy metal (cobalt) analysis chip was also described for water quality testing.

Some of his group’s most innovative work is the development of the microfluidic structures to support micro unit operations and continuous flow chemical processing. The concept of unit operations is borrowed from macroscale synthetic chemistry. In order to implement micro diffusion mixers, guide structures have been etched into the microchannel in order to maintain separation of flow streams. The guides were about 5 µm in height and were needed due to the very low flow velocity (required to provide sufficient time for transport). By polymerization at a flow interface between two streams, in situ fabrication of a nylon membrane was demonstrated. An example was described in which an substance was delivered in one phase, mixed with a second phase, and then extracted into a third phase. A particularly impressive demonstration was the co-axial flow of an air stream surrounded by fluid in a microchannel. Syringe pumps were used to drive the fluid through the microfluidic chips, with a pressure of several atmospheres at the inlets.

A second major contribution is the development of the thermal lens microscope (TLM) as a complement to fluorescence-based detection of molecules and its refinement to the point where it is capable of detecting on the order of 1-10 molecules. The work is motivated by the “small numbers problem” of integrated chemistry, which results from the need to detect nano-molar concentrations in femto-liter sample volumes. The physical basis for the TLM is that molecules emit heat to the surrounding fluid when they absorb optical energy. The result is a temperature profile in the fluid that causes a change in the refractive index and a transient optical lens. The change in focus can be detected using a confocal microscope at a different wavelength, thereby indirectly sensing the molecule of interest. The technique is non-specific, so the microfluidic system must be relied on to select the molecule of interest. Temperature sensitivities of 1 µK are needed to detect single molecules. Special lenses for the TLM are provided in the glass chip; these lenses are Selfoc™ optical communications components made by Nihon Sheet Glass.

The use of integrated chemistry chips for synthesis is also being pursued. Reaction rates are accelerated in the microscale; the rationale for this phenomenon is unclear. A stack of 10 glass chips with feedthroughs has been used to demonstrate the concept. The output of this micro chemical plant was substantial: on the order of 100 kg/year.

**Laboratory Facilities**

The KAST Integrated Chemistry clean room, rated at class 1000, was specially made by Hitachi, Ltd. The lab has very nice optical benches within the clean room. About 80% of the glass chips are fabricated in this laboratory. For the nanochannels, another laboratory at Tokyo University with e-beam lithography is used. A 50 fs pulse-width laser is used for time-resolved TLM.
REFERENCES

Site: **Micro Machine Center**  
5F, Niikura Bldg.  
2-2, Kanda-Tsukasa-cho,  
Chiyoda-ku, Tokyo, 101-0048  
Japan

Date visited: 13 November, 2001

WTEC Attendees: K. Najafi (report author, presenter), D.J. Monk, M. Yamakawa, A. Berlin

Hosts: Dr. Tsuneji Yada, General Manager, Research Department, Information Department, Micromachine Center, +81-3-5294-7131, +81-3-5294-7137 FAX, yada@mmc.or.jp  
Dr. Masaya Kakimoto, Manager, Information Department, International Exchange Department, Micromachine Center, +81-3-5294-7131, +81-3-5294-7137 FAX, kakimoto@mmc.or.jp  
Kanju Miyamoto, Deputy General Manager, International Exchange Department, Micromachine Center, +81-3-5294-7131, +81-3-5294-7137 FAX, miyamoto@mmc.or.jp

**BACKGROUND**

A review of the WTEC objectives was presented, including the purpose and timing of the study (Appendix xx). A summary of the US MEMS survey was provided to the Micromachine Center (Appendix xx). Very brief reviews of the research at each of the US panel members’ institutions were presented (Appendix xx).

MEMS has a long history in the US and Japan, the US panel was asked what we think about the Japanese MEMS research status? We believe that it is important enough for us to spend significant time analyzing the Japanese MEMS activities. Similarly, the Micromachine Center representatives see considerable excitement and energy in the US MEMS community and are curious about activities in the US.
ORGANIZATION AND OBJECTIVES OF THE MICROMACHINE CENTER

A review of the Micromachine Center was presented. The center was established on 24 January, 1992, which coincided with the start of the national Micromachine Project. Total funding plan is approximately ¥25B. The Micromachine Center is organized into a Board of Directors that supervises several committees: Administrative, Technical, Standardization, Cooperative Research, International, and Dissemination. The Secretariat is supervised by the Executive Director and has five departments: Administrative, Research, Information, International Exchange, and Planning. The Administrative Department provides overall coordination and support to member companies. The Research Department conducts R&D and standardization, manages the R&D grants, and promotes the cooperation of multiple entities in research. The Information Department provides collection and distribution of information, survey and research on basic technology and a PR magazine. The International Exchange Department organizes the Micromachine Summit and International Seminars. The Planning Department performs promotion, symposium and exhibition organization, and the Micromachine picture contest for elementary school children.

The goal of the organization was to promote micromachine technology. Figure 1 illustrates the overall philosophy of the national R&D project. There are several activities in the Center:

- Generating Research: through the National R&D Project (1990-2000), Investigating Basic Technologies (e.g., high aspect ratio through-holes), Reviewing Future Prospects, and Determining R&D Trends
- Collecting and Providing Information
- Coordinating Exchange and Cooperation: for example, the annual Micromachine Summit (1st one in March, 1995, including Prof. Muller and J. Giachino, in 2002 in the Netherlands), and the annual International Micromachine Symposium (Nov, 2000, next year is 14 Nov, 2002). Currently, a chief U.S. delegate to the Micromachine Summit is being sought as Prof. Al Pisano from UC, Berkeley is stepping down as the existing US chief delegate.
- Providing University Grants: ¥3M/2 years
- Promoting Standardization: through studying what needs to be standardized via committees (e.g., MMC TR(S001) in Oct, 1998 and MMC TR(S002) in Jun, 2000). The committees are joint Center/University/Industries. TR(S001) is available on at http://www.iijnet.or.jp/MMC/. For example, thin film testing methods are now being studied with support from NEDO (New Energy and Technology Development Organization). This has been a three-year exercise. In 2002, work will begin to propose standards. A web forum is also organized (including Michael Gaitan from NIST). An international forum is being planned in Tokyo during 2002.
- Promotion: for example, the Micromachine Exhibition (11th annual in Nov, 2000 in Tokyo). This includes some activities with elementary school children to encourage them to attend engineering school. The Micromachine Center representatives were concerned about the reduction in interest in engineering within Japan. In Japan, approx. 25-30% of entry-level college students are planning to study engineering. In the US, this is now to 5-10%. Japanese students, like American students, are becoming too busy (e.g., playing video games at a rapid pace), so there is less time to ponder, be creative, and think. The picture shown in Figure 2 is an example of several of the recent entries into the Micromachine Picture Contest. This is the 7th annual contest and asks children to envision the use of new technology. The top 4 students receive prizes, like Olympus cameras, electronic dictionaries, etc. Each year, there are approximately 2000 pictures entered. Entries come from local schools and through member companies. The goal is to get the school children to think about the technology as more than a "black box".

The Micromachine Center representatives were concerned about the reduction in interest in engineering within Japan. In Japan, approx. 25-30% of entry-level college students are planning to study engineering. In the US, this is now to 5-10%. Japanese students, like American students, are becoming too busy (e.g., playing video games at a rapid pace), so there is less time to ponder, be creative, and think. The picture shown in Figure 2 is an example of several of the recent entries into the Micromachine Picture Contest. This is the 7th annual contest and asks children to envision the use of new technology. The top 4 students receive prizes, like Olympus cameras, electronic dictionaries, etc. Each year, there are approximately 2000 pictures entered. Entries come from local schools and through member companies. The goal is to get the school children to think about the technology as more than a "black box".

The Micromachine Center representatives were concerned about the reduction in interest in engineering within Japan. In Japan, approx. 25-30% of entry-level college students are planning to study engineering. In the US, this is now to 5-10%. Japanese students, like American students, are becoming too busy (e.g., playing video games at a rapid pace), so there is less time to ponder, be creative, and think. The picture shown in Figure 2 is an example of several of the recent entries into the Micromachine Picture Contest. This is the 7th annual contest and asks children to envision the use of new technology. The top 4 students receive prizes, like Olympus cameras, electronic dictionaries, etc. Each year, there are approximately 2000 pictures entered. Entries come from local schools and through member companies. The goal is to get the school children to think about the technology as more than a "black box".
Figure 1: The chart illustrating the overall philosophy and goals of the national R&D project.

Figure 2: Example of several of the recent entries into the Micromachine Picture Contest.
The Micromachine Center has 33 member companies. These companies are mainly Japanese, but a U.S. and an Australian university are also members.

R&D ACTIVITIES AT THE MICROMACHINE CENTER

A definition of "Micromachine" is proposed: an extremely small machine, including milli- through nano-technologies. This is significantly broader than the Micro-Electromechanical Systems (MEMS) definition that is common in the US and, even, the Microsystem Technology (MST) definition that is common in Europe. MEMS researchers started from Microelectronics, whereas Micromachine researchers started from a Mechatronics background. Micromachine scope is much wider than MEMS/MST.

In the early 1990s, the Japanese economy was booming, so the science and technology shifted to more basic and original projects, like micromachining. For example, "Micronization" has occurred in Biotechnology, Materials, Electronics (e.g., Sensor array), and Mechanics (e.g., Microcar). In the late, 1980s, Micronization was becoming more necessary.

Therefore, the Micromachine project initiated in 1991. Two phases were planned (both 5 years in length). During the first phase, "conceptual" systems were explored. These were the only proposed areas of study. The key domains were:

1. Advance maintenance systems for power plant
2. Microfactory systems

3. Intraluminal diagnostic & therapeutic system - the budget for this area was not adequate, so only the elemental technologies were funded. System development was not funded.

The second phase was system technologies for development. The goal was to develop system technology for micromachines. For example, a wireless micromachine, a chain-type micromachine (for outer pipe inspection), a catheter-type micromachine, and a microfactory were used as testbeds for research.
The wireless micromachine, included a CCD camera, an electrostatic actuated focusing mechanism (like an inchworm), a microwave-based energy supply and data transmission, and a piezoelectric driving actuator. The power supply (wireless) and heat generation from the piezoelectric were the two most difficult problems to solve. In addition, communication in a harsh environment was also difficult.

The inspection for the outer surface of the tubes, small machines follow the outside of the tubes. A linked group of 10 micromachines is used. These self-assemble to form a chain. This includes a micro-reducer gear assembly and microgyroscopes.

The catheter-type micromachine was described as easy because it was wireline. This was developed as a microwelding device.

The microfactory was developed. This included an optically (laser) activated bubble pump. The laser activates a phase change in the fluid channel. It enables small, remote assembly of devices - ideally, while devices are in (traditional) inventory sites (e.g., during shipment).

Several industrial partners were involved in this development.

Finally, an ultrasonic signal-emitting device was described using high aspect ratio MEMS-like technology in ceramic. Sumitomo Electric is commercializing this.

A video of the Micromachine Center was presented.

Over 580 patents have been applied for within Japan. The patents tend to be co-owned by the company and the NEDO (New Energy and Technology Development Organization). The patents are supposed to open for third party use because these were paid for by public funds.

**SUMMARY AND FUTURE FOCUS OF THE MICROMACHINE CENTER**

The most significant outcomes from the MITI Micromachine project are the paradigm of key technologies described above. These technologies will be disseminated to a variety of potential customers. Some future efforts will be aimed at new applications for these key technologies. Additionally, emphasis in nanotechnology will begin in a "top-down" (big to small) approach. MMC will continue to bridge existing and potential technologies. MMC now has to look for specific applications. Microfluidics is one of their specific applications, and the others are IT area and environmental application. Third, to move on more precise and nano area, triggered by President Clinton's National Nanotechnology Initiative (NNI), which triggered the Japanese interest and discussion. In these discussions micromachining was a major focus because moving into the nano area through micromachines was top-down and current nano technology is bottom up approach.

**Questions and Answers:**

**Question:** Will the Micromachine Center play a role in nanotechnology and/or will there be collaboration with other organizations? What will the Micromachine Center's role be in the next 10 years?

**Answer:** No specific strategy has been set. The inclusion of nanotechnology and microfluidics are being considered, but a final strategy has not been developed. The future role for the Micromachine Center will, however, continue to be to bridge the industry and scientific communities. Funding for this effort will come primarily from public sources if the effort is to be successful.

**Question:** What lessons have been learned from the 10-year program?

**Answer:** The program ended successfully with a lot of outcomes, while a new paradigm of micromachine is recognized as more sophisticated and takes more time to complete than expected. In management we learned the R & D environment in industry changed dramatically, focusing more short-term goal. Ten years ago, much more industrial funding was possible because the
economic conditions were more prosperous. There is some concern that the more short-term focus in industry will diminish the investment in long-term research efforts like the Micromachine Center. There needs to be much more focus on long-term research. Also, ten years ago, many international communities envied the original Micromachine Project.

Question: How is international interaction?
Answer: In the mid-1980s, there was much more nationalistic focus on technologies. Today, companies are much more international. Therefore, the Micromachine Center would welcome interactions with US companies, organizations, but there does not appear to be a direct counterpart in the US. In Europe, organizations like Nexus are more closely paralleled. Membership to the Micromachine Center is open internationally for $300,000/yr. For example, SRI International (US) is a member.

Question: Who interfaces with the schools for the drawing contest, is it through the teachers and MMC?
Answer: Every year MMC collected about 2000 pictures drawn by children. The member companies have constant contacts with nearby schools and they are the ones who contact the schools. MMC did not have any direct contact with schools at the beginning but just send materials, and then the teachers will manage this. Now they have a list of schools interested in this program. They have not tracked students to see where the students go and the first generation after 8 years should be entering college this year. The idea of the drawing contest is to offer opportunities, not to collect ideas.

Question: Who selected the original projects, and why did you choose these areas?
Answer: Authorities picked up technologies proposed by researchers based on their budget. Power plants need small machines to detect defaults on narrow pipes, gases, etc., and so this was a key application domain. Other areas was for medical applications (but for the medical area the budget was not adequate, and so only work on elemental technologies was done and not on systems). The last was microfactory for energy and space saving purpose.

Question: What was the largest problem as you developed these?
Answer: There were many obstacles to overcome, especially energy supply and also heat and how to get rid of the heat.

Question: Have you looked at using inductors to conserve the energy to reuse the energy so you do not dissipate it:
Answer: In this project we did not look at this and just dispersed the heat. In this phase the most important thing was how to integrate the device in a small space and how to communicate without wire. These devices need a lot of energy and so how to manage energy took a long time to solve this problem.

Question: What do you see your role in the next 10 years?
Answer: There is no good answer. We should do something, it is a common feeling, but have no specific approach. Every one recognizes there should be key research technologies between micro and nano sciences and should be diffused by 2 approaches. The future role may be bridging industry and science society.

Question: Who will fund this future effort?
Answer: We should look for public funds for this.
Question: How has the economy affected funding?

Answer: 10 years ago companies were generous and researchers could take long term research, but now companies target is more near future, and long-term is more difficult; very dramatic change, and we are lucky that we started 10 years ago.

Question: Will you get industrial funding, but less now? Do you expect less of your money to come from industrial projects?

Answer: It depends on the project. Companies want to develop immediate products. Pendulum is swinging.

Question: The first 5 years were exploring basic technologies, and next 5 years were to develop systems with applications. What do you tell people you will do for the next 5 years.

Answer: We do not have extreme conditions like the US in defense applications. The project started for 10 years. At the beginning there was plan for only 5 years. At the end of 5 years we evaluated key technologies. Final target was to develop technologies to make machines, so system technologies was the second phase. Maintenance application for power plant was the one system that those who were surveyed selected where they want to have micromachines in the future. The main purpose was not to develop the application itself. We have many key fundamental technologies developed. Our efforts will be put on their commercialization.

Question: Do you see a potential for future collaboration with US industry and universities?

Answer: MMC could not find an appropriate counterpart. They have a lot of that in Europe like Nexus, etc. It is hard to find a similar organization in the US. It is difficult to communicate with each professor’s group. They welcome foreign members. From April they opened new membership, and members get information. Annual fees is ¥300000/year and they get information. The members get reports, and also they have a Japanese database. The only US member is SRI. They had IS Robotics, Prof. Brooks, not members any more.

REFERENCES

1. Detailed copies of Micromachine Center reports can be found at: http://www.iijnet.or.jp/MMC
BACKGROUND

Murata Manufacturing Company, Ltd., was established in 1944 and incorporated in 1950. Murata is focused on the production and manufacture of ceramic materials, and electronic devices made from these ceramic materials. It currently has over 50 subsidiaries, and FY2000 employees and sales (including subsidiaries) of over 27,500 people and 584,000 million yen, respectively. The company is organized into a number of divisions, including three Components Divisions; a Device Products Division; a Circuit Module Products Division; a Sales and Marketing Division; and a Research and Development Division.

Murata's main products focus on exploiting the dielectric, piezoelectric, magnetic, pyroelectric, and/or semiconducting properties of ceramic materials. Examples of devices in these categories include ceramic chip capacitors, EMI suppression filters, and microwave filters; ceramic resonators and piezoelectric buzzers; ferrite-based EMI suppression; pyroelectric infrared sensors; and thermistors. These devices find use in systems such as cellular telephones, PCs and displays, VCRs, and televisions.

The philosophy of the company is to emphasize vertical integration, from raw materials up through production systems. Unlike many corporations, which outsource key elements of their business, such as raw materials or packaging, Murata has elected to maintain control throughout the supply chain by internalizing the key elements of their production. Murata employs approximately 2,000 engineers, and they are divided roughly by thirds into the areas of materials engineering, mechanical engineering, and component design.

Murata has benefited tremendously from the surge in cellular and other wireless markets. Although the selling price of many of these components is low, the volumes are high. For example, Murata claims the use of approximately 190 chip monolithic ceramic capacitors in a cellular telephone application, and global market share of 45% of chip monolithic ceramic capacitors. Sales of capacitors accounted for approximately 250,000 million yen (approximately US$2 billion) in 2000.
Group Overview

The Research and Development Division of the Murata Manufacturing Company is organized into three groups: Group II, primarily concerned with raw material technology; Group III, primarily concerned with application circuitry; and Group IV, primarily concerned with thin films, opto-ceramics, and new materials. Total R&D expenditure per year is approximately 30,000 million yen, or approximately $250 million. This ranges between 5% and 7% of sales.

Murata's main R&D focus is clearly on exploiting and extending their dominance in the ceramics arenas. Areas that they have targeted include:

1. Microwave semiconductor technology, consisting of active components (e.g., GaAs) which are integrable with ceramic components to form high performance systems with application to satellite broadcasting, mobile telecommunications, and other telecommunication technologies. The investment in GaAs fabrication technology is another example of the vertical integration philosophy of the company.
2. Millimeter-wave components and module technologies, again exploiting ceramics expertise, for developments in broadband communication (i.e., anticipation of the continual increase in communications frequencies) and millimeter-wave radar for vehicle safety. Examples of such components include millimeter-wave dielectric filters
3. Ceramic multilayer module technologies, continuing to push the state-of-the-art in cofired ceramic technology, with functionality such as passive elements (R, L, C) fabricated directly within the volume of the ceramic package;
4. BGS wave devices, which exploit unique ceramic properties to create new microwave devices

MEMS R&D ACTIVITIES

The interest of the WTEC visitors was to determine the extent of Murata's MEMS activities. Although MEMS appeared to be a relatively small effort compared with the major R&D activities discussed above, activity in the MEMS area was moderate. Surprisingly, much of the MEMS activity was directed at sensors and actuators, rather than RF MEMS. However, some of the questions during the U.S. MEMS overview presentation indicated interest in the RF MEMS area, especially in the subareas of antennas and resonators.

MEMS activities in Murata began in 1990 with installation of equipment. Since then, research has progressed in three phases: development of specific fabrication technologies (1992-1994); fabrication of gyros, accelerometers, and some basic devices (1995-1997); and focusing on gyro applications with a beginning survey on RF MEMS (1998-2001). Major technologies utilized include anisotropic wet etching of silicon (especially (110) material); dry etching/deep reactive ion etching; and electroplating. Building on some of the core strengths of Murata, packaging research appears to be a priority, with emphasis on vacuum packaging approaches for MEMS.

Three specific MEMS projects were discussed; all of which were related to gyroscopic-based sensing, and tied to the Japanese national MITI project. Published papers were given to the group and are listed in the references.

The first device is a bulk micromachined gyro from single-crystal silicon. A double-frame design is utilized in order to improve performance. An interesting packaging scheme using vertical through-holes sandblasted through anodically-bondable glass to both form a vacuum seal as well as electrical feedthroughs was employed. A resilient organic mask is utilized during this process, and it takes 10-15 minutes to sandblast via holes through 500 microns of anodically-bondable Pyrex. The device is not integrated with electronics, and has a packaged size smaller than 5x5 mm. The noise-equivalent angular rate is currently 0.3 degree/second in a 40 Hz bandwidth, and they are currently on their third or fourth generation device. When asked about commercialization, the response was that they 'want to commercialize' this device, but are thinking about what is the best field. They are currently considering automotive applications, as their feeling is that the camcorder stabilization application cost structure will be unable to support it.
The second device discussed was a gyroscope fabricated as a position sensor for the MITI machine inspection catheter. The structure itself was relatively simple, similar in design to the first gyro but using only a single-frame approach. A similar packaging technology was also utilized, with the addition of a non-evaporative getter incorporated into the vacuum package. This device achieved a sensitivity of 14 mV/(deg/sec); with a dynamic range of 90 deg/s; and a noise-equivalent angular rate of 0.057 deg/s in a 10 Hz bandwidth.

The final device was a further refined gyroscope that utilized 'motion adjustment technology' (i.e., utilize multiple bias electrodes surrounding the main electrode to adjust the trajectory of the mass movement, thereby reducing the nonideal movements that would be caused by fabrication nonidealities). Typically without adjustment, nonideal excursions on the order of 0.1 micron were observed; utilizing this technology, such excursions seem to be completely suppressed on this scale. Noise is greatly reduced from previous designs, although sensitivity is not changed much (as expected). This device achieved a noise-equivalent angular rate of 0.013 deg/s in a 10 Hz bandwidth.

PARADIGM SHIFTS AND OUTLOOK

Murata's MEMS R&D effort has been influenced strongly by the Japanese national MITI initiative in the past, with a strong focus on gyro applications. Now this project is over, and the equipment base and local MEMS expertise is ready to turn to new applications. Future plans include adaptation of their gyro efforts for automotive application (e.g., measurement of rollover and yaw rate) as well as other application (e.g., as input devices and motion monitors). In addition, they are interested in hybridization of mechanical sensors, using their packaging technology to create multisensor platforms such as gyroscopes plus accelerometers within the same package. Finally, and perhaps most significantly, they are beginning to turn their attention to RF components, and mentioned RF switches, inductors, and tunable capacitors as areas of future interest. Other interest areas mentioned included 5.2 GHz wireless LAN; RF LC filters implemented in multilayer cofired ceramic technology; and dielectric antennas.

The overall philosophy appears to be that Murata is currently a components company, and would like to become a manufacturer and supplier of MEMS components to build on this core strength. They would like to keep their focus on bulk micromachining, and focus on applications where they feel only components, not IC systems, are required. They are not afraid of component assembly (e.g., MEMS components plus silicon or GaAs chips assembled onto a board) to create complex and miniature MEMS systems; instead, they point to the commercially-successful current approach of assembly of chip capacitors and chips onto boards, even in very high volume markets such as wireless handheld products, as an existence proof that assembly of MEMS components into systems is viable.

REFERENCES


Microsystems Research and Development in Japan

Site: Olympus Optical Co., LTD.
Corporate R&D center
2-3 Kuboyama-cho, Hachioji-shi
Tokyo, 192-8512
Japan

Date visited: 15 November, 2001

WTEC Attendees: K. Najafi (report author, presenter), A. Berlin, D.J. Monk, M. Yamakawa

Hosts:
Mr. Masahiro Katahiro, Manager, Integrated Precision Technology Department,
Advanced Technology Institute, Corporate R&D Center, 2-3 Kuboyama-cho,
Hachioji-shi, Tokyo, 192-8512, Japan, Tel.: +81-426-91-7261, FAX: +81-426-91-7509, e-mail: m_katashiro@ot.olympus.co.jp, http://www.olympus.co.jp/

Mr. Ryo Ota, Laboratory Manager, Laboratory 1, Advanced Core Technology
Department, Advanced Technology Institute, Corporate R&D Center, 2-3
Kuboyama-cho, Hachioji-shi, Tokyo, 192-8512, Japan, Tel.: +81-426-91-8070,
FAX: +81-426-91-7509, e-mail: r_ohta@ot.olympus.co.jp,
http://www.olympus.co.jp/

Mr. Hiroshi Miyajima, Team Leader, Integrated Precision Technology Department,
Advanced Technology Institute, Corporate R&D Center, 2-3 Kuboyama-cho,
Hachioji-shi, Tokyo, 192-8512, Japan, Tel.: +81-426-91-7261, FAX: +81-426-91-7509, e-mail: h_miyajima@ot.olympus.co.jp, http://www.olympus.co.jp/

Mr. Etsuo Shinohara, Senior Researcher, Research Group, Genome Medical Business
Project, 2-3 Kuboyama-cho, Hachioji-shi, Tokyo, 192-8512, Japan, Tel.: +81-
426-91-7261, FAX: +81-426-91-7509, e-mail: e_shinohara@ot.olympus.co.jp,
http://www.olympus.co.jp/

Mr. Kenzi Murakami, Senior Researcher, Integrated Precision Technology
Department, Advanced Technology Institute, Corporate R&D Center, 2-3
Kuboyama-cho, Hachioji-shi, Tokyo, 192-8512, Japan, Tel.: +81-426-91-7261,
FAX: +81-426-91-7509, e-mail: ke_murakami@ot.olympus.co.jp,
http://www.olympus.co.jp/
BACKGROUND

Hosts at Olympus first provided an overview of activities followed by detailed description of a few of the projects, and a demonstration of some of the projects developed as a result of the micromachine project. A review of the WTEC objectives was then presented, including the purpose and timing of the study (Appendix xx). A summary of the US MEMS survey was provided to the Micromachine Center (Appendix xx). Very brief reviews of the research at each of the US panel members’ institutions were presented (Appendix xx).

REVIEW OF MEMS ACTIVITIES AT OLYMPUS

The hosts all belong to the Corporate R&D Center where most of the research in MEMS and Micromachines is carried out. Olympus is one of the original member companies belonging to the Micromachine Center and was involved from 1991 until Spring 2001 in the development of micromachines for a variety of applications (see Figure 1). The main goal of their micromachine projects was establishing the elemental technology for realizing a micromachine that can work in restricted areas, for example, the inspection/repair in complicated machine system and diagnosis/treatment within the human body, and the miniaturization of manufacturing equipment. Its core applications and developments during the past decade were in several fields including:

- Medical Field: endoscopes, catheters, tactile sensors, and chips for DNA testing
- Industrial Field: catheters for repair, microfactory, and microsensors
- Imaging and Information Field: magno-optical recording, scanners, and inkjet print heads.
- Basic technologies:
  - Si micro-fabrication technology
  - Micro-assembly technology
  - Micro-optics technology
  - Microfluidics

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Advanced maintenance for industrial technology</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Microactry technology</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medical application technology</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>General Evaluation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Interim Evaluation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 1: Timeline showing Olympus activities under the MITI's Micromachines Project

Olympus' view of micromachines and the features that they provide include:

1. Working in tight, complicated areas, ex. Minimally invasive diagnosis & treatment, Thinner, more sophisticated endoscopes
2. Enhanced portability, ex. Smaller information system
3. Micron-level control, ex. Cell or DNA manipulation

Several presentations reviewed projects in the fields mentioned above. These are briefly reviewed here.
Medical Field

Endoscopes and Catheters

Endoscopes have been developed for several medical applications. Endoscopes need several devices to operate them in tight and complex regions of the body. They need actuators for manipulation and control, sensors for navigation and measurement of important parameters, and devices for repair of damaged parts. The concept of an endoscope/cather device is shown in Figure 2. Two different catheters have been developed. The first one shown in Figure 3 is a microfine active bending catheter that includes a contact sensor to minimize or avoid contact with the vessel as it is inserted through it. It includes a light/vision device. The second catheter is shown in Figure 4, where a piezoelectric tactile sensor is incorporated that can sense the difference between soft and hard tissues. The operation of these devices was demonstrated.

Figure 2: Conceptual drawing of an endoscope for medical and industrial applications.

Figure 3: A microfine active bending catheter for medical applications.
DNA Analysis and Proteomics:

In addition to catheters, Olympus has developed bio-chips for DNA an chemical testing and analysis. The chip developed by Olympus is based on free-flow electrophoresis that is used for rapid sample preparation. The concept for this device is shown in Figure 5. It used to Pyrex glass wafers that are bonded together. Inlet holes allows the introduction of sample into the gap (30µm high) formed between the two glass plates, while outlet holes are formed in a linear fashion at the other end of the wafer stack. Two electrodes are placed orthogonal to the path of fluid flow, and when a voltage is applied, the components of s sample are separated through electrophoresis and exit through the outlet holes. Electro-osmotic control of fluid flow is shown in Figure 6.

Figure 5: Structure of Free-Flow Electrophoresis (FFE) module. The size of the whole chip is 100x2(H) mm, while the separation bed is 48(W)x40.5(L)x0.03(D) mm.
After collecting the samples from each outlet, the solutions were analyzed by 1% agarose gel electrophoresis. This technology was first developed for DNA applications but now the emphasis of the company is to apply it in the field of proteomics. The technology has also been used to separate different dyes.

**Industrial Field**

*Endoscopes and Catheters*

The technologies and devices developed for medical catheters, shown above, can also be used in the industrial field for repair of damaged pipes. A laser-welding catheter has been developed that can weld cracks in pipes in-situ. The laser used is a YAG laser and provides a power of over 70W over a 0.5mm depth. Pneumatic actuators are used to move the tip of the catheter around as it is inserted into the pipe of interest.

*Optical MEMS and Scanners*

One of the most important applications of MEMS and micromachines is in scanners and optical switching systems. Olympus is especially interested in this area because scanners are at the heart of many instruments and microscopic inspection systems that it sells. Olympus has developed several different scanners for application in different areas. In one application, a larger mirror (2.5x2 mm) has been developed using MEMS technology that utilizes electromagnetic actuation and has a resonant frequency of 100Hz. This device uses polyimide hinges since polyimide can withstand shock in the range of 2000G better than silicon.

Because of its low frequency, a second scanner has also been developed. This scanner is also based on electromagnetic actuation but uses silicon hinges. It has a resonant frequency of 4kHz, is 4.5x3.3 mm, and can withstand a shock in the range of 100G. It has been successfully tested for more than 10E11 cycles.

The second scanner is used in a laser scanning microscope that Olympus makes (OLS 1100). The use of the micromachined device has been critical to improving the overall performance of the microscope since it achieved less power consumption, has better scan angle stability, and is more reliable. This is the first product (of all of the above-mentioned projects) that is commercially produced and uses micromachines. Another product is an AFM system that also uses some micromachined cantilever.

In addition to the above devices, Olympus is developing sub-mm size scanner that is originally aimed at a compact size optical system. The scanner uses electrostatic actuation, is about 0.5mm in size, and provides

---

**Figure 6: Demonstration of electro-osmotic flow in the FFE cell.**

---
2-D scanning capability. The technology used is based on SOI and bulk micromachining, and is applicable on optical switching systems with little change as well.

Electromagnetic MEMS scanner for a laser scanning microscope (OLS1100)

Papers based on these devices have been presented at various conferences.

Publication list:

- **Journals**

- **Conferences**

OLYMPUS MEMS FOUNDRY SERVICES

One of the most important announcements made by Olympus was that it is now offering fabrication services through its MEMS foundry. This was first announced at the Micromachine exhibition 2001, Tokyo, Oct.30-Nov.2, 2001. This MEMS foundry can be used for services ranging from prototyping to volume production. They will provide customers with the best solution based on Olympus' rich experiences obtained through the past ten years.

The foundry provides the following services:
- design service
- prototyping service
- production by certified lines

These services are supported by precision, optical, and bio technologies in OLYMPUS. One of the important features of Olympus' foundry service is that MEMS can be mixed with CMOS and BiCMOS. The foundry has about 10 engineers.

The following technological capabilities are provided through the Olympus MEMS foundry:
- 4 inch wafer
- Projection alignner with deep depth of focus
- I-line stepper
- Double sided alignner
- Thin film deposition and electro-plating
- Dry etching -including DRIE
- Wet etching
- Wafer bonding
- Test and packaging

The main motivation for providing this foundry service was that the fabrication facility had excess capacity and the company feels that it can utilize this excess capacity to provide services, generate revenues, and therefore sustain the operation of the facility. They expect this activity to bring them new seeds of technology and comprehensive collaboration with universities and other companies.

QUESTIONS AND ANSWERS

Question: Does Olympus have any plans to work on RF MEMS:
Answer: There are no plans at this moment to work on RF MEMS. They have concentrated on optical and biomedical MEMS.

Question: Does the end of the Mmicromachine project mean that Olympus will not receive any additional funding and will end its activities here?
Answer: No, although the amount of funding has reduced, there are still small project that are funded and will continue.

Question: What do you think are the areas that need additional support in Japan to further improve the state of MEMS.

Answer: the main weakness is that the universities do not have very good fabrication facilities and not very active. This means that MEMS engineers who are well trained are not yet easily available.

Question: What can you do to fix this problem?

Answer: We need more foundries so students can use these services, and the university research groups to provide the ideas and seeds for future technologies that industry can use to develop future products.

Question: Will you provide your services to universities, maybe for free?

Answer: Because of the cost involved in operating fabrication facilities, it is generally not economical to provide foundry services to universities at low cost. However, this will be done if there is a common interest, or collaboration between the company and a specific university.

REFERENCES


Site: **Omron**  
Shiokoji Horikawa, Shimogyo-ku  
Kyoto, 600-8530 Japan  
http://www.omron.co.jp

Date visited: 14 November, 2001

WTEC Attendees: D.J. Monk (report author), K. Najafi (presentor), M. Yamakawa, A. Berlin

Hosts:  
Hisao Sakuta, President, Electronics Components Company  
Sumio Horiike, Manager, Electronics Components Company, Silicon Devices  
   Development Dept., Semiconductor Division H.Q., 568 Matsuo, Minakushi-cho,  
   Koka-gun, Shiga-Pref., 528-007 Japan, +81-748-63-1417, +81-748-63-1419  
   FAX, sumio_horiike@omron.co.jp, http://www.omron.co.jp/ecb/  
Takafumi Yanagizaki, engineer, Electronics Components Company, Silicon Devices  
   Development Dept., Semiconductor Division H.Q., 568 Matsuo, Minakushi-cho,  
   Koka-gun, Shiga-Pref., 528-007 Japan, +81-748-63-1417, +81-748-63-1419  
   FAX, takafumi_yanagizaki@omron.co.jp, http://www.omron.co.jp/ecb/  
Marayuki Maeda, Electronics Components Company, Silicon Devices Strategy  
   Planning & Sales Dept., Semiconductor Division H.Q., Shiokoji Horikawa,  
   Shimogyo-Ku, Kyoto, 600-8530 Japan, +81-75-344-7074, +81-75-344-7078  
   FAX, masayuki_maeda@omron.co.jp, http://www.omron-ecb.co.jp/sc/  
Kuninori Hamaguchi, Managing Officer Manager, Electronics Components Company,  
   Semiconductor Division H.Q., Shiokoji Horikawa, Shimogyo-Ku, Kyoto, 600-  
   8530 Japan, +81-75-344-7074, +81-75-344-7078 FAX,  
   huninori_hamaguchi@omron.co.jp, http://www.omron-ecb.co.jp/sc/  
Tomonori Seki, Senior Research Engineer, Technical Development Group, MMR  
   Business Promotion Project, Corporate Research and Development H.Q., 45,  
   Wadai, Tsukuba-City, Ibaraki Pref., 300-4247, Japan, +81-298-64-4106, +81-  
   298-64-3380 FAX, tomonori_seki@omron.co.jp

---

**OMRON COMPANY/DIVISION OVERVIEW**

Omron has five virtual companies and a central Business Development Head Office. The business units are:  
Electronic Components Company (ECB); Industrial Automation Company; Social Systems Company;  
Healthcare Company; and Creative Service Company.
Within the ECB includes: Strategic Planning, Electronic & Mechanical Components (EMC: e.g., switch, relay, and connectors), Automotive Electronic Components (e.g., power switch, ABS, EVS); the Semiconductor Division; Office Automation (e.g., paper sorting); and the Amusement Component Division, among others.

The ECB core technologies include: precision assembly; sensing technology; micromachine technology; semiconductor technology (ultra low pressure sensor); wireless communication technology (pulse radar for near field); and new material technology.

Within the Semiconductor Division, there are approximately 250 people. The sales budget is about $100M. The division contains two large departments: the Silicon Device group and the Microlens business group. The factory is located in Minakuchi for fabrication. Assembly is outsourced.

The major products in the Silicon Device group include: pressure sensors, accelerometer, and analog custom ICs. Production of these devices started in the 1980s. The main applications are for blood pressure and factory automation. The Microlens group has P-MLA (e.g., projector) and B-MLA (e.g., backlight for Casio PDAs) and cellphones (e.g., for Samsung, etc.). Sales are approximately $30M/yr.

The long-term scheme for silicon devices is to be the number 1 custom analog supplier in Japan and a major MEMS supplier and foundry in the world. The strategy is:

1. To acquire BiCMOS and CMOS process and production capability. Currently, Omron only has high voltage (10-40 V) bipolar capability.
2. To improve, expand, and acquire analog design capability.
3. To develop and acquire surface micromachining technology. Currently, Omron has only bulk micromachining technology, but they would also like to acquire surface micromachining technology.

Omron believes this can happen in a variety of ways and are not limiting themselves to doing this internally.

Current capabilities include bipolar processing with > 3 µm, IC packaging, custom IC, and marketing to industrial applications with bulk micromachining. By 2003, they would like to also have BiCMOS and CMOS capability at about 1.5 µm and 15 V, modules packaging for sensor drivers, and application specified standard products for consumer markets with surface micromachining. By 2005, they are interested in CMOS integrated surface micromachining (they are not interested in bipolar integration of micromachining).

The Semiconductor Division is 6% of the entire company sales. EMC is 54%. Approximately 57% of the sales are in Japan and 20% in the North America. Five years ago, there was > 60% sales in Japan and the rest of Asia was < 10%. This is now changing as growth in the rest of Asia (especially China) has developed. Not much change has occurred in North America; there have been sales in the US for more than 2 decades. Over 70% of the sales in ECB is relays and switches. Omron has > 10% market share in this area. In the US, this is in automotive relays. Two factories are located in North America: Canada and Schaumburg, IL.

The Omron Semiconductor Division includes the MEMS development group that is located in the same building as the Minakuchi factory approximately 30 miles from Kyoto. The factory was founded in April, 1975 and employees approximately 230 people. The MEMS and bipolar cleanrooms are kept separate.

**WTEC PRESENTATION**

A review of the WTEC objectives was presented, including the purpose and timing of the study (Appendix xx). A summary of the US MEMS survey was provided to the Micromachine Center (Appendix xx). Very brief reviews of the research at each of the US panel members were presented (Appendix xx).
OMRON MEMS PRODUCT TECHNOLOGY OVERVIEW

The MEMS activity in Omron is done in two locations: in ECB, the Semiconductor Division is profit center and provides development and productization of technology. The Central R&D Laboratory is developing new MEMS technologies (e.g., the micromachined relay: MMR).

The business domain is focused on industrial, medical, and automotive for pressure sensing and acceleration sensing. Future product interests are motion sensors, RF MEMS, DNA chip/microTAS, etc. for game applications, IT, and biology markets. Competition is from ADI in the Nintendo Gameboy, Densom TI-Nanolog, Matshisita Electric Works, and Fujikura. At one point, there were several Japanese MEMS competitors, but they have fallen out because of non-profitability, according to Omron.

In 1981, the piezoresistive pressure sensors were first produced. In 1990, the Tsukuba MEMS laboratory was initiated. In 1994, a capacitive pressure sensor was developed, and in 1995, a capacitive accelerometer was developed (glass-silicon-glass). As of 2000, 8 million units have been shipped for all MEMS devices. All production is bulk micromachining on 4" wafers. The applications are blood pressure monitor, leak detection, and suspension control for automotive. Pictures of the Omron products can be found below.

![Blood Pressure Sensor](Image)

![Pressure Sensor](Image)

![Acceleration Sensor](Image)

**Fig. 1.** Silicon capacitive micromachined sensors (total shipment over 8 million chips).

In 1998, the MEMS division became a profit center (not just cost center). Omron is interested in "harvesting" their bulk micromachining technology to develop a profitable business. To do that, Omron is looking for a good partner and acquisitions. Currently, Omron is focused on becoming a profitable MEMS business in the short-term, and developing new MEMS and CMOS-MEMS technology for the long-term. They are expecting their first profitable month within the next few months, in large part because of yields in excess of 80%.

The vision is to be a major MEMS supplier and fab in the world through expanding the bulk MEMS business and to develop/acquire surface MEMS technology to realize CMOS integrated surface MEMS (e.g., ADXL). Shorter-term, they must capitalize on profits from the existing bulk micromachining technology.

The MEMS products in Omron are blood pressure sensors (0 - 40 kPa), pressure sensor for industrial application (0 - 4-6 kPa), acceleration sensor (+/− 1g). All devices are capacitive with Co of approximately 10 pF. The sensing electronics is not included on chip.

The blood pressure sensor is for a finger-type and wrist-type pressure sensor. A cap wafer with a diaphragm and a well is created. This is a backside exposure device to increase span and to isolate the wirebonds from the media. The silicon diaphragm has nitride on the backside to protect from water/media.
Fig. 2. OMRON pressure sensor for blood pressure meter with operating pressure range of 0 – 40 kPa.

The pressure sensor for gas detection is assembled into a circuit module that includes the analog custom IC chip. The topside is glass, the lower side is silicon. A central pillar is included in a circular diaphragm. This is used to improve linearity but reduces span. It is patented. Co is 10 pF. At 6 kPa the capacity changes to 15 pF.

Fig. 3. OMRON low pressure sensor for industrial applications with an operating pressure range of 0 – 6 kPa.

The accelerometer is also bulk micromachined and capacitive. It is also assembled into a circuit module. The die size is 5 X 5 X 1.2 mm and also has three layers: glass, silicon, glass. The fixed electrodes are located on the both glass layers with a bulk micromachined silicon wafer as the proof mass and moveable electrode.

Fig. 4. OMRON acceleration sensor structure with a measurement range of 1G.
The reason for going to surface micromachining is: 1) to get the new function, 2) to reduce size and 3) to improve temperature performance through integration. The strategy with surface micromachining is to re-use the same equipment as a CMOS line. With only the sensor, the foundry cannot be filled, so integration of analog technology and re-use of the CMOS line is required.

The foundry will include silicon processes, MEMS processes (anodic bond, electrochemical etch, processing glass, etc. - see list of foundry processes available), and dicing of wafer. Customers assume the risk for the qualification. Other MEMS foundry services in Japan are Sumitomo Metal (6" surface micromachining), Dai Nippon Screen Printing (surface micromachining), and Olympus. There is some foundry business also in Taiwan for MEMS. Their foundry service is available to all, including universities and/or businesses, but both for a fee. Conflicts of interest are expected but not considered a problem (because the semiconductor business is described as "shaking hands and punching each other" by Omron).

MMR TECHNOLOGY DEVELOPMENT OVERVIEW

The MMR business is a 4" wafer bulk micromachining process. There are about 700 die per wafer. The devices are 2mm X 3mm X 1mm with chip and cap. Another company in Japan is not performing the packaging in plastic or ceramic. An 8 X 8 MMR array is also possible. The MMR also uses the glass-silicon-glass structure. The silicon is SOI which has a 20 µm active layer with movable contact. The bottom side of the movable contact is made by a sputtered metal to make contact with the metal on the glass substrate (anodic bonding). Approximately 24V are required to make the contact.

The MMR is compared with SSR (solid-state relays) and EMR (electro-mechanical relays) in Table 1. The observable electrical life is > 100 Mcycles. The key improvement when compared with SSR and EMR is very good high frequency characteristics (several GHz), short operate time, and very low power consumption. The cost comparison is approximately the same as the SSR but more expensive than EMR. The cost needs to be approx. 1/3rd to 1/5th of what it is today. The MMR yield is much lower than EMR, for example. A concerted effort to improve the yield to more than 90% is required to make profit. The learning curve for MMR is very slow. Stiction is the largest yield problem. The insertion loss is -0.5 dB/2GHz, isolation is -45 dB/2GHz, and the VSWR is 1.1/2GHz.

This is for ATE applications. There are no sales yet; the MMR is still in development. The potential markets are for wireless LAN, RF measurements, digital consumer electronics, portable phones, and IC testers.

The MEMS Technology Related Organization is centralized in Tsukuba and Kyoto sites. The roadmap includes surface micromachined technology by 2005.
Table 1
Comparison of Micromachined Relay (MMR), Solid State Relay (SSR), and Electro Mechanical Relay (EMR) Characteristics

<table>
<thead>
<tr>
<th></th>
<th>MMR</th>
<th>SSR</th>
<th>EMR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>Small (2 x 3 mm)</td>
<td>Small</td>
<td>Large</td>
</tr>
<tr>
<td>Relay resistance</td>
<td>Medium (400-500 mΩ)</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Switching power</td>
<td>Small (0.1 W)</td>
<td>Varies</td>
<td>Large</td>
</tr>
<tr>
<td>Breakdown voltage (between contacts)</td>
<td>Small (150 V)</td>
<td>Varies</td>
<td>Large</td>
</tr>
<tr>
<td>Operate/release time</td>
<td>Short (0.3 mSec)</td>
<td>Very short</td>
<td>Long</td>
</tr>
<tr>
<td>Electrical life</td>
<td>Medium (over 100 million cycles)</td>
<td>Very long</td>
<td>Medium</td>
</tr>
<tr>
<td>High frequency chara.</td>
<td>Very good (Several GHz)</td>
<td>Not good</td>
<td>Good</td>
</tr>
<tr>
<td>Power consumption</td>
<td>Very low (0.05 mW)</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Drive voltage</td>
<td>Large (24 V)</td>
<td>Small</td>
<td>Small</td>
</tr>
<tr>
<td>Integration capability</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>
SUMMARY AND FUTURE FOCUS OF THE MEMS AT OMRON

Omron believes that the MITI project was not so efficient to short-term-goal Business because the selection of applications was not directly matched to commercial business, generating few commercial enterprises. Because Japan has focused on specific semiconductor fields: e.g., DRAM, and other countries (like Korea) are starting to take some of that market share, the Japanese government is interested in reinvesting in another high technology area. Omron believes that the Japanese government will continue to invest heavily in MEMS as one of these chosen fields.

Twenty years ago, Japan was more focused on copying the other advanced countries (US and in Europe). Today, Japan has the ability to scope out a new area and, thus, they are doing longer-term planning (10 year plans). Omron is doing this with MEMS. They are aggressively seeking to become a high volume supplier for MEMS products. Moreover, their approach is very flexible. They would consider developing the technology internally, partnering with a university to learn more about the technology, partnering with another company, and/or buying another company (even, another US company).

Omron's bottom line in MEMS products is not so good. The business must make money, and Omron believes that it will because they will be able to harvest products/foundry business from the basic technology that has been developed. It appears that late 2002/2003 will be the break-even point. Omron will use bulk micromachining products to make money and are interested in moving into surface micromachining.
BACKGROUND AND GROUP OVERVIEW

Dr. Okuyama is a professor in the area of Materials and Devices in the Department of Physical Science at Osaka University. The group consists of Prof. Masanori Okuyama, Associate Prof. Minoru Noda, Research associates Kaoru Yamashita and Takeshi Kanashima, 3 doctoral students, 11 Masters' students, 5 undergraduates, and approximately 7 visiting researchers. The group has worked in a number of research areas, including: device physics and processing of non-standard IC materials (including ferroelectrics); uncooled infrared detectors based on bolometry; differential spectral imaging systems; and ultrasonic microarray sensors. Much of the work is oriented toward ferroelectric materials, used either as sensors or as actuators.

At our visit, the Okuyama Group was concluding its participation in a multiyear project entitled 'SEIS', or the 'Super-Eye Image Sensor'. This project was funded by Osaka Prefecture and was performed by Osaka University and a consortium of 13 companies. The five-year project began in 1996 and was funded at a level of approximately $4.25 million, split approximately 40%/60% between the prefecture and the companies involved, respectively. Participating were approximately 32 part-time engineers from companies, 3 university researchers, and 5 students. The overall research vehicle was the fabrication of a sensing system that could mimic some of the functionality of human senses, e.g., for robotics applications. Examples of devices fabricated in this project included infrared sensing, wavelength-differential imaging, ultrasonic sensing and imaging, flavor/smell sensing, MEMS sensors for acceleration, magnetic fields, and humidity, and development of the underlying silicon process technology. Although this project is now over, a Microdevice Center has been formed and will continue to fund subprojects. Some of these projects performed by the Okuyama Group were reported on individually and are given in more detail below.

MEMS R&D ACTIVITIES

Infrared Image Sensor

The infrared image sensor utilizes barium strontium titanate (BST) as a bolometric material. The approach was to determine the change in dielectric constant of the BST due to temperature fluctuations caused by exposure to infrared radiation. A silicon substrate is etched to form thermally isolated structures. The
technology approach is wet etching of (110) silicon. Pt/Ti is used as a CMOS metallization, followed by BST deposition and an infrared-absorbing material on top. The Pt/Ti metallization is required since the film deposition temperatures are typically high (on the order of 400-600 °C). The device has a sensitivity of 1.2 kV/W and a detectivity (D*) of nearly 3x10^8 cm Hz^-0.5 / W.

Wavelength Differential Imaging

The wavelength differential imaging project involved the use of stacked adjustable filters to enhance the ability to perceive small spectral changes among an unchanging background. The approach involves the fabrication of a variable interferometer using PZT actuation. The functional approach is to operate the device at two different interferometric spacings, and sequentially read the spectrum of some object. Edge detection (e.g., to isolate a particular wavelength peak) in the transmittance vs. wavelength domain can then be performed by subtracting the two spectra. The approach was applied in the visible to image the spreading of deoxygenated hemoglobin in the human hand. It was also applied in the infrared to be able to selectively observe things like bodies of different temperatures as well as gas flow with specific infrared absorption spectra. It was also applied to the visualization of gas leakage and diffusion. Purported potential applications: Gas leakage, health diagnostics, ripeness of fruits, detection of rotting in foodstuffs, monitoring forest damage of plants, accurate color identification of clothes, and product inspection in a factory.

Ultrasonic Micro-Array Sensor

The ultrasonic micro-array sensor was a project of the New Energy and Technology Development Organization (NEDO) of Japan. The functional sensor element consists of a two micron thick silicon diaphragm with approximately 1 micron of PZT deposited on it using sol-gel approaches. Excitation or sensing of the PZT resulted in emission or detection of ultrasonic energy. The devices were typically operated in the sensing mode. The quality factor of the resonance of the membrane was approximately 250 at a resonant frequency of 176 Hz. This results in a sensitivity of approximately -40 dB (where 0 dB = 1 V/Pa), approximately 1 order of magnitude higher than bulk material. Multielement arrays of 37 elements each were fabricated, which allowed localization of an impinging sound source. By changing the interconnect pattern, it is possible to change the directivity of the array. Currently, a bucket-brigade-based signal processing unit is being developed and the ultimate goal is to integrate this unit on the same chip as the sensor array.

PARADIGM SHIFTS AND OUTLOOK

Much of the advanced work presented to us seemed to be focused on improvement and exploitation of the properties of ferroelectric materials, rather than on the sophisticated utilization of advanced MEMS technologies. This is consistent with the overall research report of the Okuyama Group, which emphasized ferroelectric and materials development. It seems this group will continue its efforts in the ferroelectric area and the application of ferroelectric technology to MEMS. Funding for basic science was described as low in general, and the importance of application in securing funding was emphasized. It was also stated that collaboration with companies, particularly small companies, was often useful in applying for research funding. Consistent with the shift toward increasing importance of patents at Japanese universities over the past few years, a Technology Licensing Office was started in April 2001. This office seems more regional in nature (Kansai, Osaka) rather than being focused directly on Osaka University. Prof. Noda stated that the group has now begun to aggressively patent its work.

REFERENCES


M. Okuyama et al., Annual Research Report of the Okuyama Laboratory in the Area of Materials and Device Physics, April 2000-March 2001
Site: Osaka University  
Professor Takeda’s Laboratory  
Dept. of Physics, Graduate School of Science  
Osaka University  
1-16 Machikane-yama, Toyonaka  
Osaka 560-0014 Japan  
http://www.phys.sci.osaka-u.ac.jp/

Date visited: November 15, 2001

WTEC Attendees: R. Howe (author), M. Allen, Y. T. Chien, E. Hui, H. Morishita

Host: Prof. Seiji Takeda, Professor of Materials Physics, Tel +81-6-6850-5751, Fax +81-6-6850-5764, Takeda@phys.sci.osaka-u.ac.jp

Also present: Dr. Hideo Kohno, kohno@temp.phys.wani.osaka-u.ac.jp

BACKGROUND

Prof. Takeda and his group are a highly productive experimental solid-state physics research team. The focus of his work is to understand the basic science of silicon nanostructures, rather than engineering applications. Over the past few years, Prof. Takeda has investigated the formation of nanoholes by the clustering of defects and discovered “nanochains,” which consist of periodic silicon nanospheres covered and connected by a thin, amorphous silicon dioxide “chain.” This discovery, and his group’s subsequent progress toward understanding the physics of nanochain formation, is a major advance toward more self-organizing nanostructures.

RESEARCH ENVIRONMENT

Prof. Takeda’s research group is self-contained, having its own fabrication and analytical equipment. Shared laboratories for micro or nano fabrication are not available at Osaka University. His focus on silicon nanostructures, in contrast to carbon nanotubes, is based on the huge knowledge base for silicon processing technologies. As a result, the work in his group should be more easily exploited by the microelectronics industry.

The high degree of interest in nanotechnology in Japan has not translated into increased funding, with the exception of nanotubes. He feels that nanotubes are too narrow a focus and that funding should be spread across a variety of topics in nanotechnology. As discussed later in this report, his laboratory has excellent transmission-electron microscope facilities and has been highly productive, despite having a very limited set of fabrication equipment.

RESEARCH PROJECTS

Prof. Takeda discussed two main research areas: silicon nanoholes and silicon nanochains. The former topic has grown out of his interest in silicon crystal defects. His lab has developed a novel technique for forming nanoholes in ultra-thin (100 nm or less) silicon membranes. A focused electron beam irradiation on one side of the membrane causes sputtering of silicon atoms on the opposite side. The resulting surface vacancies diffuse and coalesce to form shallow surface pits; their extension into the membrane is due to the uniaxial diffusion of surface vacancies on the walls. Their average diameter and density increase with increasing sample temperature. The dielectric constant of the resulting porous silicon is lower than that of crystalline silicon, implying that a periodic structure could be useful for a photonic bandgap structure.
The second topic, silicon-silicon dioxide nanochains, has attracted widespread interest in the scientific community. Drs. Kohno and Takeda accidentally discovered that these unusual structures form spontaneously using a modified vapor-liquid-solid growth procedure in 1998. Recently, they have developed considerable insight into the growth mechanism for nanochains and applied this knowledge to obtain high yields of nanochains. The process [4] consists of heating, in a closed ampoule at a pressure of around 10 µTorr, a sample of {100} oriented silicon that is coated with 10 nm of gold and a small piece of (typically) lead. The sample was then moved to a new ampoule, evacuated to about the same pressure, and heated to 1230°C for two hours. The proposed mechanism for nanochain formation is the periodic instability in the contact angle of the gold-silicon droplet resulting in a variation in the diameter of the growing nanowire. Oxidation of the nanowire’s surface, owing to oxygen outgassing from the glass ampoule, converts the thin sections into silicon oxide and the formation of the string of silicon nanocrystallites. For a typical growth condition, the diameter of the crystallites was about 10 nm and the spacing was about 35 nm [4]. The role of the tiny amount of added lead is to modify the interface tensions during nanowire growth. High yield growth of a dense carpet of nanochains can be achieved through this process.

The investigation of the optical and electronic properties of nanochains is being pursued in Prof. Takeda’s group. The discovery and understanding of the self-organizing formation of periodic structures is clearly an important advance in nanotechnology, with potentially broad applications.

LABORATORY FACILITIES

Prof. Takeda’s fabrication equipment was quite rudimentary, consisting of a furnace, vacuum pumps, and silica tubes for containing the samples. The transmission electron microscopes (TEMs) were first-rate, however. Dr. Kohno had mounted a nanowire sample in one TEM for our inspection. Another TEM had been modified by adding in situ photoluminescence spectroscopy, which is valuable in studying defects in semiconductors.

REFERENCES


Site: **Ritsumeikan University**  
Biwako-Kusatsu campus  
1-1-1 Noji-Higashi  
Kusatsu  
Shiga 525-8577 Japan

Date visited: November 14, 2001

WTEC Attendees: M. Allen, Y. T. Chien, R. Howe, E. Hui (author), H. Morishita

Host: Prof. Susumu Sugiyama, Professor, Director of Research Institute for Microsystem Technology, Department of Robotics, Phone: +81-77-561-2845, Fax: +81-77-561-2665, E-mail: sugiyama@se.ritsumei.ac.jp

Also present:

- Prof. Osamu Tabata, Professor, Department of Mechanical Engineering, Phone: +81-77-566-1111 ext. 8245, Phone: +81-77-561-2882 (direct), Fax: +81-77-561-2665, E-mail: tabata@se.ritsumei.ac.jp
- Prof. Satoshi Konishi, Associate Professor, Department of Mechanical Engineering, Phone: +81-77-561-2863, Fax: +81-77-561-2665, E-mail: konishi@se.ritsumei.ac.jp
- Yoshitada Isono, Associate Professor Department of Mechanical Engineering, Phone: +81-77-566-1111, Fax: +81-77-561-2665, E-mail: isono@se.ritsumei.ac.jp
- Prof. Dr. Jan Korvink, visiting on sabbatical, IMTEK - Institute of Microsystem Technology, Chair for Simulation, Bldg. 103, Room 033, Albert Ludwig University Freiburg, Georges-Köhler-Allee 103, D-79085 Freiburg, Germany, Tel: +49-761-203-7381, Fax: +49-761-203-7382, E-mail: korvink@imtek.uni-freiburg.de

**BACKGROUND**

In 1995 Ritsumeikan completed its second campus at Biwako-Kusatsu. That same year, Prof. Sugiyama moved to Ritsumeikan from the Toyota Central Research Laboratory and was joined by Profs. Tabata and Konishi in 1996 to form the MEMS group. At the end of 2000, they established a new center in the university, the Research Institute for Microsystems Technology (RIMST), supported by the Ministry of Science and Technology as an “open research center for private universities.” The center includes 50 member companies.

**RESEARCH ENVIRONMENT**

Ritsumeikan aspires to be the MEMS flagship for the Kansai area, with facilities second only to those of Tohoku and Tokyo. There is a particular push towards technology transfer to industry through the RIMST member companies and the coordination of MEMS foundry services.

50 member companies, mostly from the Kansai area, pay $1000 per year in exchange for seminars and research reports. Two or three visiting engineers from industry work in each professor’s lab. In the new RIMST building under construction, office space is specifically allocated for such visitors. A new Technology Licensing Office (TLO) has been started in the last year. The government is providing for half of the cost of the office for the first five years. If a professor pays the costs of obtaining a patent, he retains
all of the rights, otherwise the royalties are split with a third each going to the researcher, the university and the TLO. In the case of industrial visitors, patent royalties are usually split 50-50 between the university and company.

The RIMST professors provide a strong teaching curriculum, offering four graduate-level courses: MEMS systems, devices, processes and materials. Student interest is strong, with 80 students enrolled in the classes. However, each course is offered once every two years and students usually don’t take all four since they try to finish their coursework in one year. Ritsumeikan also includes a junior high and high school. MEMS seminars and MEMS open house sessions for high school students are part of an effort to encourage interest in science among younger students.

Prof. Sugiyama has founded a company to organize a foundry system called the Multi-user Integration Chip Service (MICS). Three processes will be offered: analog IC, done at Olympus; surface micromachining, done at Yokogawa; and LIGA, provided by Ritsumeikan.

RESEARCH PROJECTS

LIGA is a particular strength at Ritsumeikan, capitalizing on the synchrotron facility located on campus. A variety of structures beyond the typical extruded 2-D LIGA shapes are being realized. One method employs depth control through varying the exposure. Another method uses direct ablation of material at arbitrary angles of tilt and rotation.

A number of applications of the LIGA process were shown. The depth-controlled LIGA process was used to fabricate a micro lens array. Lab-on-a-chip DNA analysis has been demonstrated in a PMMA micro capillary array chip. In addition, mechanical socket and plug connectors were shown. Also, a device with tunable acoustic absorption characteristics was created using an array of Helmholtz resonators with mechanically adjustable cavity lengths. Finally, LIGA-fabricated thick-film magnetic cores are intended for use in making lighter power supplies.

A 53-nm silicon nanowire was shown. Prof. Isono is studying new physical effects in the nano regime, such as those found in quantum effect transistors. The word “nano” instead of “micro” was considered for use in the RIMST title, but “micro” was chosen to convey a sense of nearer term applications for industry.

Some sensors were shown, such as a low-g capacitive sensing accelerometer and a high-pressure piezoresistive pressure sensor. Also a gyroscope was shown, which utilizes the circular movement of a point-mass mounted on pillar. This is currently hand-assembled, but a LIGA process is under development.

Finally, a piezoelectric bimorph micro valve was shown, as well as a self-supporting polysilicon thermopile for electricity generation, fabricated in a standard CMOS MICS process.

LABORATORY FACILITIES

Ritsumeikan has well-equipped facilities for MEMS research and is expanding. A new building for RIMST, contiguous to the synchrotron radiation facility, is scheduled for completion next May. The center will include facilities for e-beam lithography, microfabrication processes, photolithography, synchrotron radiation, and microsystem design. All of the major CAD tools are available for use, including MEMCAD/IDEAS, Intellisuite, MEMS Pro, ANSYS, Mark (FEA), MicroCAD, and anisotropic etch simulation programs. The microsystems lab currently employs only two engineers.

The panel toured the synchrotron facility. There are three beam lines dedicated for LIGA, with one to be added. One line, used by Prof. Tabata, has the capability for multiaxis positioning of both the mask and substrate to achieve complex structures. Another line, for Prof. Sugiyama, is used for ablation of Teflon. The third line is used for standard LIGA. No VLSI research is being performed in this facility. The focus of the facility is split between materials research (i.e. bandgap characterization, crystal diffraction, etc.) and MEMS.
REFERENCES


FROM SHINAGAWA STATION TO SONY HEADQUARTER

On the way to SONY’s headquarter, located around Takanawa and Gotenyama areas in Shinagawa-ku, Tokyo, we suddenly noticed we were surrounded by numerous SONY buildings, passing “SONY 2 Building”, “SONY 3 Building”, …, “SONY 10 Building”, … on “SONY Street”. The headquarter building also has a museum, displaying an impressive array of historical SONY products up to the latest electronics products sold right now. One of the oldest displayed there was electric rice cooker before the age of transistor radios. I was caught by many flashbacks and then started remembering many of my memories associated with those SONY products on display. A part of the museum also had a section for environmentally conscious research, manufacturing, and products, indicating SONY’s strong commitment for environmental protection and management of manufacturing. One of them, which is based on “d-limonene”, brought into their fabrication processes, was presented (see the figure in later section) during our visit.

PRESENTATION BY MR. MATSUMOTO

Mr. Matsumoto works in Corporate Technology, where he is responsible for technology evaluation, mainly in material and device technologies, providing us with a glimpse of SONY’s traditional creative energy associated with their corporate research philosophy. Mr. Matsumoto gave us a SONY Group overview (Electronics, Entertainment, Game, Internet Communication Service, and Financial Service - connected by Global Hub), showing a schematic organizational charts, focusing on "Electronics" Organizations, which is composed of Electronics itself and other significant subsidiaries (Sony Computer Entertainment, Sony Communication Network and Sony-Ericsson Mobile Communications). Sony Electronics itself includes Electronics HQ, Sales, Manufacturing sector, Corporate Laboratories and many product segmented small companies; ERC (e.g., “Aibo”, a famous robot doggy), Semiconductor Network Company (NC), CNC (core technology), Display NC, Home NC, Broadband NC, Mobile NC, Telecom Service, S&S (Silicon & Software) Architecture Center, and Network & Software Technology Center; Corporate Lab structures.

One of SONY’s unique activities is coming from Computer Science Lab (CSL) where their engineering and research activities are almost independent from business issues according to Mr. Matsumoto’s expression. One of the panel members asked him a question about a MEMS foundry in the U.S. SONY San Antonio (http://www.foundry.sony.com/default.shtml) operates and provide services of relatively “standard” MEMS processes, implying presumably much of the state-of-the-art MEMS operations might not be happening there, and it left us with the strong impression that the state-of-the-art operations might be still partly centralized in key locations in Japan.

Mr. Matsumoto explained that SONY’s expectations and understanding are the R&D, “applicable to consumer electronics, low cost, and high performance” and “fabrications compatible with CMOS”. They reported that they were currently evaluating optical, RF, and microfluidics areas. External collaborations include Professor Esashi (Tohoku University) for microfluidics with ePrint company, and they are MMC supporting member for core technology and networking sections. They also indicated that they maintain ongoing information exchange channels with BSAC of UC Berkeley. Advanced collaboration with Tohoku
University is currently actively going on. Importance of relationship with universities was emphasized as the key part to "educate new people" (i.e., students), representing SONY’s culture.

To respond to our question if SONY have ever evaluated or survey the MEMS areas, we were told that the division represented by Mr. Shimada (Chief Technology Expert, MEMS Development Department, LSI Technology Development Division) did some evaluation of MEMS in the past like how to use the devices, how to make it in-house, what is available to buy, etc. Stimulated by NNI (i.e., nanotechnology initiatives) in the US, Japanese government now wants to accelerate the funding for national and public labs and then to collaborate with them to get the benefits of the outcome. They indicated that US-Japan collaborations have the problem of distance (especially to communicate) and time difference since they think that videoconference does not work, indicating the need for team/project communications face-to-face. Regarding the quality of MEMS facilities in Japan, they said that many US universities have better fabrication facility than Japanese universities. For technology/people exchange programs, SONY covers all the expenses when sending employees to universities for degree or non-degree programs.

PRESENTATIONS BY DR. YUTAKA TAKEI

Dr. Takei (General Manager, 4GP, CT Development Center), who mainly works in R&D, presented several overhead foils, covering selected latest areas of their MEMS research activities. His division, CNC (Core Technology and Network Company) has Nishi Battery Lab and Kubota Opto-Electronics Lab, and works with New Display Device Division.

The first presentation was on “GP4 (Thin-Film and Plastic Technology for MEMS) - for productions: 1) PBII/Plastic Surface Modification; 2) Thin-Film Coating (FCVA); 3) Thin-Film Coating on Plastic AR Film, Dichroic Mirror "Film" (optical coating)”. Plastics' weakness is mechanical property of surface and needs some modifications, and thin-film was fabricated onto plastics as a part of surface MEMS for multi-color optical film coating. The impressive actual samples were shown and passed around during the presentation. Another presentation was about their paper, "Plasma-Based Ion-Implantation (PBII)" for fast and large area and IEEE on Magnetics Sep'00 p2689-p2691 by Minehiro Tonosaki, et al.) with some practical applications to “High Impact Resistance Plastic Hard Disk (plastics sensitive to metal)”. Compared to semiconductors, ion implantation on plastics requires low temperatures (<100 degree C) and no needs for annealing to heal.

Thin-film on plastics cracks due to tensile stress. The stress of Ta-C (tetrahedral amorphous carbon) thin-film is, however, compressive on a Si or metal surface. PBII was created by UC Berkeley/LBNL with the ion source from gas material (e.g., carbon) with bi-polar pulse (-20kV/+10kV, 30µs pulse; 10^{16} ions/cm^{2}; 1 min process time; 5x10^{4} Pa operating pressure) and filtered cathodic vacuum ion chamber; bi-polar pulse attracts ion instead of hitting them as conventional methods. Application includes a high impact resistance plastic disk where the impact resistance is 3x and higher that of Ni-P plated conventional aluminum disk; however, currently the cost is high. Other application is “Micro-structure fabricated Plastics using PBII and d-limonene (APO with five-member ring) process”.

Site Reports
FCVA is a new type of deposition, “Filtered Cathodic (i.e., carbon) Vacuum Arc Deposition” where adhesiveness is high (because the deposition energy is > 100 times higher than evaporation method; > 10 times higher than sputtering) and impurity free surface for MEMS. “Multi-Layer Dichroic Coating on Plastic Webs” for rear projection TV could be made from multi-layers (25 layers) with SiO₂, Nb₂O₅, SiO₂, ... adhesive layer/SiOₓ, hard coat (acrylic), ... , PET. The PET plastic film (sputter-coated on PET laminated to glass. SONY WEGA (flat screen) with anti-reflection, anti-EM emission, anti-static is the product based on this technology. It was very interesting to know that often SONY brings the design to the vendor, who builds a manufacturing machine, and the vendor will sell to others after 3-4 cycles of productions licensed from SONY.

REFERENCES

Site: Tohoku University
01 Aza-Aoba, Aramaki, Aoba-ku
Sendai 980-8579, Japan

Date visited: November 12, 2001


Host: Prof. Masayoshi Esashi, Mechatronics and Precision Engineering Dept. and Venture Business Laboratory and New Industry Creation Hatchery Center,
+81-22-217-6937 tel, +81-22-217-6935 fax, esashi@cc.mech.tohoku.ac.jp

BACKGROUND

Under the leadership of Prof. Masayoshi Esashi, Tohoku University has been active in MEMS research for well over two decades. The MEMS research group consists of Assistant Professor Takahito Ono and Lecturer Shuji Tanaka, research associates, postdoctoral researchers, visiting industrial researchers, and graduate students. This very productive group is well known for the development of new microfabrication technologies for a variety of applications. Prof. Esashi is affiliated with both the Venture Business Laboratory (VBL) and the New Industry Creation Hatchery Center (NICHe). His group’s current research themes include:

1. active catheter-based maintenance systems for extending the life of machinery
2. wafer-level MEMS encapsulation
3. micro energy sources
4. component development for information technology (optical switches, data storage)
5. nanomachined devices

In 1996, Tohoku University established the Venture Business Laboratory (VBL), for which a new building called the Micromachining facility was constructed. There is Nanomachining facility besides the Micromachining facility. In 1999, the New Industry Creation Hatchery Center (NICHe) was established at Tohoku University and Prof. Esashi was appointed the leader of microsystems research, with a research theme of applications directed at energy and resource conservation. NICHe is a new phenomenon in Japanese academic institutions, in that it has a liaison office to promote ties with industry, a technology licensing arm, as well as an incubator for promoting the formation of start-up companies. Lead faculty at NICHe are freed from the management overhead of their home departments and furthermore, are not obligated to teach.

RESEARCH ENVIRONMENT

Prof. Esashi’s laboratory hosts many visitors from companies. The laboratory maintains an “open” policy so that researchers can share information across research projects. He mentioned that companies should patent their ideas prior to coming to Tohoku and that inventions developed there would be considered joint between the company and the university. This policy is working well and allows visitors from competing companies to work on projects at NICHe.

The laboratory facilities are designed according to Prof. Esashi’s “slim” philosophy, which he learned at Tohoku under his thesis advisor, Prof. Nishizawa at the Semiconductor Research Institute. This philosophy is to develop fabrication equipment specifically for academic research that uses smaller wafers (and thus, fewer materials) and that is robust and flexible. Much of the fabrication equipment has been designed, built, and is maintained by graduate students and postdoctoral researchers. The cost to access the laboratory is very low, about $30,000 per year, which is possible because of many (15 in average) companies which
dispatch their researches to his laboratory and of government subsidies of about $400,000 per year for the operating costs of the VBL.

The Esashi group has a long history of successful technology transfer dating to the 1970s and the portable pH sensor based on an ion-sensitive FET. A capacitive pressure sensor developed at Tohoku is the basis of several products of the Toyoda Machine Works. Another commercial development is an immobilized enzyme biosensor for detecting pyroli bacteria, the cause of many stomach ulcers. Nihon Kohden has products based on this device. Recently, shape-memory actuators (coil and spring) have been used to make a steerable catheter with 0.5 mm outer diameter. A spin-off company is being launched by Dr. Yoichi Haga, a medical doctor working as a research associate in his laboratory, to commercialize the active catheter.

**RESEARCH PROJECTS**

Prof. Esashi is the leader of the Energy and Natural Resource Conservation research activity at NICHe, which describes a primary motivation for his research activities. In his presentation, he provided an overview of several recent projects. Many of them exploit wafer bonding, which is a core fabrication technology at Tohoku. By bonding pyrex wafers with electrical feedthroughs to silicon device wafers, Prof. Esashi’s group is working toward an inexpensive wafer-scale hermetic packaging technology for MEMS. High density electrical feedthrough can be fabricated by deep RIE of the pyrex glass and metal electroplating inside holes. He noted that this approach could enable small-scale production of MEMS, by eliminating expensive traditional packaging processes.

Among the projects outlined was a spinning, electrostatically levitated mass gyroscope developed cooperating with Tokimec, a Japanese manufacturer of navigation-grade gyroscopes. This device is capable of simultaneous measurement of all three axes of linear acceleration and two axes of rotation. Tokimec is preparing for commercializing the device. A safining switch for side-impact airbag sensors was described, in which a spring contact was used as an anti-stiction solution. A silicon micromachined probe card for VSLI testing was described, which utilized TiC as a wear-resistant material for the contacting probe tips. Spray photoresist and an Ushio projection lithography system with a 100 µm depth-of-focus were needed for 3-D patterning on the tips. This project is sponsored by Tokyo Electron, a manufacturer of IC test equipment.

Ball Semiconductor, a start-up in Dallas, Texas, has close ties with the Esashi laboratory, with four members from his laboratory joining this company. A recent project that also involves Tokimec uses a 1 mm diameter silicon ball for inertial sensing. A polysilicon sacrificial layer is removed in a novel way: XeF2 permeates an porous ceramic coating to free the ball. Electrodes patterned around the ball are used to levitate it, with the electrostatic forces required to maintain a stable position reflecting the inertial forces on the ball. This project will be reported at the upcoming MEMS-02 Conference in Las Vegas.

Prof. Shuji Tanaka outlined research in the area of micro power generation and microfluidic control. He is leading a two-pronged approach to developing a small gas turbine by investigating both conventional mechanical machining and lithography-based fabrication technologies. A prototype rotor is 5 mm in diameter and fabricated from SiN ceramics by nitridation of silicon powder. Sintering using sacrificial silicon molds leads to parts with small deformation and shrinkage. The assembly of this mechanically complicated device is a major hurdle. Regardless of the technology used in the demonstration, Prof. Tanaka points out that it is very important to built and test a small turbine. Cost is felt to be a major issue for many consumer applications, but not, for example, in the case of power sources for a humanoid robot.

Multi-nanoprobe data storage is the subject of a recent Ph.D. thesis by Dong Wong Li, who has recently joined IBM Research’s Zurich Laboratory. The leader of this project is Associate Prof. Takahito Ono. There are 32×32 arrayed probes, each probe with an integrated heater tip being used to write the 30 nm x 30 nm area bits onto a DVD-RAM media. This was presented at MEMS-01 and will also be presented at MEMS-02. Since this data storage device uses contact recording, wear is a major issue. Visiting researcher from ITRI (Industrial Technology Research Institute) in Taiwan is involved in this project.
Nanostructures have been studied by Associate Prof. Takahito Ono in this laboratory using several techniques. Carbon nanotubes have been selectively grown on AFM tips. Resonance of the AFM provides information on the mass of the nanotubes, which is greatly increased by hydrogen absorption. Given the outstanding facilities in the Nanomachining facility, Prof. Esashi and his group are well-positioned for ground-breaking research in the practical application of nanostructures for sensor applications. Prof. Esashi is involved in the planning for a new nanotechnology initiative by the Japanese government, which is scheduled to start next year.

**Education:** Prof. Esashi, as a leader in NICHe, is freed from his regular teaching obligations. However, he does teach a one course a week and a 3-day short course in the summer as a continuing education course for engineers from industry. Last summer, it was oversubscribed by a factor of two. However, the regular Tohoku University students do not appear to be overly interested in MEMS compared to other areas of engineering.

**LABORATORY FACILITIES**

The research facilities at Tohoku are outstanding and include a micromachining facility, a nanomachining facility, and several optical, surface-science, and general test labs. The analytical, synthesis, and evaluation tools in the nanomachining facility were particularly impressive. In addition, there is a well-equipped traditional machine shop and a new milling machine capable of 70 nm precision, which is used for the micro turbine project. Most of newer equipment in the facilities has been purchased from vendors, which is possible due to the large (about $1 million per year) annual budget of which half is from the government and the other half is from industry. Many of the older equipment is customized or built from scratch.

**VBL Micromachining Lab**

This 600 m² laboratory is based on 2” inch wafer facility and includes a variety of process tools, most of which are commercial systems. The process equipment includes:

- Lithography: high-speed direct-write e-beam, 5X reduction optical stepper, mask making
- Deposition: sputtering, CVD (including tungsten), and laser evaporation
- Etching: two, 4 inch-capable STS deep RIE tools, fast ion beam, eximer laser ablation for polymers, laser-assisted silicon wet etching apparatus, focused-ion beam, XeF₂, femto-second laser
- Wafer bonding: multi-stack wafer aligner
- Ion implantation: very simple, robust machine
- Analytical tools: SIMS, SEM, thin-film mechanical property tester,

**Nanomachining Laboratory**

- CVD synthesis: carbon nanotube growth with integral FTIR, diamond
- E-beam lithography
- Optical, E-beam mask making
- Photon counting video camera for electrical breakdown study
- Analytical tools: vacuum STM, near-field optical imaging, optical resonant frequency pickup

**2 cm Laboratory**

This laboratory is for processing 2 cm x 2 cm square wafers and contains many home-made process equipment.

- Etching: inductively coupled deep-RIE for glass, oxygen RIE for polyimide, PZT deposition, APCVD for polysilicon, oxide, wet silicon etching
Machine Tools

- 5-axis milling machining (Zephyros) with 70 nm jitter in rotation
- stainless steel lamination

Test Labs

There are spacious facilities in VBL for testing microsensors and microactuators using electrical and optical techniques. One room contained a museum of silicon MEMS.

REFERENCES FOR TOHOKU UNIVERSITY – ESASHI LAB


TOYOTA CENTRAL R&D LABORATORY OVERVIEW

A video overview of the Toyota Central R&D facility was presented. This lab was established to pursue fundamental technologies for the Toyota group. There are several "stockholder" companies to the Toyota CRDL, Inc. The goal of the Toyota Central R&D facility is to develop research ideas to transfer to component production facilities within the Toyota Motor Company keiretsu (e.g., to Denso for semiconductor components). Key topical areas of research include:

1. Environment: for example, the labs are doing combustion analysis to continue developing the perfect "green" car. This includes in-cylinder observation to enhance performance while minimizing emissions. Also, catalytic converter research is being performed to minimize the nitrous oxide emissions in exhaust gases. Technology being developed includes titanium metal matrix composites for improving lifetime on automotive engine moving parts. Also, inorganic electroluminescent thin films for display technology, to reduce the operating voltage and provide better high temperature performance. Rubber recycling research has led to a technique to break cross-linking points that facilitates higher yield in reclaiming rubber. And, fuel cell research using hydrogen and oxygen electrochemical reactions (membrane electrode arrays) is active.

2. Safety: for example, a finite element model of the human body has been developed for accident simulations. An outcome of this research was "whiplash injury lessening" seats.

3. Information and Communications: for example, electronically scanned millimeter-wave automotive radar. This can be used for object and lane detection systems. Ultimately, it would be applied to crash
avoidance systems. Also, traffic simulations and controls are being researched and were demonstrated at the Nagano Olympics.

The Toyota CRDL is active in research meetings (e.g., JSME). They boast about the corporate culture that empowers individuality and the enthusiasm of all staff members.

**TOYOTA CENTRAL R&D LABORATORY SENSOR OVERVIEW**

The Toyota CRDL organization includes: Mechanical Engineering, System Engineering & Electronics, Materials, Research Fundamental Technology, and Frontier Research. The sensor group is within the Electronics Device Division.

Electronic Device Division includes: power semiconductor devices (for electrical vehicles), reliability physics of ICs (especially, gate oxidation), and sensor technology.

The goal of the Toyota CRDL sensor development is to develop sensor research concepts for the Toyota Motor Corporation (sensor systems application). These technologies, once through the research stage, are transferred to Toyota Motor Group semiconductor supply partners (e.g., Denso Corporation) to do the sensor fabrication. The focus has been on surface micromachining. Technology has been developed for sensor fabrication (stiction, vacuum sealing), material characterization (tensile strength measurement), and sensing mechanical analysis. To date, the technology has been three-layer polysilicon surface micromachining. Examples of specific projects follow.

**POLYSILICON VIBRATING GYROSCOPE VACUUM-ENCAPSULATED IN AN ON-CHIP MICRO CHAMBER (TSUCHIYA)**

The gyroscope is expected to be used for vehicle dynamics. The goal is small and low cost. It is required to be encapsulated in vacuum because of the small mass and small Coriolis force. Vacuum sealing is required. To date, glass or silicon cap anodic bonding is used for sealing.

The basic gyroscope is a polysilicon multilayer structure fabrication without CMP [1]. On-chip vacuum encapsulation is being attempted by using HF permeable films [2]. An opening is created in the structural material and backfilled with thin (0.1 µm) phosphorus-doped polysilicon. The sacrificial layer etching is performed through the thin polysilicon, so not direct etch openings are used. Following sacrificial layer etching, a sealing process is performed with silicon nitride.

The gyroscope technology is created with a three-layer polysilicon structure [1,2]. The second layer is the resonator and the third layer is the sealing chamber, with pillars. The third layer is polysilicon and sealed in vacuum with plasma CVD silicon nitride. The p-doped, 0.1 um polysilicon film permeated with HF. The deflection of the sealing film must be minimized, so a pillar is needed (must thicken silicon nitride to over 10 um otherwise).

A compensation oxide is used around the pillar to minimize the lack of lateral travel because of the pillar (etch profile). Mechanical shock is not so severe vs. accelerometers. Pillar structure optimization was used with FEM analysis (through the use of NASTRAN) and analytical methods that provide the spacing (75 um) needed. This is optimized for air pressure only. The resonant properties were measured with the sensor (Q) as a function of pressure. Using the Q as a function of time, reliability evaluations could be gleaned. The initial chamber pressure is 250 Pa; after 2 years, it increases to only approx. 350 Pa. The output of the sensor is not as good as 3-layer type. It needs to be 1 deg/sec, and the on-chip encapsulation is only 5 deg/sec.

Toyota CRDL is in discussion with Denso for productization of this device. There are still issues: cost, reliability, performance, but... the major issue is cost. Currently, the gyroscope project has ended and another project has started and is consuming the 4-5 person project team.
TENSILE TESTING OF THIN FILMS USING ELECTROSTATIC GRIP

MEMS devices include many thin films (brittle) but their reliability is unclear. Strength properties are a large concern. A proposal of an electrostatic force grip system is made [3-5]. Thin film measurements include LPCVD polysilicon, PECVD silicon dioxide, PECVD silicon nitride. The system is a cantilever beam with a large paddle on the free end and a dogbone shape on the paddle. The principle for chucking the specimen is to use electrostatic force on the sample until the dogbone breaks.

The testers are in vacuum (SEM) or in air. They can test samples < 5 µm thick. An electrostatic actuator is used with a loadcell to measure tensile strength. Brittle fracture is observed in all films. The defects on the surface initiate the fracture. High strength was observed. Air does reduce the tensile strength, especially with SiO2 (by 50%) at room temperature. The conclusion is that accelerometers and angular rate sensors must be packaged in inert gas.

Toyota Central R&D Labs is participating in the standardization activities in Japan as a part of the Micromachine Center NEDO activities in Japan. The program focus is on the tensile testing, including a round robin tester: Nagoya/Sato, ME Labs (AIST, MITI), Tokyo Institute of Tech/Higo, Gunma/Saotome, Toyota CRDL. Also, Toyota CRDL has performed round robin test with Sandia, Caltech, and Johns Hopkins to compare results with rest of the world.

A NEW PROCESSING TECHNIQUE TO PREVENT STICCTION USING SILICON SELECTIVE ETCHING FOR SOI-MEMS (FUJITSUKA)

SOI can be used to create thicker devices with easier CMOS integration, but it is expensive and exhibits stiction. Currently, Toyota CRDL is using an Applied Materials deep RIE for these structures. Several alternative techniques have been surveyed, including: vapor HF, sublimation drying, phoro resist ashing, supercritical CO2, SAM, fluorocarbon polymers (special apparatus, materials, thermal stability). However, a single process was not available and reliable for both in-use and release stiction. The purpose of this work was to develop a single, reliable technique to minimize both in-use and release stiction [6].

Silicon etching of HF-HNO3 (3 parts)-CH3COOH (8 parts) was used following sacrificial layer etching to undercut the movable structure. The advantage is that roughening of substrate occurs, formation of asperities occurs (dimples - micropyramids), and the increase in the z-axis gap occurs. Release stiction, caused by capillary forces, is reduced because the contact angle of water increases dramatically on the substrate after silicon etching. This technique is only valid for vertical stiction (not for lateral stiction). Nevertheless, the maximum detachment length was over 2 mm (using a technique similar to Mastrangelo et al.) vs. 200 µm with previous technique.

WTEC PRESENTATION

A review of the WTEC objectives was presented, including the purpose and timing of the study (Appendix xx). A summary of the US MEMS survey was provided to the Toyota CRDL (Appendix xx). Very brief reviews of the research at each of the US panel members were presented (Appendix xx).

SUMMARY AND FUTURE FOCUS FOR TOYOTA CENTRAL R&D LABS

For Toyota Central R&D Labs, automotive system conversion to electronic systems drives the need for additional sensors (e.g., MEMS). Toyota CRDL is chartered to produce technology for the Toyota group (e.g., Denso, first). Research will continue to support this conversion; however, it is difficult because the internal research infrastructure is not available. There are approximately 10 MEMS people in Toyota Central R&D - not enough for a critical mass of researchers. Co-research is being performed with Denso to augment the personnel. In the future, it may be possible for Toyota CRD Labs to use external foundries (like Omron).
Another issue with these sensor devices in the automotive arena is power. How will micro-power generation be created? Toyota CRDL is interested in several techniques: e.g., scavenge from environment (Seiko watch, tire rotation), micro fuel cells, combustion systems, etc. This would open an alternative of using wireless automotive sensor nodes. However, little progress has been made to date on this front.

When asked "what is the status of MEMS research in Japan?", Toyota CRDL answers as follows. There is much technology for MEMS in the world, but there are few real applications that require MEMS. Industrial research is very focused on making new products. There may be some devices - like optical MEMS - that may succeed in the commercial environment, but not many. Toyota is using accelerometers, pressure sensors, and gyroscopes from Denso, Toyoda Machine Works, and some from outside the Toyota keiretsu. Semiconductor MEMS devices require significant infrastructure, so to succeed, mass production is needed. With this large barrier to entry, success is very limited. External infrastructure, like foundries, could provide this needed infrastructure to create small volume fabrication that can then be transferred into high volume.

REFERENCES


Site: Wacoh
Tsuzuki Bldg. 4F, 4-244-1 Sakuragi-cho
Saitama-shi, Saitama Japan

Date visited: 16 November, 2001

WTEC Attendees: D.J. Monk (report author), K. Najafi (presentor), M. Yamakawa, A. Berlin

Hosts: Kazuhiro Okada, President, +81-048-641-9995, +81-048-641-9996 FAX, okada@wacoh.co.jp, http://www.wacoh.co.jp

WTEC PRESENTATION

A review of the WTEC objectives was presented, including the purpose and timing of the study (Appendix xx). A summary of the US MEMS survey was provided to the Mr. Okada (Appendix xx). Very brief reviews of the research at each of the US panel members’ institutions were presented (Appendix xx).

WACOH COMPANY/DIVISION OVERVIEW

Wacoh was established in September, 1988 with 1M¥ and 1 employees. Prior to 1988, Mr. Okada worked in pressure sensor development for another company. He got his start in inertial sensing by reviewing the literature, especially Professor Ken Wise's dissertation. During the first 8 years, Mr. Okada worked alone, then acquired a staff as the company developed products, and now employees 7 people and 30M¥.

The company has created a large patent portfolio: approximately 100 (US, Japanese, and European) patents from Mr. Okada, himself. Mr. Okada has achieved a 98% acceptance rate on his disclosures vs. the average rate in Japan of approx. 30%. Currently, the patent portfolio costs 300M¥ to maintain. The legal work for this intellectual property is outsourced.

The resulting business strategy and sources of revenue are as following:

- License micromachining technology
- Consult on sensor technology
• Obtain revenue from production and sales (including royalties) on:
  - 3-axis accelerometers: piezoresistive, capacitance, and piezoelectric (each technology has own characteristic and market)
  - 3-axis force sensors: capacitive (for example for IBM PC keyboard)
  - 2-axis angular rates: piezoelectric

The stated corporate policy, or long-range corporate plan is the following:

1. First stage, 1988 - 1993: create patent portfolio for 3-axis accelerometer, force sensor, angular rate sensor 6-axis motion sensor
2. Second stage, 19893-1998: product development on patents obtained
3. Third stage, 1998 - : production and sales of developed products
4. Fourth stage: 2003-2005: introduction of publicity traded shares (then retire and farm)

Currently, Wacoh is looking for partners to outsource manufacture in the US and Europe. It would like to establish business in the U.S. In Japan, there are 10 companies producing sensors for Wacoh, depending on the technology (some are silicon based and some are ceramic for the piezoelectric devices).

Not only is manufacturing outsourced, but much of the marketing and sales are outsourced as well, mainly to the manufacturing site organization. For example, the sensor technology for the Sony Aibo is sold directly from the manufacturing partner to Sony. Much of the marketing is done through word-of-mouth from academic meetings. After the first academic paper was presented in 1992 at the Sensor’s Symposium in Japan, Mr. Okada received 1000 inquiries about his device. He is also receiving significant inquiries through the internet.

Venture business in Japan is challenging because: there are funding limitations, the social/business environment does not encourage this, and there are significant personal ramifications for failures. In Japan, personal funding/backing of new businesses is a necessity. There is very little venture capital, like there is in the US. If one fails in Japan, the company loses everything and it is impossible for the entrepreneur to start again. In fact, if a person goes bankrupt, they lose their right to vote! In the US, it is much easier to obtain money and much less detrimental take business risks, even if the result is bankruptcy. Wacoh is a corporation with stockholders, but initially, it required a loan with some collateral (Mr. Okada’s property).

Starting Wacoh was a big risk. However, Mr. Okada did not want to work in a large company anymore, so he went against the advice of many of his friends and started it anyway.

**WACOH MEMS TECHNOLOGY OVERVIEW**

The bulk micromachined or surface micromachined accelerometer typically is just 1-axis. The technology that Wacoh has developed is a 3-axis technology. These are boss-like proof mass structures that can be used for force sensing, accelerometers, angular rate sensors, and motion sensors, as shown in the following figure.
Three sensing mechanisms have been used for the accelerometer: piezoresistive (bridge), capacitive (second bonded wafer), and piezoelectric. In 1992, the first 3-axis accelerometer was developed and commercialized (5 mm x 5 mm). This product is fabricated with a Japanese company under NDA. The assembly was done in CerDIPs. All manufacturing has been outsourced. Complete product descriptions are available at [2].

The capacitive accelerometer is 2.5 mm x 2.5 mm. This die size reduction has been enabled by deep RIE (STS) and SOI. The cost is 10% less than previous devices. This is a 2g device, and Analog Devices is the key competitor. Mr. Okada is very confident that Wacoh will win this market.

Also, Wacoh offers 3-axis accelerometers, and 2-axis angular rate sensors using the same fundamental micromachining technology. The accelerometer sensitivity is 5.8 fF/g with less than 5% cross-axis sensitivity. The angular rate sensor is 2.8 aF/deg/s with less than 3% cross-axis sensitivity. A comparison is done with the Systron Donner sensor with slightly more noise, but similar performance. The Sony Aibo contains a Wacoh 3-axis acceleration sensor. Also, the Sony Playstation Dream Cast Fishing game has a 3-axis acceleration sensor.

A 5-axis motion sensor has been developed. It is not in production yet. It is believed that a 6-axis motion sensor can be introduced in the next year.

A 3-axis force sensor is planned for future PDA or cell phone human interfaces. Next March, a handset manufacturer is looking to add this.

Testing of the each of these devices is mainly outsourced at the manufacturing company. However, Wacoh also has a lab near the Japan Sea.
DEMONSTRATIONS

Three demonstrations of the products in which Wacoh sensors are used were presented:

- Two-axis gyroscope - piezoelectric 2-axis gyroscope: dc to 20 Hz. -5 to 75 C.
- Capacitive force sensor for PDA, cell phone, and possibly some notebook computers
- Gyroscope and accelerometers - Sony Aibo

SUMMARY: SMALL BUSINESS DEVELOPMENT IN JAPAN

Wacoh's initial funding was 1M¥. The company has always been in the black. Today, the capital stock is worth 30M¥.

The first development project was done jointly with a university. The investment is limited because of outsourcing. The manufacturing partners are also partially the sales/marketing arm of the organization. Therefore, the profit margin is quite high. Of the 7 employees, 5 are engineers and Mr. Okada himself does some of the sales.

Foundry service is vital to the Wacoh business. Ten years ago, there were no foundries in Japan, and the level of the technology was quite low. Mr. Okada went to the foundries and trained the engineers himself to help develop the foundry service. The manufacturing company now has developed products beyond those for Wacoh. The manufacturing company is not an investor in Wacoh.

The ultimate goal in 2005 is to go public. Wacoh is also open to being bought out so that Mr. Okada can retire (5B¥ is the asking price).

Wacoh has received no Japanese government funding. They did apply for funding through the Micromachine Project, but it was not accepted. The Murata gyroscope was accepted instead. Approximately 15 companies participated in this project, including Olympus for the catheter endoscope. However, when asked whether government funding is a prerequisite for MEMS business success, Mr. Okada provided the following answer: the market will dictate the final assessment of a product. Even if the government provides funds, the market will define success. If there is a good project, the government should help with funding, but this is very difficult to evaluate.

Finally, the three-axis sensing mechanism concept has allowed the introduction of 5 types of sensors. Because of this basic concept/principle, Wacoh has been successful [3]. Mr. Okada would start another company if he had another basic concept like this that he saw considerable future.

REFERENCES

2. http://www.wacoh.co.jp
Site: Waseda University
Okubo 3-4-1
Shinjuku-ku
Tokyo 169-8555 Japan

Dave Visited: November 13, 2001

WTEC Attendees: A. Berlin (Report Author), K. Najafe, D.J. Monk, M. Yamakawa

Host: Professor Shuichi Shoji, Department of Electronics, Information and Communication Engineering, School of Science and Engineering, tel: +81-3-5286-3384, fax: +81-3-3204-5765, shojis@mn.waseda.ac.jp

BACKGROUND

Waseda is a private university located on the outskirts of Tokyo. Professor Shoji moved to Waseda university 7 years ago from Tohoko university in Sendai, where he worked in Professor Esashi’s research group. Professor Shoji’s research program focuses on MEMS for biological and chemical applications. The primary source of funding for his research group, of which Prof. Iwao Ohdomari is the head of the group, is a 5-year Center of Excellence award from the Japanese Ministry of Education and Culture (1.1 billion yen), which was initiated in June of 2001. As a result of this award, a new fabrication facility is under construction, which will augment an extensive analytical laboratory capability and shared departmental cleanroom that is already in place.

RESEARCH OVERVIEW

One of Professor Shoji’s areas of research is microfluidics, using polymer, silicon, Teflon, and glass substrates. Teflon, which is somewhat unusual in MEMS applications, is deposited via spin-coating by Asahi Glass Company (brand name is ‘Cytop membrane’). Professor Shoji has developed a microfluidic check-valve based on PDMS soft lithography, which was presented in the most recent Micro Total Analysis conference. His group is developing a modular approach to enable system-on-chip ASIC-style fluidics. A library of building blocks of pumps, valves, reactors, separators, and sensors is being designed and tested.

Fig. 1: Professor Shuichi Shoji standing in the doorway of a small coat closet that he has transformed into a highly compact and surprisingly effective fabrication facility. Space is at a premium at Waseda while a new state of the art fabrication facility is under construction.
His group has also integrated an antibody array as a surface coating on a PDMS substrate, permitting high throughput antibody-based screening of biological fluids as they flow through a microchannel, primarily for protein detection applications. Professor Shoji is also interested in chemical synthesis applications. He has a collaboration with Prof. Ikuta and Kitamori in this area, again to be based on the microfluidic building block library his group is developing.

Professor Shoji has an active collaboration with Olympus in the biomems area. One collaborative project involves development of an on-chip bioreactor, essentially a PCR chamber on a chip. This effort is funded by the government’s Bioinformatics initiative (DNA analysis). Prof Shoji also commented that Olympus seems to work with many universities on bio applications of MEMS. The head of the MEMS division of Olympus worked in Tohoko university previously, and has decided to encourage these sorts of collaborations. Prof. Shoji also presented a laser-driven valve being developed in collaboration with Olympus. The valve works through laser-based heating, which is used to trigger gelation of methyl cellulose, which in turn blocks a microchannel. The gelation is reversible by cooling, permitting the valve to be turned on and off repeatedly. When the gelation site is placed at a T-intersection, a multiplexor-style switch is formed.

A unique aspect of Waseda COE research involves single ion implantation to form nanostructures. A single ion is used to create localized damage to a surface. Scanning the ion beam creates an array of tightly spaced (a few nm) damage sites. Anisotropic etching is then used to create arrays of small pyramid-shaped tips. These tip arrays have potential application for ROM, biochemical and biomedical applications. The single ion implantation equipment was developed locally by Professor Ohdomari at Waseda university. This nanostructures effort is part of a university emphasis on wafer-level nanotechnology, i.e. electrochemical processing at a wafer level.

**EDUCATION**

MEMS/MST undergraduate and graduate level courses are both available in Waseda University. During the undergraduate course, Waseda provides an opportunity to develop a student project on a multi-project wafer, utilizing a service being set up through the IEE of Japan. This is not a foundry in the sense of MCNC-Cronos-JDS, but rather is a network of professors who request assistance from various companies they have relationships with, such as Yokagawa (for MEMS) and Olympus (for circuitry). Individual devices for a student project can be obtained at a cost of approximately 200,000 yen for 100 die ($20/die). Government support for this fabrication network has been requested but not yet funded. Historically, multichip fabrication has not been recognized by the government as valuable for education, although this may be changing now.

**INDUSTRY INTERACTIONS**

Professor Shoji’s lab also brings in researchers from industry to learn micromachining in the university environment. Through collaborative projects with companies such as Olympus and Shimazu (in the microfluidics area), industrial researchers gain experience with Microsystems technologies. The university recently created a technology licensing office.

**GOVERNMENT RESEARCH SUPPORT IN JAPAN**

We had a discussion with Professor Shoji about Japanese government support for Microsystems research. Currently, the main focus of Microsystems government research funding in Japan is nanotechnology, in part in response to the US nanotechnology initiative launched by President Clinton. Other focus areas include biotechnology and environmental technology. In Japan, 'nanotechnology' historically means 'material science', so involvement of MEMS and fabrication technology is a bit of a change. MITI is very interested in MEMS applications for biochemistry, and has an effort led by Prof. Kitimori and Shoji. There is much interest in MEMS/MST from the chemical industry in Japan. There is little government interest in RF and
optical MEMS, although NTT does have an interest in optical MEMS research. Similarly, micropower generation is not a major focus in Japan, although it is a major focus area for DARPA in the US. Prof. Shoji indicated that the next large government project is most likely going to be MEMS for bio and chemical applications.

EQUIPMENT AND TOOLS

Prof. Shoji’s research group uses the Coventor design tools for microfluidics analysis and for surface micromachining simulations. An 80 square-meter cleanroom (class100), 160 and 180 square-meter cleanrooms (class10000), facility is under construction. A single ion implanter, a high resolution E-beam lithography, Deep RIEs and fine electrochemical process equipments will be prepared in the facility. An extensive analysis capability is shared by the faculty, including multiple NMR scanners, AFM, TEM, STM, Mass Spectrography, and other test equipment.

US/JAPAN COLLABORATIONS

Professor Shoji feels that communication issues are an important factor limiting Japan/US collaboration in the Microsystems field. He recommends further exchange of Professors giving talks between Japan and the US to improve communication.
BACKGROUND

The Ando lab focuses on visual, auditory and tactile sensing, approaching these problems from the system perspective. A particular strength of the lab is in algorithms for processing and enhancing sensed data. Previous work includes the processing of video images and sound to extract three-dimensional position and motion, as well as the development of robust tactile sensors.

RESEARCH ENVIRONMENT

The lab focus is on the entire sensing system. As such, MEMS technology is seen to be useful for subcomponents where miniaturization brings novel functionality. On a lean budget, the lab is adept at demonstrating innovative sensing principles using low-cost, hand-built apparatuses, many of which were exhibited to the panel in an impressive laboratory tour.

A high level of creativity can be partially attributed to an emphasis on the biomimetic approach. The group often looks to nature for inspiration on novel approaches to sensing or signal analysis.

Prof. Ando cited a large gap between the device and system sides of MEMS. Monolithic on-chip integration of MEMS structures and associated circuitry was emphasized to be highly important. The primary motivation was the realization of large arrays of sensors with each element containing its own computational circuitry and actuation, required for high-performance implementation of certain sense algorithms. Similarly, silicon is seen to be the dominant material due to its ease of integration with VLSI circuitry.

RESEARCH PROJECTS

Prof. Ando explained that the human eye exhibits involuntary eye movement to provide a vibration used to extract a correlation signal. With this motivation, the group has developed a correlation image sensor in
which the relative magnitude of adjoining pixel is measured. Correlation in the time domain can also be measured. Coupled with a vibrating mirror (at 240 Hz), this system simulates the effect of involuntary eye movement and accomplishes real-time image processing such as edge detection. The correlation sensor can also be applied to ranging and spectral image matching. The latest sensing chip integrates the image sensors directly with the correlation processing circuitry, and the hope is to further integrate the vibration actuators with the sensors as well.

B. Mustapha explained the tag-based machine vision project. Bar code tags are used to identify an object, followed by Internet retrieval of descriptor information related to the tag in order to allow the machine to have the most knowledgeable understanding of the sensed object.

Inspired by the human cochlea, the Fishbone sensor mechanically separates an audio signal into its frequency components. Used in conjunction with a logarithmic spiral reflector, this decomposition can be used to accomplish sound source localization. Used in reverse by actuating the “bone” fingers, the structure can be used to generate an impulse single. The cochlea has also been the inspiration for auditory scene analysis algorithms based on decomposition of volume, pitch and timbre. Finally, other types of direction-sensitive audio detectors have been demonstrated mimicking the ears of the barn owl, as well as the fly.

The group has developed a number of robust tactile sensors that take various approaches to sensing the deformation of a layer of silicone, which would be applied to the surface of the sensing appendage. The latest sensor principle achieves six-axis deformation sensing by launching ultrasonic waves from a 2 x 2 transmitter array and measuring the waves with a similar receiver after they have traversed the medium.

Extending the work in tactile sensing, the group is now investigating methods of generating tactile feedback. In one device, a SAW device is used to modulate the stick-slip behavior of a slider on its surface. As the slider is pushed around by the user, the perceived surface roughness can be modulated by changing the SAW frequency. Another device launches ultrasonic waves at the user’s finger under water.

Dr. Shinoda also demonstrated an ultrasound emission device that utilizes the vibration from heat exchange between porous silicon and surrounding air.

LABORATORY FACILITIES

The laboratory facilities are limited, but the group has nonetheless been effective with limited funding. The MEMS fabrication of the Fishbone sensor was done by Prof. Fujita’s lab and then later done at Sumitomo, but the project no longer has funding to continue.

In place of expensive fabrication equipment, the group has proven to be highly adept at constructing prototype sensors by hand for proof-of-concept demonstrations. The barn-owl ear sensor is built out of wood, and while it is rather large, the fly ear sensor consists of a 2 cm film with two poles providing the connection to the transducer below, meticulously glued together by hand.

REFERENCES


Site Reports

Site: University of Tokyo
Center for International Research on MicroMechatronics
Laboratory for integrated micro-mechatronic systems
4-6-1 Komaba, Meguro-ku
Tokyo 153-8505 Japan

Dave Visited: November 16, 2001

WTEC Attendees: A. Berlin (Report Author), K. Najafe, D.J. Monk, M. Yamakawa

Host: Professor Fujita, tel: +81-3-5452-6248 fax: +81-3-5452-6250, fujita@iis.u-tokyo.ac.jp

Professor Fujita directs the Center for International Research on Micro-Mechatronic within the University of Tokyo Institute of Industrial Science. A unique feature of his work is a high degree of international collaboration, which is described in more detail below.

RESEARCH DIRECTION

The major research areas in Professor Fujita’s group are Optical MEMS and NEMS. A 3-D packaging system (see Figure below) has been developed that utilizes a micromachined wafer as a backplane for interconnecting electrical, optical, and mechanical microdevices to the external world. In this system, arrays of MEMS chips ‘plug-in’ to a back-plane using a V-grove-based latching mechanism. This packaging/assembly methodology has been demonstrated to achieve 10 micron alignment.

In the optical MEMS research area, a focus area is electromagnetic actuator development. An array of electromagnetic actuators is being used to construct an optical matrix switch. Magnetostrictive actuation (Terfenol-D TbDyCoFe alloy) is also being used to form a 2-D micro-optical scanner, in which both torsional and bending-mode vibration is induced in a mirror plate to achieve two-dimensional scanning of a reflected laser beam. The 2D-scanner is being supported by Renault-Nissan (a French-Japanese company) for collision-avoidance sensing. Additionally, a magnetically actuated optical scanner for an optical fiber diameter measurement system is being developed in collaboration with Gilbert Reyne and Hiroyuki Fujita of Institute of Industrial Science at the University of Tokyo, supported by Anritsu Corp. Other projects underway include development of MOEMS based on organic materials, as well as development of a III-V based tunable emitter at 1.3um wavelength.

In the NEMS research area, the projects include:

- Using Piezo-Resistive probe for hole inner profile measurement
- Twin nano-probes for characterization of nano structures in TEM
- Micromachined STM for direct observation of atom transfer phenomena in a phase-detection TEM
- Magnetic STM with a non-magnetic tip
- Bio-microsystems for cells manipulation: application to the gene transfer
- Neural growth BioMicrosystem
- Design and realization of an home-made robot for depositing pico-liter volumes of liquid

A multi-layer selective masking process has been developed to form multi-step structures (gears, pyramid, holes). This was presented in a poster at MEMS 2000. This process can also work from the backside of a wafer, and may produce masters for use in PDMS-based soft lithography.
International Program

A key distinguishing feature of Professor Fujita's work is its international flavor. As part of the Center for International Research on Micromechatronics (CIRMM), Professor Fujita operates a very active researcher exchange program with CNRS in France, as well as with other international institutions. Professor Fujita is personally involved in the researcher exchange, spending 1-2 weeks at a time in Paris 4-5 times per year. His laboratory maintains an office in Paris near the Eiffel tower. Over the past 6 years, 35 researchers have visited Professor Fujita’s group from abroad, participating in more than 30 joint projects and resulting in almost 200 publications-communications. A recent trend is that an increasing number of companies are becoming involved in the joint projects as well.

Enrollment in the University of Tokyo Electrical Engineering department is quite limited, and as a consequence Professor Fujita typically has only 5-6 students at a time. The international collaborations augment the research staff with 10-11 visitors, about half of whom are postdocs. Additionally, the lab has two permanent staff members who maintain the microfabrication facility. A small number of industrial visitors are part of the research group as well. For instance, Anritsu Co. currently has a researcher visiting the lab.

The CIRMM exchange program was funded by direct approval of the Japanese Diet in April, 2000 for a period of 10 years. Professor Fujita feels that the exchange is of high educational value because it creates an international environment within Japan, providing even those students who do not travel overseas with an international experience -- new ways of thinking and communicating -- that would not otherwise be available.

Visitors to Professor Fujita's lab usually have technical backgrounds in optics or RF, not in Memes, and are coming to the lab to learn micromachining. Visitors typically stay for two years, with a minimum commitment of one year. Student visitors receive a Ph.D. from France based on research work started in Japan, typically followed by 1 year of followup work in France. At present, approximately 10 visitors from France are in Professor Fujita’s lab. Additionally, 2 postdoctoral fellows from Japan are working in France, supported by the French government with scholarships and a small research budget. Professor Fujita indicated that one of the biggest challenges in these collaborations is communication via the English language. English is a language that both the French and Japanese researchers have in common, yet neither party is a native speaker.
Intellectual property is handled in an interesting way. Postdocs own their own IP as individuals. A Professor can also write his own patent. If a project uses national resources (not including student/postdoc support) in a substantial way, then a national patent owned by the government must be written. Professor Fujita has found that it is necessary to have a patent when industry gets involved. For basic studies like nanotechnology one often needs to quickly publish and typically does not write patents.

FACILITIES AND FABRICATION NETWORK

- Professor Fujita’s group just moved into this newly constructed building about 6 months ago. Information on the new fabrication lab and its capabilities is available on their web site at Http://fujita3.iis.u-tokyo.ac.jp/

DISCUSSION OF STATUS OF MEMS IN JAPAN

Professional Society

MEMS in Japan recently achieved a new milestone with the formation of a new IEE sub-society focused on sensors and micromachines. This society was founded by Dr. Isemi Igarashi, and the first president of the sub-society is Prof. Kiyoshi Takahashi. 1500 members subscribe to the journal of this new society, and 400-500 people attended the annual symposium. The sub-society includes three technical committees: physical sensors, chemical sensors, and micromachines and systems. 60% of the papers in the journal and annual meeting are in English. Some members are from Korea – all are welcome regardless of nationality.

Foundry Service

![Figure 2: MEMS commercialization issues. Professor Fujita views the role of commercial foundries to be lowering the slope of the line delineating the lower/winer boundary. In other words, making it easier for companies to enter the MEMS market successfully by reducing the risk level and costs associated with creating a captive foundry.](image)

Professor Fujita is a strong proponent of creating a national MEMS foundry service in Japan, analogous to the MEMS exchange in the US. Professor Fujita participates in an informal network, organized by Professor Ikeda at Tokyo Agriculture university, that provides multi-project chips for educational purposes. The
University of Tokyo’s VDEC (VLSI Design and Education Center) has a mask making machine. It takes about a day to make a 4-inch masks.

Professor Fujita observed that performance, rather than price, is now the key issue when MEMS technology is used. Without such strict specification and requirements it is difficult to choose MEMS for real problems. It may not be possible to find many large markets where MEMS is a necessity, as illustrated in Figure 2. Many niche markets implies necessity of the foundry approach, so as to enable sharing of facilities. He views as positive the role of Coventor and MEMS exchange in providing the service of being interface between application needs and manufacturing capabilities. In Japan, Sumitomo, Die-Nippon, Olympus, and Omron offer fabrication services, and TSMC in Taiwan is sometimes used as well. However, there is no organization to serve as the interface between the various foundries and the users. Professor Fujita sees this interface role as critical because when multiple organizations contribute to fabrication of a component, reliability becomes a critical issue – which step in the fabrication process, i.e. which organization, is responsible? As a consequence, users are reluctant to use MEMS because there is no reliable set of foundry services, while foundries are reluctant to start because there are no users. Professor Fujita would like to push for this to create a boom for the field, and is looking to the government to help make this happen.

**What are the big obstacles to MEMS in Japan?**

In research, there is a substantial need for resources beyond students skills. In commercialization, the need for foundry services, risk taking willingness on behalf of large companies, and risk-taking willingness on the part of individuals to form a small company. Large companies have good researchers on MEMS but managers always ask about market size - need a huge market size to get attention from large players.

**Government Research Funding Directions**

The Japanese Micromachine Center efforts did not produce real products based on micromachines. There is no corresponding product to DARPA’s DMD display and inertial sensors. However, commercialization was never a goal of the Micromachine project. Ten years ago the metrics of success for research funding did not include commercialization, although that situation has changed today. The Micromachine project did have a major impact, in effect establishing micromachines as a field unto itself – creating awareness that had substantial impact on industry and led to creation of multiple industrial efforts which were not funded by the government.

In terms of government funding, Professor Fujita expects a long-term research funding program from METI, although this has not yet been announced. He expects the new program to focus on microchemical analysis and synthesis systems, as well as microfluidics, to be funded at a level close to the micromachine project - perhaps a 5 year program at half the level of the original Micromachine project. Prof. Kitamori is the key person working on this.

In conjunction with the automobile industry there could be some micro-fuel-cell activities initiated in the future, but this is not a major focus area for govt funding at this time. In contrast to the US, RF MEMS is not a major national research focus at this time. There are some government-funded activities in the area of intelligent transportation systems (ITS) in which the sensor system is very important. “If I hold a special session at a conference on ITS with MEMS, many people will come.” This involves not only sensors, but also wireless communication, collision avoidance, and so forth.

There has been a major improvement in university facilities and equipment since 10 years ago. A couple of years ago, the government enacted a law to support basic science. The government has been supporting universities and research institutions, and there are many opportunities to have $1M level of projects which previously had been very difficult for a university professor to achieve. The funding model in Japan is different than in the U.S. Grants do not pay for overhead or for students, so the bulk of the money goes to facilities. The Japanese Ministry of Education has a rule: you can't use more than 90% of your budget for facilities! This is in contrast to the US, in which funding agencies generally will not pay at all for facilities, instead funding personnel.