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New Development in MEMS Research — Technical and Social Aspects —

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8.1 Introduction

MEMSs (Micro Electro-Mechanical Systems) are defined as micro mechanical systems including the movable parts produced by utilizing the processing technology that has been accumulated through the development of semiconductors.

Not only in the United States and European countries that are advanced in MEMS technology but also in Asian countries such as Taiwan and Singapore with aids by governments, there is a strong trend to develop MEMS technology as a new core technology of industry. Currently, the targets of MEMS research cover a wide range of application fields including, in addition to machine parts, medical- and bio-related technologies and energy storage technology [1-4]. Products that are manufactured utilizing MEMS technology are basically characterized by small-lot production of a wide variety of goods, and the technology is expected to activate the development of industry including the creation of venture businesses. Since overseas countries are directing their efforts toward the development of MEMS technology that may endanger the future of the parts supply industry, which has been the specialty of Japan, we cannot take a wait-and-see attitude.

In this report, we will review the history and highlights of MEMS research in Japan, and point out problems in the present research system in Japan.

8.2 What is MEMS?

8.2.1 Typical MEMS devices

One of the typical MEMS products is the Digital Micro Mirror Device (DMD™) (see Figure 1) [1-4].

Figure 1: Optical element with mirrors rotated by electrical voltage. Digital Micro Miller Device (DMD™) [1]

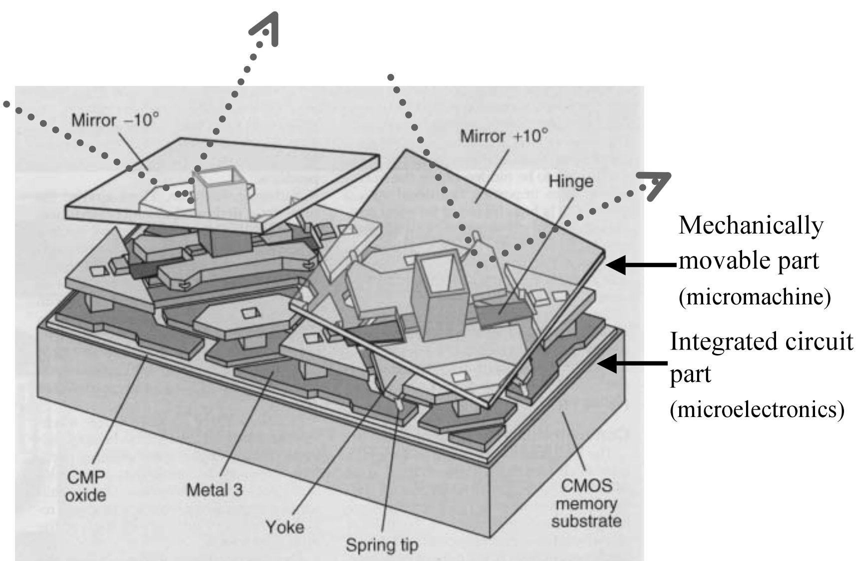
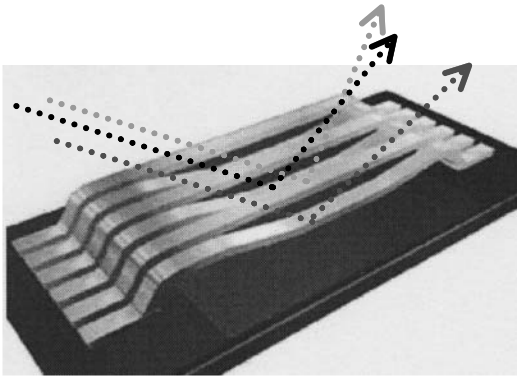


Figure 2: Optical element in which ribbons sink alternately by electrical voltage. Glating Light Valve (GLV) [5]



This is an array of more than a million small aluminum mirrors. Each mirror is 16 μm-square, which is arranged on a silicon integrated circuit. It rotates within the range of ±10 degrees, with a response speed of 1 microsecond. This means that micro machine technology is being placed on microelectronics technology. It gives an advantage that a large number of chips can be formed on a single wafer.

Another example of MEMS devices is GLV (Glating Light Valve), which aims at a display similar to the DMD array (see Figure 2)[5]. This device is made of 1,080 sets of six nitride ribbons (3 μm W × 100 μm L) coated with aluminum. Each set corresponds to a picture element. The laser beams are reflected by the alternate sinking motion of the ribbon caused by an electrical voltage sent from the integrated circuit. It is said that the GLV device could operate 1,000 times faster than the DMD array. It is also produced by making use of semiconductor processing technology.

The present research on MEMS technology is not restricted to such optical devices and covers a wide range of applications (see Table 1) [6].

8.2.2 Definition and historical background of MEMS

"MEMS" is a term that has been used mainly in

Table 1: Applications of MEMS (Underlined applications are especially promising)

Information and communication — Printing: <u>ink jet printer head</u>, etc. — Optical devices: <u>optical switch</u>, <u>display (DMD</u>, FED, etc.), optical scanner, optical modulator, optical connector, variable wave length filter, spectrometer (environmental measurement, etc.), variable focal length lens, mirror, lens array, variable wave length laser, optical detector, free space integrated optical system, micro-encoder, tip sensor for optical fiber, etc. — Electronic devices: high frequency devices (resonator, variable capacitor, inductor, submillimeter wave zone resonator, array antenna, etc.), micro magnetic devices (micro-transformer, etc.), micro relay, mounting parts such as connectors, etc. — Recording: <u>recording head</u> (magnetic, optical, magnetic optical, thermal, etc.), actuator for tracking, etc.
Automobiles, consumer products and environment — Inertial measuring units: <u>acceleration sensor</u>, (automobile use such as with air bags, pace maker, games, seismometer, etc.), <u>gyro</u> (automobile use such as with the brake system, camera shake prevention, motion control, etc.) — Pressure measuring units: <u>pressure sensor</u> (automobile use, medical use, industrial use, etc.) — Other sensors: thermal sensors such as <u>thermal type infrared imager</u>, microphone, ultrasonic transducer, environmental sensing, infrared gas sensor, spatial localization cognition sensor, personal identification sensor (fingerprint, etc.), and others.
Medical and biological — Biochemical: <u>biochemical analysis on chip (DNA chip</u>, capillary electrophoresis, etc.), dispersoid analysis on chip (flow cytometer, etc.), micro reactor (reagent synthesis, etc.), tools for biotechnology (cell fusion, etc.), and others. — Medical care: <u>minimally invasive operations</u> (catheter, endoscope, drug delivery, etc.), embedded devices (artificial internal ear, telemeter, etc.), interfaces to organisms (electrode, probes for sampling and injection), etc.
Production and inspection — Micro fluid: micro valve/pump, flow sensor/controller, etc. — Micro probes: <u>scanning probe microscope</u> (AFM, SNOM, etc.), micro-prober, etc. — Local thermal control: micro cooler, micro heater, micro-calorimetry, thermal actuator, etc. — Energy and resource saving: maintenance tool, active fluid control, micro factory, space applications (micro thruster, micro spaceship artificial satellite, devices for space experiments), etc. — Micro structures: mask for X-ray exposure, collimator for X-rays, shadow mask, electron and particle beam sources, electron and ion beam control, channel plate, micro tool, micro turbine, injection nozzle, etc. — Micro motor/actuator: electrostatic, electromagnetic, piezoelectric, etc. — Micro energy sources: micro fuel cell, micro engine generator, etc.

(According to Professor Esashi of Tohoku University) [6] the United States, and "MST" (Micro System Technology) has been used in Europe, whereas the term "Micromachine" has been used in Japan [7]. The definition of MEMS varies from person to person, and it is still under discussion how far MEMS technology covers the application fields.

It is said that the research on MEMS originated at the School of Electrical Engineering of Stanford University in around 1970. In those days, the results of research on pressure sensors and gas chromatographs, though not so miniature, made on silicon wafers were reported. The research and development of gas chromatographs was commissioned by NASA (National Aeronautics and Space Administration) with the intent of reducing the size in order to be mounted on spaceships. In the latter half of the 1980s, research into creating a new concept, "systems including micro movable parts," was carried out extensively at Berkley Campus of the University of California and Bell Laboratories by combining micromachines, microelectronic devices and sensors, making use of semiconductor technology that was rapidly being developed. The term MEMS was used as a general expression for these research activities. In 1992, a MEMS program was started with the support of DARPA (Defense Advanced Research Project Agency)[8]. The most successful example in the early stage of the program is the above-mentioned DMD™ developed by Texas Instruments (see Figure 1)[9]. Because the mirrors could reflect very strong light and made it possible to provide a large screen display using a small gadget that could not be realized with a liquid crystal display, small-size projectors using DMD devices monopolized the market for a while.

In Japan, micromachine technology represented by microminiature motors attracted attention from 1985, and the Agency of Industrial Science and Technology of the former Ministry of International Trade and Industry started a ten-year big project from fiscal 1991 under the Industrial Science and Technology Development Program. The four themes that have been announced as successful results of this project by the Micromachine Center are: prototype system for in-pipe self propelled environment recognition, prototype system for external inspection of a group of small tubes, prototype system for internal work inside equipment, and prototype system for a micro factory; each of which is a micromachine in the order of mm size [10]. Although none of the systems has been commercialized yet, elemental technologies of each system have continuously been developed in the industry.

8.3 Main points in the research and development of MEMS

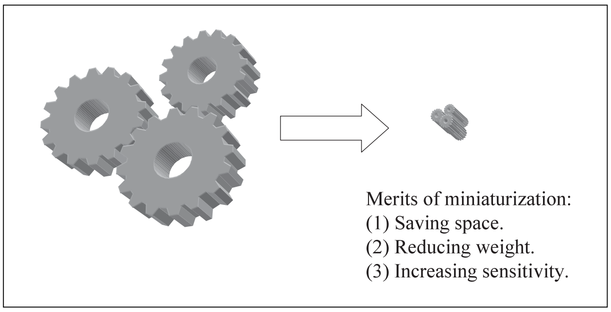
8.3.1 Characteristics of the research and development of MEMS

One of the characteristics of the research and development of MEMS is that the results of the research are very close to commercial products. Therefore, even when the research is carried out at an educational institution, not only the ability to solve a problem as pure science is essential but also the attitude when launching a venture business is required. The research and development of MEMS consists basically of three stages: conceptualization, design, and embodiment (prototyping). And the target of research and development cannot be achieved without passing through all of these stages. The outline of each stage is described below.

8.3.2 Conceptualization stage

Researchers must begin with the discussion "what type of system can be created by miniaturizing particular movable parts." The very beginning of the concept of micromachines was the question, "what can be created if machines of human size are reduced to the size of silicon chips?" or "what will happen if the machines we use daily are reduced to the size of insects?" At lectures on MEMS relating to biotechnology, the film "Fantastic Voyage," which was put on the screen in the latter half of the 1960s, is always introduced. It is also said that the ultimate target of a sensor is "to realize each function in the living organisms on the silicon chips." It is a very interesting concept to replace biological systems with equivalent circuits. Therefore, it is necessary for the researchers at the beginning of the research to discuss from not only the viewpoint of mechanical engineering and biology but also from the viewpoint of energy and social issues.

Figure 3: Subjects requiring miniaturization are good target in the MEMS research



Consequently, in the research of MEMS, subjects requiring miniaturization are good targets (see Figure 3). Three significant merits of miniaturization are:

1. Saving space.
2. Reducing weight.
3. Increasing sensitivity.

Miniaturization enables the installation or movability of electromechanical systems in a limited space such as in a narrow mechanical space or living organisms. As a result, the following effects are expected [4]:

1. Electrical, optical, and heat energy can be converted to mechanical displacement or high-speed motion.
2. Low electric power consumption can be targeted.
3. Multiple functions can be integrated.
4. Very small amounts of material resources are required.

Although the mechanical strength of silicon single crystal is rarely discussed in the processing of semiconductor devices, it possesses excellent mechanical properties. The micromachines can utilize such properties of silicon single crystal, which cannot be realized with bulk silicon.

Key points for the new system conception are where these advantages are made a good use of and how much flexible idea is taken up (see Figure 4). As can be understood by observing the diversity of living organisms, problems can be solved in multiple ways.

In some cases, it is more significant to integrate technologies of different fields, that is, to integrate mechanical parts, electric circuits, and chemical reaction parts on one chip, than to miniaturize a single function. In such a case of integration, it is of no use to make one function much superior to the other functions, not to mention that the worst part determines the overall performance. This is a very important point when trying to increase the speed and sensitivity of the total system.

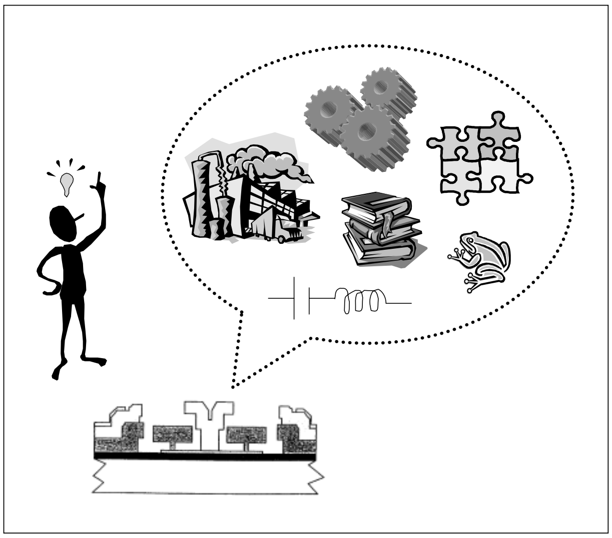
8.3.3 Design stage

After the concept of research is fixed, the total design technology is required for the next stage. Designing capability and simulation technology are required including the mechanical calculation, electric circuit design, and the designing of the silicon fabrication process. Recently, design tools for MEMS have become available even in Japan [11]. And there is also a system that assists in the designing as an activity of scientific society [12]. However, it is true that comprehensive design capability of researchers is attained only through their experience.

For the mechanical calculation in smaller world by four to seven orders of magnitude than the size of human beings, the following requirements must be carefully considered. If these requirements are fully satisfied in the designing stage, noticeable effects will be obtained. [4]

1. Large electrostatic force: in a micro system in which the ratio of surface area to weight is relatively large, the form of the accumulation of usable energy is different. For example, electrostatic motors have an advantage for

Figure 4: Various systems are realized on silicon wafers using semiconductor fabrication technology.



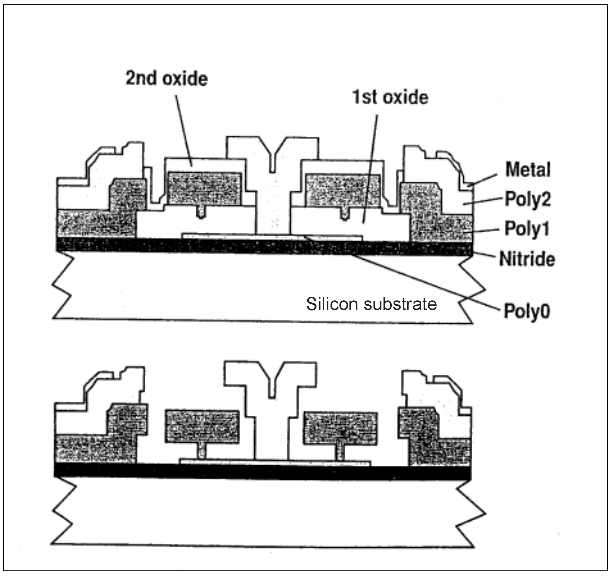
micro actuators from the viewpoint of accumulation capacity, whereas electromagnetic motors are widely used in our daily environments.

2. Small thermal time constant: sensitivity to heat is quite high in micro systems. Therefore, it is possible to produce thermal stress and local thermal change at a high speed making use of this characteristic.
3. Intermolecular and interatomic interaction cannot be neglected: interatomic attraction force (van der Waals force) is more dominant than the gravitational acceleration by the earth.
4. High sensitivity: relatively small changes in physical and chemical properties, such as piezoelectricity, crystal phase change, and chemical reaction in solution, can be utilized by converting them into mechanical displacement.

Even in the design stage, there can be multiple solutions for a single target. For example, there are several types of ink jet printer heads that are typical MEMS parts. All of them inject ink particles of 10 to 30 μm with an energy between 0.5 to 10 mW at intervals of several microseconds and at a high speed of between 5 and 20 m/sec. The dot size is less than $0.2mm^2$. However, several principles of operation are applied including electrostatically driven heads utilizing electrostatic force, bubble jet heads utilizing thermal response, and piezoelectric heads utilizing piezoelectricity. All of which provide high-resolution images [1-4].

Although most of the MEMS products rely on processing technologies that have been developed in the semiconductor manufacturing industry, the technology for MEMS differs from that of semiconductors in that the former requires three-dimensional shapes. In semiconductor integrated circuit technology, patterns are formed on thin films by lithography (a processing technology based on a photo printing method) and these patterns are stacked layer by layer, in which a three-dimensional arrangement is performed, so to speak, by repeating two-dimensional processing. In MEMS technology, on the other hand, patterning with high aspect ratios (height-to-width ratio) is applied providing three-dimensional, movable parts. To realize this, it is necessary to reconsider the technologies that have been neglected in the development of the miniaturization technology for integrated circuits, such as thick film formation and isotropic chemical etching (see Figure 5). It is also necessary to develop equipment again for these processes. In addition, different materials and processes than those used in integrated circuit technology, in which impurities must be strictly avoided, may be used. For example, organic materials may be laminated or mechanisms for flowing chemicals may be provided on the surface of silicon chips. Although there is a move to assign old-generation semiconductor plants for the research and development of MEMS, it must be remembered that success cannot be expected without some new investment and a flexible attitude for the development.

Figure 5: Three-dimensional formation using thick film technology and deep etching technology [2]



8.3.4 Embodiment (trial manufacturing) stage

The trial manufacturing stage follows the design stage. In MEMS technology, successful prototype products are very likely to be developed directly into commercial products, and many trial manufacturing fabs can be converted into commercial production fabs as they are. Therefore, research and development of MEMS is an appropriate theme for cooperative work between industry and academia. Generally speaking, research and development relating to hardware requires more initial investment compared with that of software. The mass production requires still more investment. So it has been difficult to start a venture business in hardware. In the research and development of MEMS, however, it is very possible to connect the results of trial manufacturing directly to the startup of business. In Europe and the United States, most of the research works at this stage are often carried out by outsourcing; also in Japan, it seems to be effective for research organizations that do not have their own trial manufacturing fabs to utilize the facilities of universities provided with ample equipment for common use or private foundries (contracted manufacturing).

8.4 Promising fields for MEMS in the future

8.4.1 Sensors and optical MEMS

Japan has been considered to be in the leading position in the world in the research and development of micro sensors. Japan's advantage over foreign countries in this field could be maintained by effectively promoting cooperation within and between private companies [13]. MEMS in the optical industry is specifically called Micro Optical Electro-Mechanical System (MOEMS). The development of switches for optical communication are attracting attention, in addition to the elements for conventional optical sensors and displays. The research and development works in this field will be extensively carried out mainly in private companies.

Except in these fields, however, it is very difficult at present even to realize trial manufacturing for other applications as described below.

8.4.2 Medical and biological MEMS

In the field of medical and biological MEMS, the size of the market for individual products is rather small. The difficult silicon processing technology is not necessarily required. For this reason, it seems to be possible even in Japan, where the development structures for MEMS are not yet established, to realize small scale production within a short period of time by making use of the small-scale facilities of universities and other public institutions. Therefore, venture businesses are most likely to start in this field. While it is a usual practice in the United States that facilities of universities are used for the research work of private companies, this is not usual in Japan. The reason is because, in many cases, cooperation between universities and private companies has been made by commissioning research to universities through the donation of funds, with the mass production developments done by private companies. In other countries, "Spin-in" is the term used when private companies use the facilities of universities and public institutions. In the medical and biological field, utilization of "Spin-in" including with the production stage seems to be effective because production tends to be in small-lots of a wide variety.

8.4.3 RF MEMS

In the field of RF MEMS (High Frequency MEMS for communication devices), on the other hand, the keyword is "Integration" and the accumulated technologies of semiconductor production can be utilized most effectively (see Figure 6).

Presently, it is said that the domestic semiconductor industry has entered a structural recession. And everyone is changing the lean-to-memories strategy to the production of so-called "System LSIs" in which even passive elements such as capacitors and resistors are integrated into chips. By integrating everything into one chip, the wiring length is reduced and improvement in the Q value, a factor indicating speed-up, is expected. This concept of integration is called SoC (System on Chip). Because even movable parts such as resonator and power supply circuits will be integrated into one chip or one package [14], this may be considered as the stage that follows SoC [3]. It may not be commercially profitable to integrate

Figure 6: MEMS chips arranged on a silicon wafer [1]

movable parts into one chip due to the complexity of processing, increased number of processes, process contamination (contamination by impurities), etc. Therefore, it may be effective at the initial stage to add MEMS parts to other SoC chips or to package multiple parts in one package. In such a case, the products are called SiP (System in Package) rather than SoC.

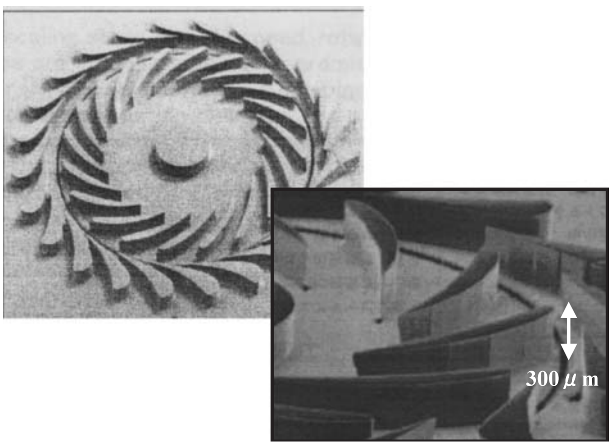
Although RF MEMS is not yet in the stage of practical applications, foundries in Taiwan are paying close attention to the advances because the market is expected to be very large. If large scale of manufacturing of RF MEMS would be realized, some of the discrete parts would become obsolete and bring about a serious crisis in the parts supply industry, which has been the specialty of Japan. Therefore, the Japanese semiconductor industry, which is aiming at the field of system LSI, must take action immediately including patenting activities in the field of RF MEMS, which is an extension of system LSI. Otherwise, Japan's international competitiveness would be lost in this market.

8.4.4 Power MEMS

Research on micro power sources is also a matter of international concern. Workshop "Power MEMS 2002" was held at the Tsukuba International Conference Hall on November 12 to 13, 2002, where prominent researchers in this field gathered. Among the topics of the conference were: miniature combustion electricity generator; micro fuel cell; miniature fuel reformer; and thermoelectric transducer [15].

A miniature combustion electricity generator (see Figure 7) was developed at the Massachusetts Institute of Technology [16], which is a gas turbine produced by deep etching (Reactive Ion Etching) of silicon to form turbine blades of the order of μm, and the blades are rotated at a speed of a million revolutions per minute or higher to generate electric power.

Figure 7: Micro turbine [16]



The micro fuel cell is a miniature fuel cell that is further downsized from the one that is being developed for portable devices at present. It is considered as a possible replacement for lithium cells, whose efficiency is as low as several percent. Great expectation is applied to the microminiature cells produced by MEMS technology, which have a longer life than conventional cells, because they will enable the continuously connection of cellular phones to the Internet. There is also an attempt to realize MEMS engines that use gasoline stored in a cartridge [17]. Such engines will replace the cells for portable tools such as drills and saws, because present cells cannot supply enough power. For these applications that require high heat resistance, silicon carbide (SiC) would be used instead of silicon, or SiC would be coated on the surface. For portable device applications, there is a new concept that fuel is supplied by changing cartridges that are sold at convenience stores.

Although developing the field of power MEMS is a target that is difficult to complete, it is one of the most promising fields due to its expected market size and impact on society.

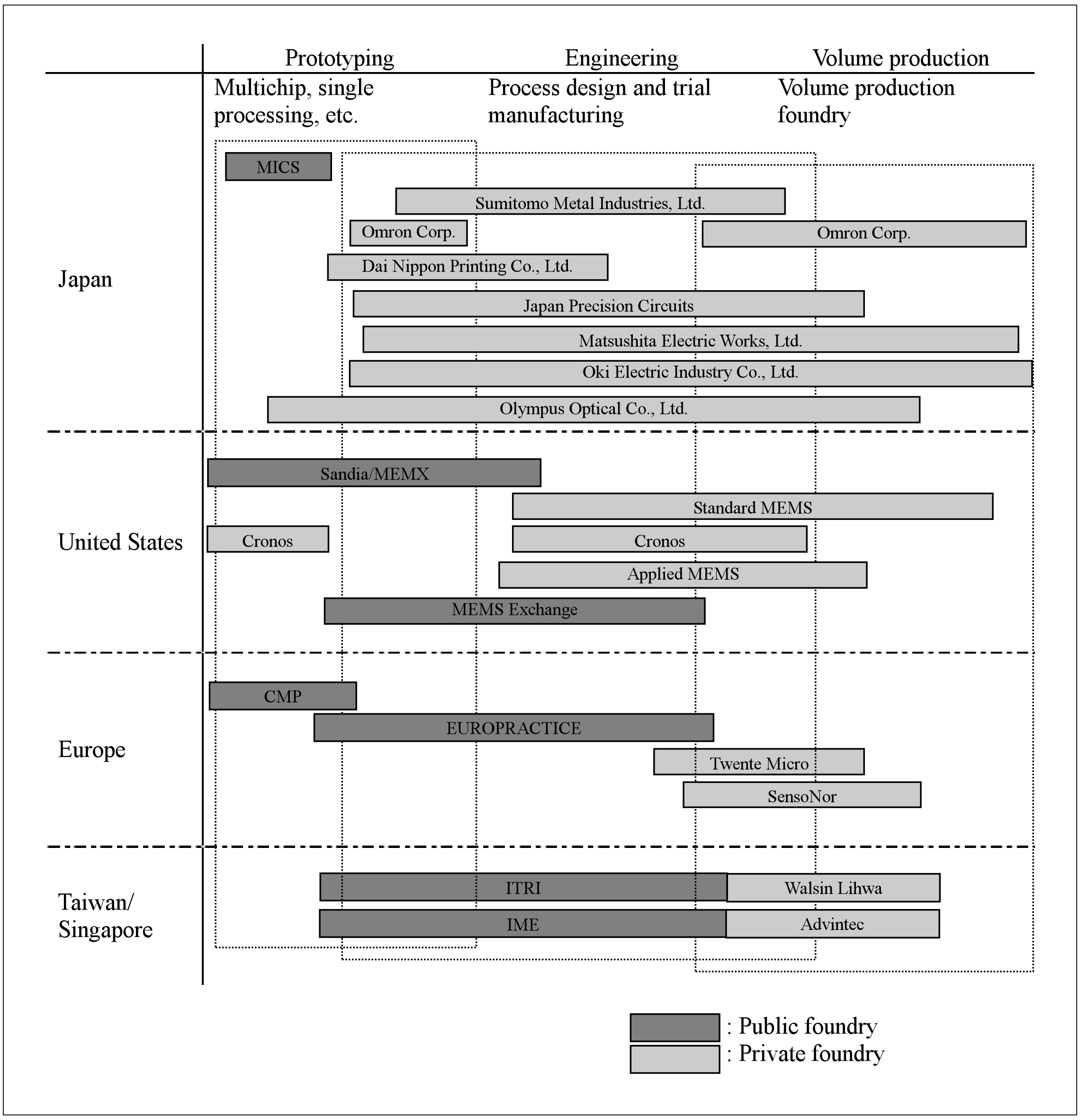
8.5 Development status of MEMS in foreign countries

8.5.1 Development status of MEMS in the United States [8,18]

In the United States, MEMS projects sponsored by DARPA (Defense Advanced Research Project Agency) were started as national projects in 1992. The outline and policy of the project leaders were announced to the public through their website. And a system has been established so that public institutions and private companies can utilize the research results.

Cronos (now JDS Uniphase), a private foundry that became independent of a nonprofit organization, undertakes trial manufacturing of MEMS, and it is now possible to place an order from overseas. They reportedly supply 15 chips in

Figure 8: MEMS foundries in the world



(According to Micromachine Center) [18]

about 11 weeks at a cost of about ¥600,000. In 1998, MEMS Exchange, a network system that connects many MEMS research bases in the United States, was established in order to contribute to the promotion of MEMS development (see Figure 8). This system is a kind of virtual fabrication on the network, and, at present, it can be used only within the United States.

In the ATP (Advanced Technology Project) sponsored by NIST (National Institute of Standards and Technology) of the Department of Commerce, which reflects more national industrial policies, research and development of sensors and displays using MEMS are also promoted.

In the United States, cooperation between universities and outside organizations is actively done, and trial manufacturing by "Spin-in" described in Section 8.4.2 is a common practice. Facilities of universities are provided not only with national funds but also with donations from private companies. It is a characteristic of the research activities at universities in the United States that mass production is taken into account in trial manufacturing, and wafers of practical size up to six inches are used even in the research facilities of some universities.

8.5.2 Development status of MEMS in Europe [18,19]

Europe started MEMS programs behind the United States. Although the scale is smaller, they have established networks corresponding to the size of Europe and open foundry systems taking after the United States (see Figure 8). The system formation was not spontaneous but purposefully carried out with French LETI (Electronics and Information Technology Laboratory), etc., at the center, so that each country of the EU functions as a member of the network. A representative MEMS network is NEXUS, and the foundry exclusive for MEMS is EUROPRACTICE; anyone can use these facilities for trial manufacturing. In EUROPRACTICE, users bear only one-third of the prototyping cost, with one-third being subsidized by local governments and the remaining one-third subsidized by the EU. They accept orders from all over the world, and some Japanese universities are using the European foundries.

8.5.3 Development status of MEMS in Asia [18,20]

As in the cases of other fields, exchanges of engineers between Western countries and Asia are growing, contributing to the rise in the technical level of Asian countries. Particularly in Taiwan and Singapore, the governments are placing great emphasis on this technology and the roles of the public sector and the private sector are clearly played. Public institutions take charge up to trial manufacturing and private foundries take charge of mass production. In Taiwan, common laboratories are provided in ITRI (Industrial Technology Research Institute of Taiwan), and private foundries such as Walsin Lihwa Corp. are implementating small-lot production of a wide variety of products after taking over the results achieved at ITRI (see Figure 8). Since MEMS manufacturing processes are difficult to standardize, it is unlikely that MEMS foundries will grow as fast as the semiconductor foundries did in the past. However, this field is being seriously considered as a remedy to avoid the hollowing-out in Taiwan, because their semiconductor foundries may be jeopardized by the uprising of China. The product field that is drawing the most attention is RF MEMS described in Section 8.4.3.

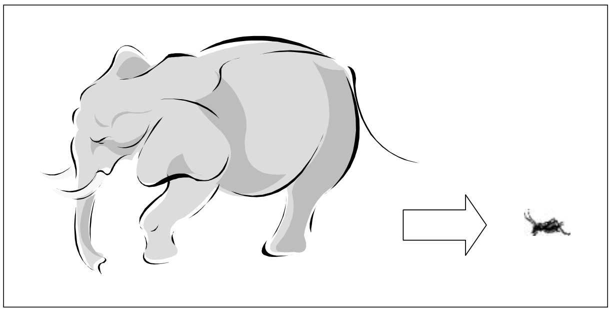
8.6 Progress from MEMS to NEMS

Many phenomena in nature are based on reactions at the nano-level, and the science intended to understand these phenomena is being rapidly developed. In the research on MEMS as well, there is a trend to mechanically or electrically reproduce such phenomena, and processing technologies at the nano-level are being investigated. Such research activities have been called NEMS (Nano Electro-Mechanical Systems) since around 2000 [21]. For example, miniature tubes provided on chips are considered to be a highly efficient reactor, because chemical reactions become more efficient with increasing surface area. The concept that intends to automatically reproduce on a chip chemical experiments that are normally carried out in chemical laboratories is called “Lab. on a Chip (Laboratory on a chip).” The pioneer in this field was the trial manufacturing of gas chromatograph in 1975 as described in Section 8.2.2.

From the viewpoint of human size, it seems that MEMS and NEMS have no great difference, but, as a matter of fact, there is a great difference comparable to that between an elephant and an insect (see Figure 9). The miniaturization from μm to nm by three orders of magnitude means that the characteristics described in Section 8.3.3 are further enhanced. Higher resonance frequency, higher mechanical response speed, lower power consumption, lower noise, and higher thermal response are expected. While many improvements are expected, it must be taken into account that the effect of surface conditions becomes greater and static electricity has stronger effects. This means that changes effected by environmental conditions cannot be neglected.

The processing accuracy required for NEMS is much severer than that required for MEMS. In the present lithography technology, it is not easy to form a line of 100 μm with a dimension error of ±1 μm; it is even less possible to obtain a dimension error of ±1 nm for 100 nm. The level of

Figure 9: There is a great difference between micro and nano, comparable to that between an elephant and an insect.



processing accuracy for NEMS is comparable to that for MEMS several decades ago [22]. Furthermore, even quantum fluctuations cannot be neglected for a line width of 10 nm or less.

For these reasons, it is not conceivable that all the research activities on MEMS should shift to NEMS. The progress in miniaturization from micro to nano is only one direction of the diversified MEMS research activities. MEMS technology essentially grows by diversification, and, in this sense, it is different from semiconductor device technology whose supreme target is miniaturization, even though the same silicon processing technology is involved. The evolution of organisms was a history of the fearless struggle for diversification, and it must be remembered that in the history of organisms any attempt to unify the form to the one considered to be the best solution at the time resulted in failure. The latest semiconductor processing technology is not always required for medical devices such as minimally invasive operation (a treatment that does not cut the body very much, such as the one in a blood vessel), biological devices such as DNA chips, and chemical devices such as micro reactors; more often than not, low costs are more important than miniaturization. For example, it has been shown that holes of about 100μm for micro reactors could be processed without using silicon processing technology [23]. Therefore, the ability to optimize the design process is required, including judgment as to whether the use of silicon processing technology is necessary.

8.7 For the promotion of research on MEMS in Japan

8.7.1 Reflection on the peculiarity of the development of MEMS in Japan

Generally speaking, it is unlikely that the quality or progress of research is affected by what the technology is called. But in the particular case of MEMS in Japan, it seems that the appellation gave a significant effect on the course of research. Even now, MEMS is often regarded as “micromachine” in Japan. As is understood from this fact, research on MEMS in Japan has been made mainly on miniature machines typically represented by micro robots. On the other hand, according to a report on the investigation of nanotechnology in the United States [24], micromachine (miniature machine) and MEMS are classified into separate fields that pursue different targets. It says that, while Japan is ahead of the United States in micromachine technology, it is far behind in MEMS technology. We must admit that such situation in the development of MEMS over the past 15 years has been caused by the difference in understanding — whether MEMS is considered as “miniature machine” or as “miniature system.” In Japan, micromachine technology has progressed along with the development of robot technology in which Japan is advanced. Although Japan has made great progress in this field, commercial products are still on the way to being developed. In the past in Japan, microsensors were considered to belong to another technical field or as components used for micromachines, and they have been developed mainly by private companies as products for the parts supply business. Ironically, sensor technology has grown into one of the specialties of Japan. From now on, micromachines should be regarded as components for MEMS from a more comprehensive viewpoint.

8.7.2 Development of human resources for system engineering

As described in Section 8.3.3, capable human resources who have the ability to design a whole system are required for the research on MEMS, but it seems that Japan has a shortage of such qualified personnel. Furthermore, it has been neglected in technical education to train students in discussing what to make in the manner as described in Section 8.3.2. It has been pointed out that Japanese industries excel at “how to make” but are weak in “what to make” [13]. If one starts with “how,” one cannot foster the capability to design the whole system. One of the important roles of Japanese universities and colleges in the future is to nurture the engineers of “system engineering” in its true sense.

8.7.3 Outsourcing of prototypes

MEMS products are essentially manufactured by large variety, small volume production [6]. Therefore, the mass-production-oriented concept that costs are reduced through volume production even if prototypes are expensive must be discarded, and commercialization factors must be considered from the prototyping stage. However, it is very difficult for organizations, even existing private companies, to complete the cycle from research and development through production to marketing using their own facilities.

The Venture Business Laboratory of Tohoku University and the Microsystem Technical Center of Ritsumeikan University are examples of common use facilities owned by universities in Japan. Also, there are more than 10 private foundries that accept orders for research and small-scale prototyping [25]. At present, however, most of the foundries cannot complete the desired prototyping using a single process fab, and sometimes it is impossible to complete the prototyping through multiple process fabs due to the difference in the size of silicon wafers. These problems must be solved in the future by appropriate means such as establishing networks. So, now is the time to discuss how to effectively utilize common facilities rather than constructing new clean rooms for MEMS.

In the past, Japanese universities were unwilling to carry out “fab-less” research, that is, without having their own facilities to make the prototypes. However, it is unrealistic for universities to have on their own all the silicon processing facilities required for providing prototypes. It is not always economical even for private companies. If the research on MEMS is understood as the “creation of a new system,” it is more efficient for studying “system engineering,” from the viewpoint of time and economy, to eliminate the intermediate prototyping stage. For education in MEMS, more time should be spent on the verification and analysis of finished products. To operate trial manufacturing fabs that require diversity, the researchers must prepare a considerable amount of expense and labor as well as a certain number of exclusive operators to keep them. It is necessary to avoid increasing the number of inefficient facilities neglecting these disadvantages.

In March 2002, the Mechanical Social Systems Foundation published a report compiled by the Micromachine Center called the “Report on the Investigation of the Foundry Network System Concept for Micro/Nanotechnologies, Fiscal Year 2001” [18]. This report points out that there is a mismatch between the expected initial market size of MEMS and enormous investment required for the processing facilities. It also advises that in order to clear entry barriers, network systems (FNS) should be established so that assets and technologies, which are now being developed randomly and separately, are integrated for the best efficiency. In the concept of FNS, research activities at universities and public institutions and developments by private companies are integrated into one system. When establishing a network, it is important to make its size appropriate to the market size and funding ability, and European systems should be considered as models to follow.

8.7.4 Promotion of the venture aspect of MEMS research

Regarding MEMS research activities, it is worth noting that the orientation of research at universities and that of the industry are in the same direction, showing little discrepancy between the two. This means that MEMS research is an appropriate theme for the cooperative work between industry and academia. It also should be noted that MEMS is suitable for commercialization by small-size companies and venture businesses.

Particularly, medical- and biology-related technologies represent fields where venture businesses are created most, with about 1,300 companies in the United States and more than 200 companies in Japan having been established up to now [26]. Included among these venture businesses are companies created by MEMS technology. For example, Protein Wave was established in 2000 based on μ-TAS (μ-Total Analysis), a technology for the crystallization of protein indispensable in the research of genome (gene information) [27]. They plan to commercialize silicon chips provided with grooves or dents, in which protein solutions to be crystallized are poured. They also intend to develop new medicines by themselves. A road to fund procurement has been opened in this field. For example, a venture development association has established [28] and a business plan competitions have been held [29].

8.7.5 Services available in Japan

If funds are sufficient, there is no restriction for using universities and private foundries for the research on MEMS. As a matter of fact, however, universities without facilities and researchers who intend to create venture businesses are suffering from financial barriers. For these people, one solution may be to utilize the facilities of other universities and public institutions.

The following are examples of services available to anyone. As for universities, the two mentioned in Section 8.7.3 have the most experience. The Institute of Electrical Engineers of Japan offers a service called MICS (Micromachine Integrated Chip Service), which provides micromachine integrated chips [12]. In this service, multiple prototypes are shared on one mask in order to save the costs of trial manufacturing. But it must be said that the available technologies are limited. The Ministry of Education, Culture, Sports, Science and Technology (MEXT) has established a technical support system called the Nanotechnology Support Project, and designated 14 organizations that anyone can use at no charge. In this project, MEMS prototyping technology is included [30]. Other than universities, efforts by public institutions for shared research are not yet active [18], however, one example of services provided by local governments is the Technical Support Center for Micro Device Development of the Technology Research Institute of Osaka Prefecture [31].

Some universities and private companies already have experience in ordering prototypes of MEMS from foundries in Europe and Taiwan, and international cooperation has started in order to cover the lack of domestic prototyping facilities. However, if Japan loses the capability to develop MEMS by itself, the hollowing-out of industry would accelerate because the MEMS industry also requires an integrated system from development to manufacturing.

8.8 Conclusion

The research and development of MEMS is an activity that creates new systems by integrating microelectronics, nanoscience and other technologies into micromachine and sensor technologies that have been the specialty of Japan. It requires system engineering education that discusses “what” to make rather than “how” to do, and it is very important to foster human resources to handle the overall design including all of conceptualization, design, and prototyping. Also, for Japanese universities and private foundries for MEMS, which are now being arranged to function effectively for the vitalization of industry including venture businesses, it is necessary to make organic systematization taking after Europe.

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