

## CHAPTER 6

# MICROSYSTEMS TECHNOLOGIES IN JAPAN

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### INTRODUCTION

This chapter is divided into several sections. In the first section, some definitions of microsystems technologies from both the Japanese and the U.S. perspective are examined, both historically as well as current day. In the second section, specific examples of current fabrication technologies and devices achievable using those technologies are specified. Finally, overall conclusions and recommendations are drawn from the microsystems technologies observed.

#### **What are Microsystems Technologies – the Definitional Problem**

It is very difficult to discuss ‘Microsystems Technologies in Japan’ without first precisely defining terms. In the United States, the term ‘microsystems’ has grown out of MEMS, which in turn grew from micromachining, the use of integrated-circuit-related fabrication technologies to create mechanical structures in silicon and other materials, potentially in addition to electronic devices. This *manufacturing-related* definition has persisted throughout the United States, and micromachining, or more recently MEMS, has been defined as ‘a way of making things’ rather than structures of a particular geometry or size range.

In Japan, a very different view of MEMS grew, perhaps due to the influence of the MITI project of the early 1990s (described below), as well as to building upon core Japanese industrial strengths and to the desire to open new fields of research not being exploited by U.S. researchers of the time. The Japanese approach, perhaps more precisely termed ‘micromechatronics,’ was exemplified by many Japanese submissions to the IEEE MEMS meetings of the period, in which precision machining and utilizing ‘big machines’ to make ‘small things’ was quite common. Although difficult to generalize, it seems clear that much Japanese development in MEMS emphasized the device itself, rather than a manufacturing-related approach.

This interesting difference of opinion has led to some interpretive issues when defining whether, researchers in Japan, especially industry researchers, are performing what U.S. MEMS researchers are defining as MEMS. For example, in spite of the microfluidic elements present in one host company’s systems, representatives of that company stated, “we don’t do MEMS.” Similarly, researchers at another Japanese company have stated that “[there are] no MEMS in our products,” even though they offer products known to incorporate micromachined accelerometers. It should be emphasized that these are not failures to communicate or attempts to mislead, but that these statements arise solely from the definitional issues described above.

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<sup>1</sup> With assistance of WTEC staff.

On the other hand, in general academic researchers in Japan tended to take a much broader view of MEMS and microsystems, more analogous to the U.S. definitions. More recently, these two viewpoints are coming together in the term ‘microsystems,’ and each country is recognizing the merits of (and incorporating some of the approaches of) the other in their current microsystems research.

### **Historical and Current Viewpoints**

It is instructive to compare the relative viewpoints of both Japan and the United States 10 years ago (approximately the timeframe of the last report) and to compare that situation with today. Ten years ago, U.S.-based MEMS programs had their roots firmly in silicon and complimentary metal-oxide-semiconductor (CMOS) processing. Based on this infrastructure, the fabrication technology expanded to build lithographically-based microsystems. Although there were clear exceptions to this paradigm, like ion-beam fabrication and laser-assisted sequential etching technologies, by and large the batch-fabrication approach along with silicon integrated circuitry was utilized as the foundation for microsystems development. On the other hand, as discussed above, Japanese ‘MEMS’ clearly had its roots in mechatronics. Perhaps the classic example of this approach was the ‘micro-car,’ a *tour de force* of conventional precision machining, in which large machines were used to make tiny functional objects in a serial fashion, including (as a technology demonstrator) a microscopic metallic car with functional doors, hood, trunk, and wheels—and an electric motor.

The diverse viewpoints were reflected in the subsequent research directions of the two countries over the decade of the 1990s. The United States invested heavily in the development of lithographically-based fabrication technologies, in silicon as well as a variety of other materials. Japan invested heavily in the micromechatronics approach, exemplified by the MITI MTP project. In this project, several end applications for microsystems helped to define research vehicles for technology advancement. These end applications included telerobotics and catheter-based systems for investigation of the internal integrity of pipes for power plants; medical applications of catheter-based systems; and a ‘microfactory’ project for the rapid fabrication of small-scale parts. This device-based approach, with few to no constraints on the manufacturing approach, contrasted strongly with the U.S.-based manufacturing-approach definition of microsystems. Today, after a decade of research, both countries are recognizing the merits of the other’s approaches. Significant investments in lithographic-based MEMS capability and equipment over the past few years were observed, as Japanese laboratories have sought to capitalize on the decade of advancement in lithographic-based MEMS.

Perhaps key insight into the current Japanese philosophy toward microsystem technology can be gleaned from the following comment from one of our hosts: “[A] system has its own size. Miniaturization is not always possible or necessary. But, for many key devices of the system, miniaturization can be very essential and important.”

### **Facilities and Funding**

In general, the visiting panel was struck by the great improvements in university facilities over the past 10 years. These improvements are clearly driven by the large investment of the Japanese government in universities. Due to the nature of government funding of universities in Japan, almost all of this funding was directed at facilitization. As described elsewhere, in Japan most discipline-specific funding of universities is directed at equipment. Student stipends and faculty salaries are covered in the base budget allocations to universities, unlike U.S. government-based research funding. Furthermore, there is an extensive presence of visiting engineers from industry in the university laboratories. The engineers are a valuable resource in the research and development of microsystems at the universities; and since their salaries and expenses are covered by their home companies, their presence allows further use of government funds on infrastructure research and development. At some laboratories, investments of greater than 90% of received government funds were utilized for infrastructure. This approach is very different from the U.S. approach, in which much government funding is directed away from equipment and infrastructure investment with the exception of certain targeted infrastructure development programs.

In addition to the concentration of government resources on equipment and infrastructure, funding is uneven from institution to institution. Some university facilities, such as the national universities and so-called

‘venture laboratories,’ received substantial benefit from this approach, while other facilities and universities have not benefited as much. The concentration of resources has led to the establishment of a few world-class concentrations of microsystems laboratory equipment in Japan. Several of the research projects that illustrate some of the Japanese approaches to microsystems over the past several years are illustrated in the next section. It should be emphasized that this review is not an exhaustive list, due to the time constraints of the WTEC visit as well as the vast number of technologies observed even during this limited visit. However, the technologies have been selected to give a flavor of the current state of the art of microsystems technologies in Japan.

## **REVIEW OF JAPANESE TECHNOLOGIES**

Although it would be impractical to detail every fabrication technology in use in Japanese microsystems laboratories, highlights of some of the various approaches are given below. These illustrate not only some of the capabilities of the Japanese laboratories, but also some of the current thinking regarding the approaches to microsystems fabrication that are currently being undertaken.

### **Batch Assembly Processes (active catheter)**

The original plan for the MITI Micromachine Project included a project for the development of a MEMS-based catheter device for medical applications (Wise et al. 1994, p. 111). This WTEC panel saw some results from the MITI-funded work, and some follow-on work as well.

In particular, Olympus, one of the original participants in the MITI program, has developed several different types of catheters and is exploring industrial applications of this technology, including field repair of damaged pipes. A laser-welding catheter that can weld cracks in pipes in-situ has been developed. The laser used is a YAG laser and provides a power of over 70 W over a 0.5 mm depth. Pneumatic actuators are used to actuate the tip of the catheter as it is inserted into the pipe of interest. Murata has developed a gyroscope-based MEMS position sensor for the original MITI catheter project, which it has continued to develop and has targeted towards automotive applications. See site reports in Appendix B for details of the work at Olympus and Murata.

Prof. Esashi of Tohoku University lists active catheter-based maintenance systems for extending the life of machinery as one of the principal topics for research in his laboratory. Also at Tohoku University, shape-memory actuators (coil and spring) have been used to make a steerable catheter with a 0.5 mm outer diameter. Dr. Yoichi Haga, a medical doctor working as a research associate in this laboratory, is launching a spin-off company to commercialize the active catheter.

This WTEC panel saw a large, diverse range of research projects being performed in Japan using catheters as a unifying example. In general the panel observed batch assembly processes frequently. The Japanese (and we will see this again in other examples below) do not seem to be afraid of the concept of non-integrated MEMS, of assembling components to form a system.

### **Selective Laser Ablation**

Selective laser ablation is one of the technologies that this panel observed under development for MEMS device fabrication in Japan. Laser patterning, especially excimer laser ablation of aromatic polymers such as polyimide, was used to fabricate a variety of biomimetic structures. This approach has led to structures that include the swimming and flying microactuators shown in Figures 6.1 and 6.2, from Prof. Esashi’s laboratory at Tohoku University. The flying and swimming microactuators consist of a polyimide ‘tail’ or ‘bridge’ that connects the magnetically permeable ‘wings’ or ‘head’. By placing the microactuator within an oscillating magnetic field, the actuator can be induced to swim or fly.

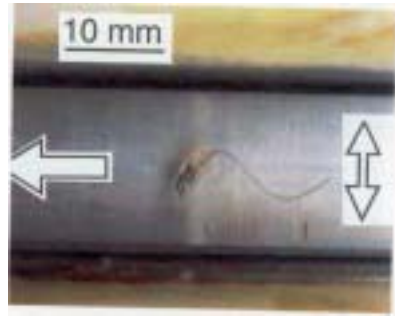


Figure 6.1. A fin-type swimming microactuator composed of a small magnet with a polyimide film (Esashi Laboratory, Tohoku University).

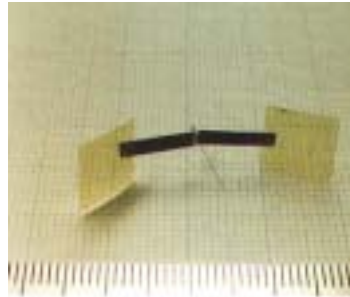


Figure 6.2. Flying microactuator with two magnetic wings attached to the body of a soft magnetic wire (Tohoku University).

### Projection Exposure for Non-Planar Lithography

Projection lithography for non-planar surfaces was demonstrated, not only for spherical surfaces such as that utilized by Ball Semiconductor in its spherical MEMS devices, but also for cylindrical surfaces such as the tips of catheter devices. One non-planar lithography technology that was discussed was being exploited in the fabrication of suspended, spherical-proof-mass, multi-axis accelerometers. Prof. Esashi's laboratory at Tohoku University is working with Ball Semiconductor in the United States and with Tokimec, a Japanese manufacturer of navigation-grade gyroscopes, to develop a 1 mm diameter silicon ball for inertial sensing. A polysilicon sacrificial layer is removed in a novel way:  $\text{XeF}_2$  permeates a 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.

Projection exposure for non-planar lithography was also demonstrated using X-ray approaches at Ritsumeikan University. This was utilized in the direct micromachining of polytetrafluoroethylene and is described in the LIGA subsection below.

### Piezo and Pyroelectric Film Deposition (sensing and actuation)

As an example of the combination of 'traditional' MEMS fabrication technologies with new materials, Professor Okuyama's laboratory at Osaka University is experimenting with the development of infrared image sensors using barium strontium titanate (BST) as a bolometric material. The approach was to determine the change in the 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  $3 \times 10^8 \text{ cm (Hz)}^{0.5}/\text{W}$ . (See site report in Appendix B for details.) Olympus is offering thin film deposition and electroplating as part of its MEMS foundry service.

### High Temperature Materials for Power MEMS

Other nontraditional materials for high temperature and power MEMS are also being investigated. For example, silicon carbide and silicon nitride micromachining for microturbine applications is being researched at Tohoku University under the direction of Prof. Shuji Tanaka (Fig. 6.3). Since silicon carbides and nitrides are such inert materials (thus their desirability in aggressive environmental applications), forming fine features many tens or even hundreds of microns in thickness is very difficult. Prof. Tanaka is therefore leading a two-pronged approach: the first is to use conventional machining techniques to create the desired structures; the second is to utilize microsintering into ‘traditionally-micromachined’ (e.g., lithographically-defined and ICP-etched silicon) molds to create the desired microstructures.



Figure 6.3. Micro air turbine capable of 10,000 rpm. The prototype rotor is 5 mm in diameter and fabricated from SiN ceramics by nitridation of silicon powder (Esashi Lab, Tohoku University).

### Microfluidics: Straightforward MEMS Technology with Sophisticated Chemistry

Several research groups in Japan are focusing on microfluidics as a key application area for MEMS, with significant activity underway at Olympus, Shimazu, Sony, Tohoku University, Waseda University, and Kanagawa Academy of Science and Technology (KAST). Professor Kitamori’s group at KAST is among the more active university-based groups in this arena. His approach is to use standard microfabrication techniques to form microfluidic platforms, in which he does highly sophisticated, innovative chemistry. A major goal of this 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 microns in diameter. However, his group is interested in the possibilities of “nanocapillaries” in which the behavior of water is unconventional. He hypothesizes that the capillary walls constrain the water clusters, 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. Recently Prof. Kitamori founded a small startup company co-located with KAST to market the microfluidic chip technology he has developed.

Prof. Shuichi Shoji at Waseda University is also working in 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 (the brand name is ‘Cytop membrane’).

Microfluidics and integrated chemistry will be the focus of a major METI program that will start in 2002. Another potential initiative is in microfluidic systems for cell-based biochemistry, which could be the focus of a Ministry of Agriculture program starting in 2003.

### SAW Devices

Surface acoustic wave devices were exploited in a number of ways. Although much of the fabrication technology being performed was ‘straightforward,’ e.g., the lithographic-based fabrication of interdigitated electrodes on planar, bulk lithium niobate substrates, the applications of interest were novel. For example, in Prof. Shigeru Ando’s laboratory at the University of Tokyo, such devices were being exploited as haptic devices for robotic interfaces, in which the perceived ‘smoothness’ of the surface was electronically alterable by adjustment of the amplitude of the acoustic wave propagating between the interdigitated electrodes (Fig. 6.4). These technologies are also being pursued actively within the United States.

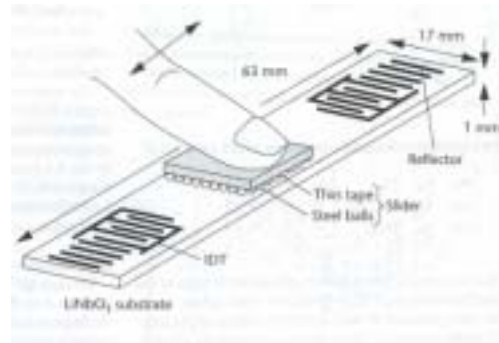


Figure 6.4. SAW devices: interdigitated electrodes on lithium niobate (University of Tokyo).

### Advanced Electronic Bulk Ceramics

The WTEC panel observed some Japanese work on ceramics, including ceramics with interesting electrical properties, high dielectric constants, piezoelectrics, ceramic antennas, and sensors. Figure 6.5 shows some examples of piezoelectric and pyroelectric devices currently manufactured by Murata.



Figure 6.5. Murata ceramic-based products.

Although Murata’s MEMS work has been emphasizing the gyroscopes that were developed as part of the MITI project (see above), Murata representatives did express interest in RF MEMS. They felt that their expertise was in ceramics, and therefore, they were motivated to use ceramics to do what some researchers in the United States are doing with, e.g., micromechanical switches and relays. In addition, they see opportunities for high-dielectric-constant micromachined ceramic antennas as operating frequency ranges increase, and consequently, wavelengths decrease to on the order of the size of their parts. Murata plans to apply the RF MEMS concepts to 5 GHz cell phones.

Some of the Murata researchers stated a very intriguing philosophy. Perhaps influenced by their very successful components and parts business, they felt they had a potentially strong opportunity in the

manufacture of ‘MEMS components,’ whereas many of the other industries that we visited were working more on ‘MEMS systems’. Further, they felt that the opportunity for the hybrid assembly of MEMS parts could follow the successful manufacturing paradigm of pick-and-place hybrid assembly of complex systems that has been used for cellular telephones. This was exemplified by a (paraphrased) comment from one of our hosts: we are a components company and should play to our strengths.

Another ceramic development the panel observed in Japan is an ultrasonic signal-emitting device, developed under Micromachine Center funding, that uses high aspect ratio MEMS-like technology in ceramic. The device is being commercialized by Sumitomo Electric.

### **Wet and Dry Etching of Silicon**

In addition to the work at Osaka University (mentioned above), the panel observed wet etching of silicon v-groove technology for alignment at Murata, Olympus, Tohoku University, and Hitachi. This is quite mature technology that is now being deployed in products. The panel heard a presentation at Hitachi’s Mechanical Engineering Research Laboratory (MERL) on 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.

Some silicon dry etching and deep reactive ion etching research is being done in Japan (e.g., at Murata, Tohoku University, AIST/ISEMI) and is offered as part of some of the foundry services (in particular at Olympus). This technology approach is also one that many U.S. researchers have been working on quite aggressively.

### **Glass Micromachining**

Murata showed the panel an interesting packaging scheme using vertical through-holes sandblasted through anodically-bondable glass to both form a vacuum seal as well as electrical feedthroughs (Figure 6.6). 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 it has a packaged size smaller than 5 x 5 mm. The noise-equivalent angular rate is currently 0.3 degree/second in a 40 Hz bandwidth, and Murata is currently on its third or fourth generation device. These and other back-end processes are discussed further in Chapter 4 of this report.

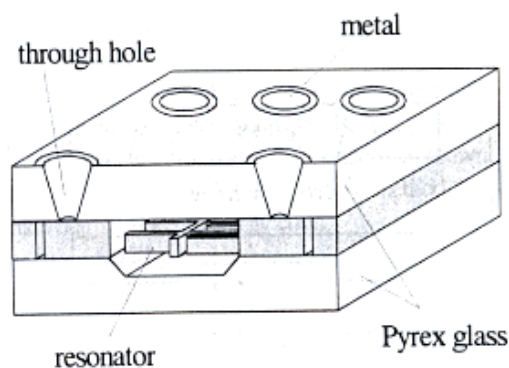


Figure 6.6. Glass micromachined packaging (Murata).

### **Synchrotron Radiation (LIGA) and Associated Processing**

#### *LIGA facility*

Ritsumeikan University has a significant investment in infrastructure that enables the so-called LIGA process (Lithography, Electroplating, Molding). The synchrotron ring (Figure 6.7) is based on a superconducting

magnet that allows a relatively high beam energy to be achieved in a relatively compact machine. 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.

Applications being developed at Ritsumeikan University for this fabrication technology include micro lens arrays, a PMMA micro capillary array chip, mechanical socket and plug connectors, a device with tunable acoustic absorption characteristics created using an array of Helmholtz resonators with mechanically adjustable cavity lengths, and thick-film magnetic cores for use in lightweight power supplies.



Figure 6.7. Synchrotron at Ritsumeikan University.

#### *Associated beam lines and advanced lithography*

The beam lines associated with the synchrotron were being utilized in three ways: “standard” LIGA exposure of thick resists, precision-positionable moving sample stages for 3-D exposure of thick resists, and lines to perform physics-based experiments enabled by high energy X-rays. A variety of resists were being examined, ranging from the standard thick PMMA followed by electroplating, to direct synchrotron-beam writing of polytetrafluoroethylene (PTFE — Teflon) materials (Figure 6.8).

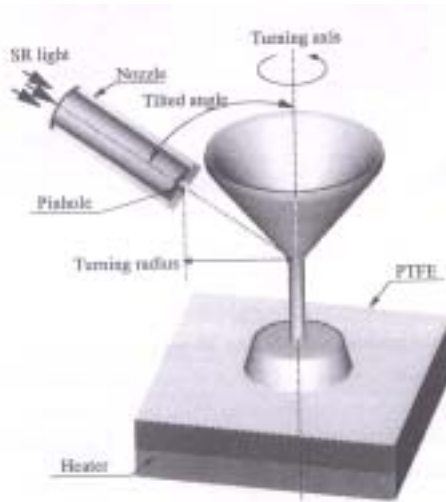


Figure 6.8. Schematic diagram of experimental setup for synchrotron ring beam direct writing (Ritsumeikan University).

### *LIGA supplemented by foundry CMOS*

The potential of performing LIGA technology on foundry-fabricated CMOS circuitry was advertised as ‘coming soon,’ to realize highly-electrically-integrated, LIGA-based microsystems. In parallel with this effort was a development effort to make available foundry-based LIGA services to the outside community. Foundry-based LIGA services are expected to be generally available in the 1-2 year timeframe.

### **Nanochemistry Fabrication**

If microsystems is ‘a way to make things’ based on lithography and semiconductor-related processes, nanosystems might be considered a way to make things based on chemistry-induced molecular assembly. Such work is being aggressively pursued in the United States and is also proceeding in several laboratories in Japan. As an example, the WTEC panel saw some research on nanochemistry-based fabrication, where it is possible to build nano-chains relying solely on thermal and chemical interactions—MEMS or NEMS in a beaker. The work of Profs. Kohno and Takeda at Osaka University on silicon-silicon dioxide nanochains is of particular note. They discovered in 1998 that these unusual structures form spontaneously using a modified vapor-liquid-solid growth procedure. Recently, they have developed considerable insight into the growth mechanism and have applied this knowledge to obtain high yields of nanochains. The process (Kohno, Iwasaki, and Takeda 2000) consists of heating a sample of {100} oriented silicon that is coated with 10 nm of gold and a small piece of (typically) lead in a closed ampoule at a pressure of around 10  $\mu$ Torr. 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 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 is about 10 nm, and the spacing is about 35 nm. The tiny amount of added lead modifies the interface tensions during nanowire growth. High yield growth of a dense carpet of nanochains can be achieved through this process.

Professor Takeda’s group is investigating the optical and electronic properties of nanochains. Discovering and understanding the self-organizing formation of periodic structures is clearly an important advance in nanotechnology and in fabrication technology generally.

### **Ferroelectric Thin Films**

Japanese researchers are depositing ferroelectric thin films using many different approaches (e.g., pulse laser deposition, sol-gel, metal-organic deposition), in addition to the thin film sputtering approach that is more common in the United States. In particular, Professor Okuyama’s group at Osaka University has focused much of its effort on fabrication using non-standard IC materials including ferroelectrics and on the application of ferroelectric technology to MEMS devices such as sensors or actuators. Figure 6.9 illustrates some of the work of the Okuyama group in fabricating micromachined ferroelectric bolometers, which can be applied to the development of non-cooled infrared detectors.

### **Micro-stereolithography**

Stereolithography is the selective, light-induced polymerization of appropriate resins by the accurate positing of impinging laser beams. Japanese researchers have been investigating the limits of this technology to create extremely small structures. The laboratory of Prof. Ikuta at Nagoya University has been a leader in this area. Current applications of this technology involve the fabrication of biochemical ‘IC-chips’ for microfluidics, microreactors, and microanalysis systems.

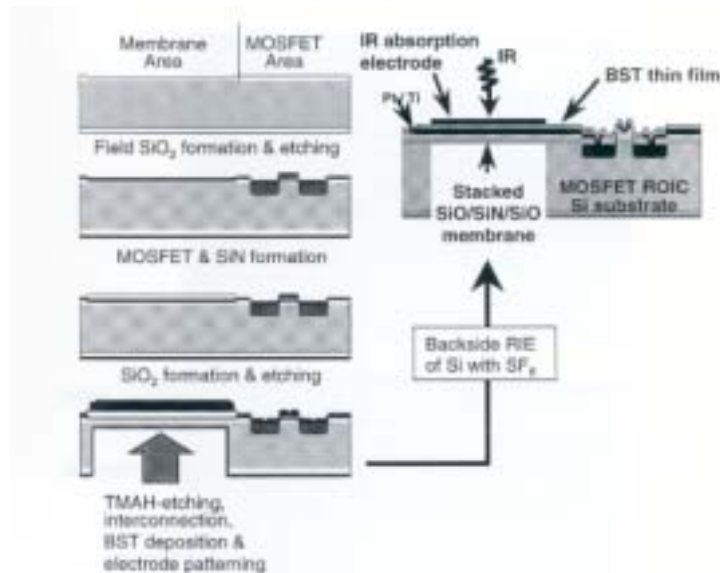


Figure 6.9. Monolithic process sequence in the fabrication of micromachined ferroelectric bolometers (Osaka University).

### Injection Molding of Metals

Researchers at ISEMI (a METI lab) are working on the development of molds for vacuum casting metals using deep reactive ion etching to form channels that are later filled by injected metal using a vacuum casting process at a small company called Optics Precision (see <http://www.d1.dion.ne.jp/~rtc/>). The vacuum casting process requires one hour, which is much faster than the many electroplating steps that would be needed to form the structures conventionally. ISEMI also 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; mold fabrication may be done at Ritsumeikan University using the LIGA process.

### V-groove Technology for Optical Alignment

Professor Fujita’s group at the University of Tokyo has developed a 3-D packaging process that utilizes a micromachined wafer as a backplane for interconnecting electrical, optical, and mechanical microdevices with the external world. In this system, arrays of MEMS chips plug into a back plane using a V-groove-based latching mechanism. This packaging/assembly methodology has been demonstrated to achieve 10 micron alignment. Other applications of this approach have been mentioned above.

### Plastic Treatment

Researchers at Sony have developed a method for ion implantation in plastics (Tonosaki et al. 2001) with some practical applications for impact-resistant plastic hard disks (plastics sensitive to metal). Compared to semiconductors, ion implantation on plastics requires low temperatures (<100°C) and no need for damage annealing. See the Sony site report in Appendix B for more details.

### Polymer Gel Fabrication

Professor Shoji’s work at Waseda University (see above) also includes the development of a microfluidic check-valve based on laser-induced thermal gelation of methyl cellulose (Tashiro, 2001).

## OVERALL IMPRESSIONS

As indicated above, Japanese researchers are developing a rather wide variety of what U.S. researchers might consider unconventional processes and materials for MEMS device fabrication. The variety of alternative approaches being considered is impressive. “Standard” thin film MEMS processing is present in Japan as well, but appears to be much less strongly emphasized than in the United States.

In general, the WTEC panel saw a lot of assembly, components, and devices. In many institutions, relatively inexpensive or older fabrication tools are being used to produce very nice results. Significant new investments are also being made in MEMS fabrication tools (e.g., ICP machines at Tohoku University, a superconducting synchrotron with advanced beam lines and rotating lithography at Ritsumeikan University, and E-beam and nanolithography tools in a variety of institutions). Even more significant, many institutions boast excellent analysis and measurement systems (e.g., multi-hundred-gigaflop fluid analysis systems at Hitachi, TEM facilities at Osaka University, and analysis systems at Waseda University). One potentially important development the panel observed was the inception of MEMS foundry services in Japan.

Perhaps what is equally important is what the panel did *not* see, although again it must be emphasized that our coverage of Japanese research was necessarily incomplete. We did not see: much use of the latest plasma tools (e.g., ICP); much research on silicon surface micromachined MEMS (with the notable exception of Omron’s “harvest” investment in bulk etching spurred by the MITI project); or many integrated MEMS or highly integrated systems. As an example, our Hitachi hosts commented that the company is no longer making airbag accelerometers, because ‘others can do it at lower cost.’

## CONCLUSIONS

The Japanese definition of microsystems technology and MEMS reflects a unique Japanese perspective on the need for alternatives to the silicon and lithography-based approaches that are so strongly emphasized in the United States. It also reflects the 10-year legacy of the Micromachine Project’s funding in non-lithography-based, device-focused approaches and the project’s application thrust areas (e.g., pipe-inspection, catheters, and the attempt to demonstrate a microfactory). Many U.S. researchers, including the WTEC panelists, accept (and endorse) the broader Japanese perspective, which is essential if the “S” (systems development) in MEMS is going to be realized.

A relatively new issue that has arisen is the boundary between “micro” devices and “nano” devices. Certainly it is not size; it would be difficult to defend the assertion that a device 999 nm in size is ‘NEMS’ while 1000 nm is ‘MEMS.’ Even the ‘manufacturing’ separation of lithography versus molecular assembly suggested above is blurred when one recognizes that these techniques are often combined in the manufacture of *systems*. This awareness is also the view of many Japanese researchers, i.e., that these domains are inextricably linked and that there is no clear dividing line between “micro” and “nano.” The panel did not see much in the way of explicit “NEMS” R&D in Japan, although the work observed at Osaka University on “nanochains” was impressive. Professor Esashi also presented an interesting paper at IEEE MEMS-2000 (Miyashita, 2001) on carbon nanotube resonators. Japanese researchers seem well positioned to move ahead quickly in NEMS, given their excellence in doing aggressive “build & test” R&D. The availability of excellent analytical equipment for nanoscale research will be a big advantage as well. The panel noticed particularly outstanding facilities at Tokyo University, Tohoku University, and Osaka University.

Many of the Japanese researchers who spoke with the panel felt that Japan on the whole is not leading the world in silicon micromachining technology. However, there are notable centers of excellence in this area in Japan—in particular the work of Professors Esashi and Fujita. Japan has also contributed significant innovations in new materials, processes, and equipment. Japanese contributions include developments in wet bulk processing, dry bulk processing, surface processing, and LIGA. LIGA innovations are focused on lower cost fabrication of “traditional” projected structures through lower capital cost equipment, thereby enabling the establishment of LIGA foundry services for Japan; and on advances in X-ray mask fabrication, beam lines, and sample holders that enable the fabrication of complex, 3-D devices.

One should not underestimate the potential importance of the development of low-cost precision plastic parts for microfluidics applications. The reusable plastic connectors developed by Prof. Kitamori (see above) cost over ¥1000 in small quantities, but the cost could be reduced to less than ¥1 per unit if replicated using a LIGA technique.

The Japanese in general are very strong in non-silicon technologies. Murata is a center of particular excellence in ceramics. Integrated “PC board” fluidics work at Hitachi, KAST, and Waseda University was also particularly impressive.

The panel saw some evidence of an entrepreneurial MEMS specialty manufacturing business developing in Japan, with small companies spinning off from and sub-contracting to projects at KAST and ISEMI, for example.

There is relatively little public information on Japanese packaging and encapsulation technologies, for obvious proprietary reasons. The wafer bonding work at Tohoku University is one notable exception. The panel did not see much in the way of assembly technologies, with the exception of lamination for fluidics, and dense hybrids at Murata.

In conclusion, Japan appears to have taken a leadership role in non-Si MEMS technologies. The U.S. MEMS community should take note, given the importance of these technologies for *microsystems*, as opposed to “only” discrete MEMS devices.

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