1st JOINT SEMINAR POLAND - JAPAN
PROGRAMME

Opening

Dr J. K. Frąckowiak from Secretary of the State Committee for Scientific Research (KBN)
Under-secretary of State
Prof. T. Hirano from the Micromachine Center

09.30 Welcome Address

Prof. A. Jeleński from the Institute of Electronic Materials Technology

Presentations by the Japanese Speakers

Chair: Prof. T. Hirano and Prof. A. Jeleński

T. Hirano (Micromachine Center) - *Future Prospects of Micromachines*
R. Ota (Olympus Optical Co., Ltd) - *Medical Applications of Micromachines*
T. Ataka (Corporate R&D, Seiko Instruments Inc.) - *The Microfactory in Japanese National R&D Project*

11.15 -11.30 Coffee break

K. Namura (Mitsubishi Electric Co.)- *Multiple Distributed Micromachine System*
N. Kawahara (Denso Corporation) - *In-pipe Wireless Inspection Micromachine*
H. Iwaoka (Yokogawa Electric Corporation) - *Micromachined Silicon Sensors*
Y. Hirata (Sumitomo Electric Industries, Ltd.) *Applications of Deep X-ray Lithography*

13.30 -14.00 Lunch

Presentations by the Speakers

Chair: Prof. T. Hirano and Prof. A. Jeleński

W. Torbicz, D. Pijanowska - (Institute of Biocybernetics and Biomedical Engineering Polish Academy of Science) - *Semiconductor biosensors for medical applications*
J. Dziuban - (University of Technology Wrocław Institute of Microsystems) - *Integrated Instruments for Total Chemical Analysis*
L. Dobrzański - (Institute of Electronic Materials Technology) - *Detectors of UV and infrared radiation obtained using silicon micromachining*

15.30 -15.45 Coffee break

T. Pisarkiewicz - (Department of Electronics, Cracov University of Mining and Metallurgy) - *Microsystems and Sensors in the Department of Electronics UMM*
J. Łysko - (Institute of Electron Technology) - *Modelling, simulation and design of micromechanical devices in ITE*
P. Grabiec - (Institute of Electron Technology) - *Silicon microengineering technology in ITE*

16.45 -17.30

General discussion and conclusions

WELCOME ADDRESS

On behalf of Polish organisers of the 1rst Joint Seminar Poland-Japan on Micromachining I would like to welcome our Japanese friends.

Prof. T. Hirano - the director of the Micromachine Centre and the head of the Japanese delegation and the initiator of this seminar.

Prof. M. Wada - a long time adviser for the minister of Economy in Poland and all members of the Japanese delegation and our guests from Japan.

I would like to welcome also our Polish guests:

- Dr M. Matczyński - vice president of the Technical Sciences Division of the Polish Academy of Sciences,
- Prof. W. Torbicz - president of the Polish Sensor Society,
- Prof. St. Nowak - from the Committee for Scientific Research and Univestity of Mining and Metallurgy, Kraków,
- Prof. K. Badźmirowski - director of the Institute of Industrial Electronics, who is hosting us in his Institute,
- Dr Z. Łuczyński - director of the Institute of Electronic Materials Technology,
- Dr P. Dumania - deputy director of the Institute of Electron Technology,
- Dr M. Daszkiewicz - director of the Institute of Applied Optics,
- Dr Cz. Kiliszek - director of the Institute of Vacuum Technology,

and all Polish participants of the Seminar.

But in particular I would like to welcome Minister Jerzy Frąckowiak - Secretary of State in the Committee for Scientific Research who was so kind to accept to open officially our seminar. The Committee for Scientific Research plays an essential role in financing all Scientific Research in Poland performed in Universities, Institutes of the Polish Academy of Science and other Institutes depending upon different Ministries.

The Committee is also coordinating Scientific Cooperation with other countries and Minister J. Frąckowiak personally is very active in establishing closer links between scientists from Poland and other countries. I would like to express my gratitude for cosponsoring this seminar.

The seminar is the first meeting between Japanese and Polish scientists in the rapidly developing area of micromachining, but not the first contact between our scientists. Our friend Prof. M. Wada can confirm that several Japanese delegations visited our laboratories and recognised that the areas of special common interest are optoelectronics, new materials and computer engineering. These contacts were not limited to visits of delegations from scientific and industrial communities. Let's take as an example our institute whose activity is concentrated in the area of optoelectronics, new materials for optoelectronics, electronics and microsystems. We spoke with Prof. S. Nakamura from Nishia Corporation, about cooperation in our works in the area of "blue electronics". Prof. M. Kopcewicz (from ITME) is participating in a NEDO Project in the area of new magnetic materials, one of our young scientists received a Japanese scholarship and we expect a strong Japanese participation in the Workshop on "New Materials for Electronics" which we are organising in autumn 2000.

We fully acknowledge the importance of the new area of micromachining, which we tend to call in Europe "microsystems" and many of us participate, in the European Network of Excellence Nexus in which I have the pleasure to coordinate the activities in Central and Eastern Europe. This new area of micromachining found in Poland its place in areas of research and teaching but has not yet reached the industry.

We hope that this seminar will give us the opportunity not only to be familiarised with your scientific achievements, which are among the best in the world, but also to learn how to implement these results into an industrial activity. Therefore, with a great interest we will listen to your presentations this morning and we will try to describe, what is done is this area in the leading institutions in Poland. We hope that after these presentations, a discussion about common interests and possibilities of cooperation will be a good starting point for some common research or industrial activities.

Prof. DSc. (E.Eng.) Andrzej Jeleński

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FUTURE PROSPECTS OF MICROMACHINES

T. Hirano[1]

Micromachine is expected to be a Japanese industrial base in the 21 st. century. The reason is it would create a new technological paradigm, which presents solutions to current human problems and, at the same time, presents fresh opportunities for a new human life and also new industries.

1. TECHNOLOGICAL TREND

1.1. The history

The most prominent technological impact on human life appeared in the Industrial Revolution which took place in England in the 18th century. During this period a string of inventions, e.g. James Watt's steam engine was born.

As many of the technological innovations during the Industrial Revolution were related to machine technology, such as power-generating machines, mechanization of processes, and the development of new processing methods, the industrial revolution is also known as the machine revolution.

After the Industrial Revolution and up to the early 20th century, the next generation of technological innovations occurred in the petroleum, automobile, electricity, chemical industries, etc., and this was followed in the mid-twentieth century by another group of technological innovations in the areas on nuclear energy, electronics and computers which have continued to the present day.

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[1] Micromachine, Center
http://www.iijnet.org.jp./MMC

Today, the information network has developed on a global scale and the information flows so fast and massively. And also information technology has been utilized widely to make industry more efficient and make daily lives more joyful. IT Revolution is a tag of this area.

1.2. The emerging trend

Present research trend in the most technologies, i.e. biotechnology, material technology, microelectronics looks like heading for the micro environment. In machine technology, gigantization had been dominant until quite recently. It is far behind other technology research in the micro environment.

The government initiated support for micromachine technology R&D in 1991. A main concern at that time was how to catch up with the micronization trend.

The initiative also reflected emerging needs to implement research on machine micronization. On the industrial front, power plant and manufacturing facilities have become so complex that the technologies which can be used in the confined spaces for maintenance have become indispensable. Another example is downsizing manufacturing facilities for small products to reduce energy consumption and manufacturing space.

In our daily lives, health care has become increasingly important in order to achieve quality of life *(QOL)*. Minimum-invasive diagnosis and surgery which minimize pain and reduce recovery time has become main issue. Smaller medical equipments could be useful.

On the precision machining front, machine technology has developed into mechatronics through integration with electronics over the past twenty years. Although there has not been any basic innovation on the machine technology side, the electronics side has progressed so fast toward micro-electronics. It may be the imbalance between these two technologies that underlies the move toward micromachine.

Furthermore, following developments in precision machining technology, it has now become possible to manufacture miniaturized components which we had never used before.

These changes on the fronts have contributed toward triggering "micronization" of machine and subsequently government R&D project.

The National Project is a driving force toward a technological paradigm of micromachine. It is in the last year of the ten year project and seeking technologies to build up micromachines as a system. So far R&D has been generating promises one after another.

2. CHARACTERISTICS OF MICROMACHINE TECHNOLOGY

The National Project is not sufficient to realize the paradigm. Besides it, a variety of efforts are essential because of micromachine characteristics. It is summarized in four points.

First, multidisciplinary aspect. The technologies required for the manufacturing of micromachine extend into various fields including mechanics, electronics, chemistry, biotechnology, material, and so on. It is a completely new and multidisciplinary set. Micromachine technology encompasses a variety of device technology, including MEMS and MST, of course.

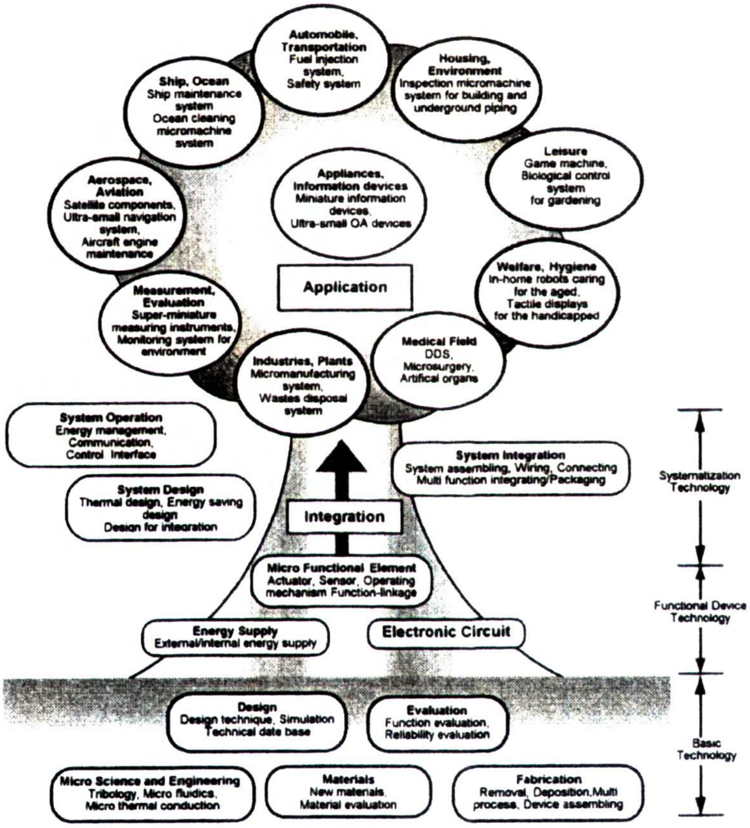


Fig.1. Techno-tree of micromachine.

Second, wide applications of micromachine are foreseen in future. Today, the machines in the macro environment are used in every area of human activity. In the same way, the use of micromachines has potential wide applications in industry, society and everyday life.

Third, there are various phenomena in the micro environment to be clarified in terms of science and engineering. These are totally different phenomena from the macro environment. For example, in the macro environment inertia force is great and friction and viscosity are not important. In the micro environment, friction and viscosity are relatively greater than inertia.

Fourth, micromachine technologies are at the very early stage. Present research is mainly centered on fundamental technologies common to various micromachine systems. Still, we can anticipate many new technological seeds.

3. PROMOTING APPROACH

Considering the unique characteristics, a best-suited promoting approach is required to effectively advance micromachine technologies toward a paradigm.

Most important is to generate new technologies. Japanese government has already initiated National R&D Project. Academic research into microscience and microengineering is also essential.

Next is how to integrate traditional different knowledge bases and manufacture a multidisciplinary micromachine as a system. This integration ranges from research to commercial products.

Third issue is related to application. The characteristic of micromachines is seeds-oriented. Applications are assumed to extend to every area of human activities, but the primary needs in micromachine technology arise from actual users necessity. Users will develop applications by looking at the technologies when they become available, so that dissemination of technological information is crucial. However, since human beings have not experienced such technologies in a confined space, it is also effective to actively seek for applications, through the development of ideas by mixing needs and seeds.

It will take considerable time to establish a new technological paradigm of micromachine. It is necessary to create a scheme through which the next generation will continue these technological advancement.

4. NATIONAL R&D PROJECT ON MICROMACHINE TECHNOLOGY

This project aims at establishing a technological paradigm of micromachine. This paradigm is multidisciplinary and in particular, R&D is focused mainly on mechanisms, an area which has not moved much towards micro scale.

The Project which began in 1991 is a ten year plan divided into two five year phases. The estimated cost is approximately 25 billion yen.

The project will be implemented by three research institutes - the Mechanical Engineering Laboratory, the National Research Laboratory of Metrology, and the Electrotechnical Laboratory - under the auspices of the Agency of Industrial Science and Technology, as well as 26 organizations and companies of Micromachines Center, commissioned by the New Energy Development Organization (*NEDO*) under the overall supervision of the Agency of Industrial Science and Technology.

The first five years was aimed at the search for elemental technologies. In order to do this, a micromachine system which might by used in the future was envisaged, and R&D was carried out by extracting the elemental technologies based on the concept of three systems: a maintenance system for power generating facilities, medical application system and a microfactory system.

After completion of the first phase and its interim assessment, the Project has entered the second phase in which systematization technologies to build micromachine itself as a system are main subjects. There are the variety of systematization technologies to be developed. So, the Project is proceeding to build four experimental micromachines solely for the development of those technologies.

First one is a wireless micromachine which is operated in the tube (Fig. 2). Main objectives of this research are how to supply energy, how to communicate with the machine because of "wireless". The experiment will be done with the size of 10 mm diameter.

Second is a chain-type micromachine which consists of numerous homogeneous module micromachines (Fig. 3). All modules shares energy and data through cooperative action. This moves in the free space. Main researches focus on these features of the micromachine. The size of an experimental module is 1 cm^3.

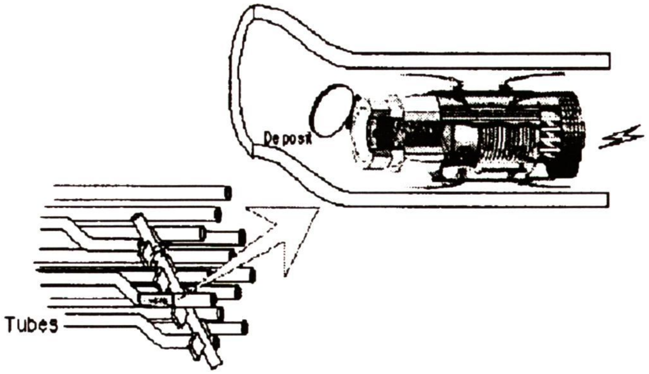


Fig. 2. Experimental wireless micromachine for inspection on inner surface of tubes.

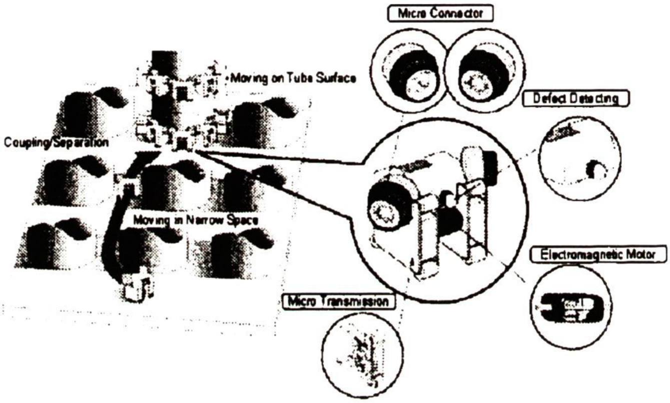


Fig. 3. Experimental chain-type micromachine for inspection on outer surface of tubes.

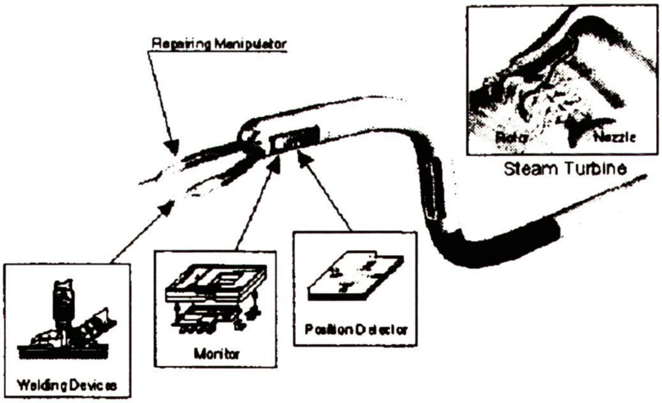


Fig. 4. Experimental catheter-type micromachine for repair in narrow complex areas.

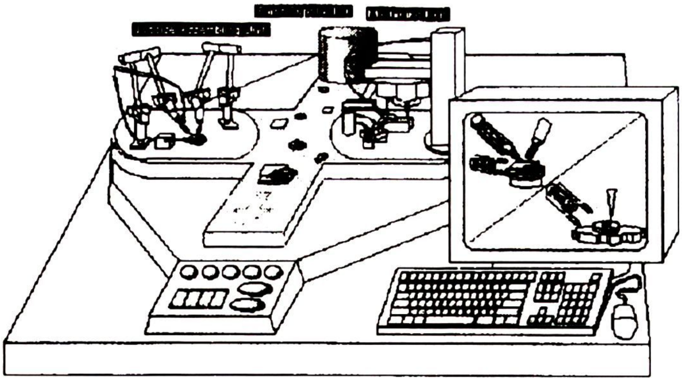


Fig. 5. Experimental micromachining and assembling system.

Third one is a catheter-type micromachine which is somewhat free of energy supply limitation (Fig. 4). The feature of this machine is work capability. In this experimental system, welding in the narrow space will be performed. The size is 8 mm diameter.

Fourth is "Microfactory" in which micromachining and assembling can be done (Fig. 5). This concept has never been defined ever before, so research and development was started with developing the concept. The size of experimental system will be desk - top and work space is 1 cm^3.

5. MMC ACTIVITIES

Besides the National Project, Micromachine Center (MMC) has been implementing various measures since it was established in 1992.

MMC activities are grouped into five pillars as follows:

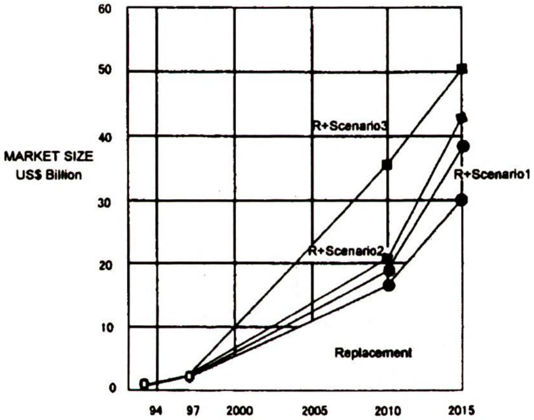
Research Investigation ---	National R&D Project, Future outlook (economical, industrial, technological), Grant
Information ---	Home page (http://www.iijnet.or.jp/MMCn, Publications
Exchange ---	Symposium, Exhibition, Overseas seminar
Standardization ---	Publication of Technical Report on Terminology and Measurement method, International Forum
Promotion ---	Children's drawing contest, Educational video

6. FUTURE PROSPECT

MMC, through its activities, found five crucial points to overcome for successful micromachine future.

6.1 Commercialization

Currently technological initiatives are full-fledged and experimental micromachine systems will be demonstrated in the year 2000 as the results of the National Project. Still, it takes considerable time for new industries to emerge. However, even before that, the elemental technologies might be utilized in the current commercial products. MMC's study (Fig. 6) suggests that the current market scale for micromachine in Japan would be approximately 419 billion yen, 3.5 billion US dollars. And it is estimated this will reach about 6,040 billion yen, 50.3 billion US dollars in the year 2015. And the market which competes with current products could grow 2,092 billion yen in the year 2010, by five times.



(US$ Billion)

Market		1997	2010	2015
Replacement(R)		3.50	17.44	30.17
New Market	Scenario 1	0.00	1.61	7.87
	Scenario 2	0.00	3.83	12.30
	Scenario 3	0.00	18.15	20.17
Total	Scenario 1	3.50	19.05	38.03
	Scenario 2	3.50	21.27	42.47
	Scenario 3	3.50	35.59	50.34

Fig. 6. Japanese future market of micromachine.

6.2 Needs realization

MMC is studying the future application of micromachine as a system, but does not have many definite applications. As the history of the technological progress suggests, new technology changed a way of life and also a sense of value. The new generation will emerge with new values toward technologies and a way of life, so that they would develop applications as seen in the children's drawings (Fig. 7).

"EXPERIENCING BALL'S EYE" MICROMACHINE

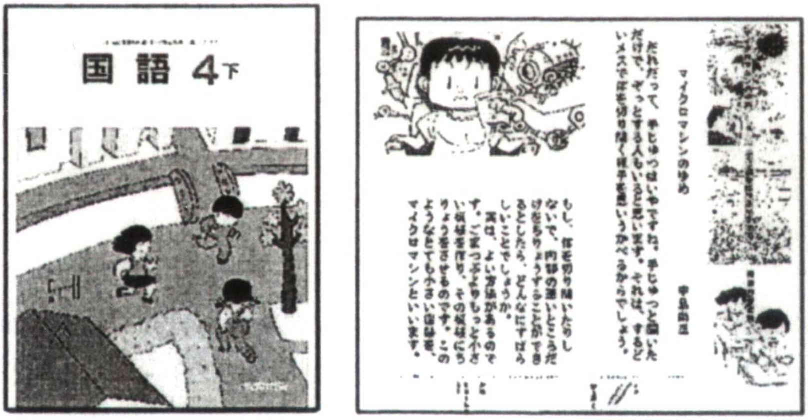
MACHINE TO RESTORE ART OBJECTS

ECO - MONITOR "GE - NOMI"

Fig. 7. Children's drawings.

6.3 Continuation

In Japan, children have some good opportunities to learn micromachine. In a school textbook (Fig. 8), micromachine is picked-up in teaching a logical thought and development of an idea. Approximately a quarter of million school children at the fourth grade of elementary school are involved every year.



マイクロマシンのゆめ　中島尚正

だれだって、手じゅつはいやですね。手じゅつと聞いただけで、ぞっとする人もいると思います。それは、するどいメスで体を切り開く様子を思いうかべるからでしょう。

もし、体を切り開いたりしないで、内部の悪いところだけをちりょうすることができるとしたら、どんなにすばらしいことでしょうか。

実は、よい方法があるのです。ごまつぶよりもっと小さい機械を作り、その機械にちりょうをさせるものです。このようなとても小さい機械を、マイクロマシンといいます。

"Japanese Language"　"Dream in Micromachine"

Fig. 8. Micromachine in a textbook.

More aggressive measure is children's drawing contest in MMC. Over four thousand pictures have been collected in the past four years. The pictures contain fresh ideas of micromachine applications.

6.4 Worldwide awareness

A research society tends to be deaf to the outside. It might not be the case in the Micromachine. The Micromachine Summit (Fig. 9) has been expanded to 15 member countries/regions. Foreign media are interested and made reports. (Fig. 10). Research on micromachine has been spreading around the world. A coming question is whether it is necessary to put together these efforts into a single structure for close exchange. The Micromachine Summit may be a start point to it.

Fig. 9. Micromachine summit.
Mar. 13-15, 1995.

Fig.10. TIME Dec. 2, 1996.

6.5 Next technological tasks

The current National R&D project aims at development of common, fundamental technologies necessary to build micromachine system. The technologies have been emphasized more on mechanism and electronics.

In the next phase of development, more multidisciplinary approach will be taken with chemistry, biotechnology, material science, etc.

Furthermore, the wide dissemination of micromachine technology needs scientific and technological knowledge base in the micro environment.

7. CONCLUSION

Micromachine Technology would be applied widely in future human activities and enhance the quality of life (*QOL*). It has been under development since a decade ago. It already produced new devices. But it is still a long way to reach completion of Micromachine Technology Paradigm.

International cooperation in research and development and competition in the market may contribute to further progress of Micromachine Technology.

MEDICAL APPLICATIONS OF MICROMACHINES

Ryo Ota[1]

In the medical field, there are great needs for sophisticated and less-invasive procedures. If we can realize the inspection and treatment devices much smaller by the micromachine technology, it would produce significant benefits for society as a whole in the form of saved lives, shorter hospital stays, and the prevention of complication. We are committed to the development of micromachine technologies to meet these requirements. As an example, we are developing the elemental technology for realizing a diagnostic and therapeutic microcatheter for cerebral blood vessel. We will present micro-tactile sensors for transmitting tactile information from the inner wall of the tubing or body cavity to the catheter to ensure safe and positive guidance. And we will also present the other technologies which constitute the microcatheter.

1. INTRODUCTION

Recently medicine and its related technologies have developed from simple and barbaric treatment to early diagnosis and minimal invasive techniques for the quality of life after treatment, as follows:

1. As the diagnosis has become increasingly sophisticated, it is now possible to treat an affliction at an earlier stage, thereby reducing the primary effect and the need for rigorous therapy.

2. With the identification of morphological and functional aberrations inside the body, the need for treatment without trauma to surrounding healthy tissue has increased. Consequently minimal invasive surgery (*MIS*), also called *endoscopic surgery*, is gaining increased acceptance as a powerful technique beneficial to the patient's integrity, time of recovery and cost for assistance. And the

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[1] Olympus Optical Co., LTD, Research Department

precise delivery of very specific drugs in small volumes will serve as the minimal invasive technique.

3. Quality of life would be dramatically improved if the body functions affected by the treatment or diseased could be replaced. Artificial organs or some medical equipment is very useful for the improvement of the patient's quality of life.

Toward these trends of medical field, micromachine is an appreciable technology and has a number of advantages to offer:

1. Reduction of size to reduce traumas in use,
2. Functional integration for in-situ inspections and treatments,
3. Reduction of power consumption to improve heat generation, and to lengthen dwelling or usage time,

and so forth.

Concerning the importance of this new technology, Agency of Industrial Since and Technology (*MITI*) has been running a project entitled "Micromachine Technology". And we are developing the elemental technology for realizing a diagnostic and therapeutic microcatheter for cerebral blood vessel [1]. We chose for a development target "diagnostic and therapeutic microcatheter for cerebral blood vessel " for its wide range of application, novelty, and difficulty. Cerebrovascular diagnosis and treatment offer many opportunities for fatal complications. The microcatheter will possess high dexterity at the tip and all along its length, and also incorporate some of sensors and micro devices for diagnosis and treatment at the tip of catheter.

2. ACTIVE BENDING CATHETER & MICRO TACTILE SENSOR

Current system for steering of catheter or endoscope work with mechanical connections between surgical instrument and surgeons. They cannot touch the lesions and sense with their fingers for diagnosis purposes. They control the catheter with feeling the forces/torque and pressure when they are operating the catheter. If the catheter will become thinner and will be used in ductile spaces, it must be more difficult to control the catheter. Therefore, we have been developing the active bending catheter and microtactile sensor.

A conventional endoscope has the bending mechanism with tendon-wire. And it is utilized to manipulate the bending mechanism. In this case, however, the length of insertion tube is very long, or a shape of pass to which an endoscope is inserted is complicated, bending is not sufficiently formed because friction increases. We developed a catheter with built-in *SMA (Shape Memory Alloy)* at its distal to solve the above problem. (Fig. 1) [2] *SMA* wires are placed along with the axis, deviated from the central axis of the catheter. Three micro sensors (strain sensors) are mounted on the tip of the catheter, detecting a contact pressure of the vessel wall and forcing the catheter to bend so as to avoid its contact with vessel wall (Fig.2). The catheter has a channel inside of it to insert an ultra-thin fiberscope or a guide wire. By using this catheter, pancreas duct or bile duct can be accessible to an endoscope, and also observation or treatment can be performed with remote control. The outer diameter of the catheter is 1.5 mm, the inner diameter of the channel to which ultra-thin fiberscope can be inserted is 0.6 mm.

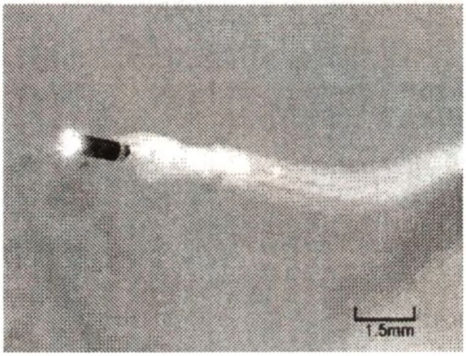

Fig.1. Active bending catheter.

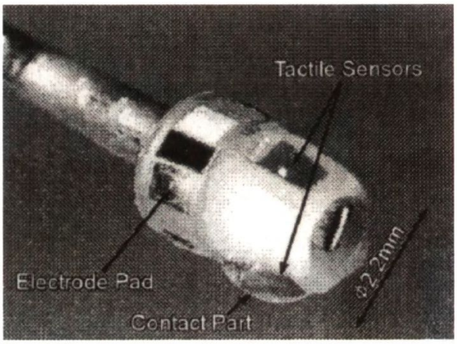

Fig.2. Micro tactile sensor.

3. MICRO TACTILE SENSOR USING PIEZOELECTRIC RESONATOR

Needless to say, palpation is important in diagnosis . Physicians, however, cannot directly touch a tissue to obtain a tactual sense with the endoscopic diagnosis. To measure the stiffness of biological tissue, we developed a micro tactile sensor probe that can be inserted to the channel of the endoscope.

We have studied a smaller size tactile sensor using piezoelectric resonator with energy trapped electrodes [3]. This sensor has a simple structure with a few elements and high Qm as shown in Fig. 3.

Live tissues are known to show viscoelastic property which is expressed as an electrical equivalent circuit consisting of an inductance and a resistance in series. When a viscoelastic object contacts onto the piezoelectric resonator of tactile sensor, the resonant frequency of the resonator changes due to the viscoelastic characteristics change. Therefore, the piezoelectric resonator having high Qm is required for the tactile sensor. Fig. 4 shows Colpitts circuit including the equivalent circuit of the piezoelectric resonator and a viscoelastic object. Fig. 5 shows the experimental results. The frequency change depends on the compliance of the test piece.

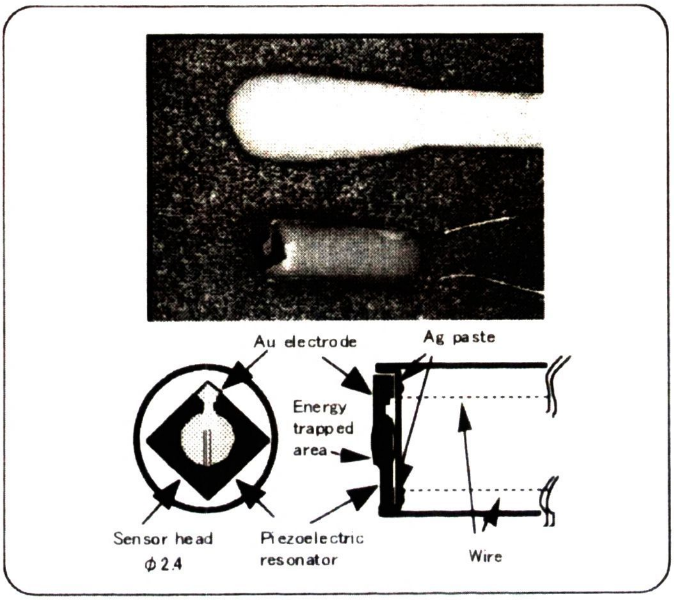

Fig.3. Photograph and structure of the micro tactile sensor.

In order to improve the tactile sensor probe system for the practical use,

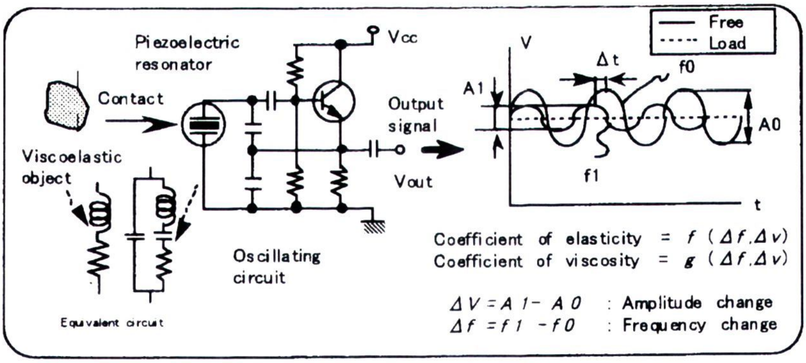

Fig.4. Schematic circuit and output signals.

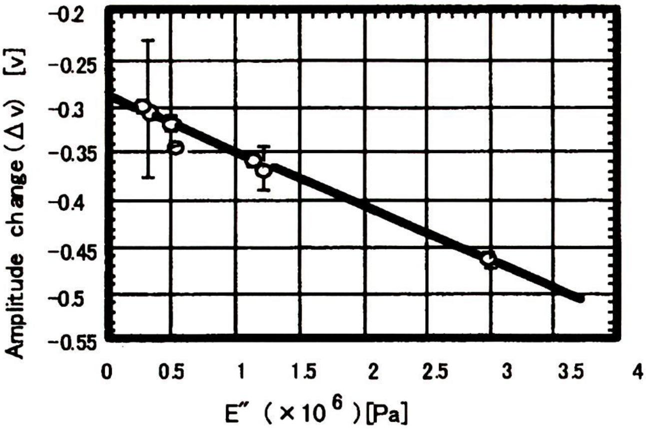

Fig.5. Relation between E" of elasticity- coefficient and Δv.

we have to optimize the structure of the sensor and the electric circuit.

4. CONCLUSION

We have presented some of micromachine technologies which constitute the microcatheter. In medical field, micromachine technologies is very attractive, and must be developed widely. However, the micromachine of today has some of drawbacks. For instance, it has low power output, difficulty of energy supply, and so forth.

Therefore, for the present, it is important for us to apply the micromachine technology to the field where we can avoid these drawbacks.

We also have to develop to realize mufti-functional devices (rather than from single-functional devices), smaller size device, and develop new technology which is peculiar to medicine, such as a disinfection resistant technology and bio-compatible material for catheter coating.

ACKNOWLEDGMENTS

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THE MICROFACTORY IN JAPANESE NATIONAL R&D PROJECT

Tatsuaki Ataka[1], Kazuyoshi Furuta[1]

We have been developing an experimental microfactory system in R&D project of Industrial Science and Technology Frontier (*ISTF*) of MITI. The aims of this project are to investigate technological possibility of "microfactory" and to make clear the problems to be solved in realizing it. The microfactory system consists of three units; processing, assembling and conveyance unit, in the same way as present manufacturing system. The system will be about the size of a desktop and can handle small parts several grams in weight. Two different ways to reduce the size of the system have been pursued and the system will be achieved in 2000.

1. INTRODUCTION

Up to the present days we have not paid great attention to the imbalance between the size of manufacturing system and that of products manufactured by it. The ratio of the size of manufacturing system to that of products remarkably becomes large as the products become small. For example, in watch manufacturing many of parts are of the size below 1 mm and are of the weight less than several milligrams. On the other hand, the length of the system line is about 40 m and the weight of a robot in the line is about 250 kg, as in Fig. 1 showing an automatic assembling system for watch wrapping. High speed, high accuracy, high reliability, and other features are required for manufacturing systems and these are considered one of the main origins that make systems large compared with the size of products manufactured.

Here comes another thinking way about a manufacturing system ; Are there other possible kinds of production styles to remarkably reduce the size of it? By a small manufacturing system with new kinds of production styles, we

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[1] Seiko Instruments Inc., Corporate R&D,
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will be able to realize various styles of manufacturing, such as front shop manufacturing, mobile manufacturing in a vehicle.

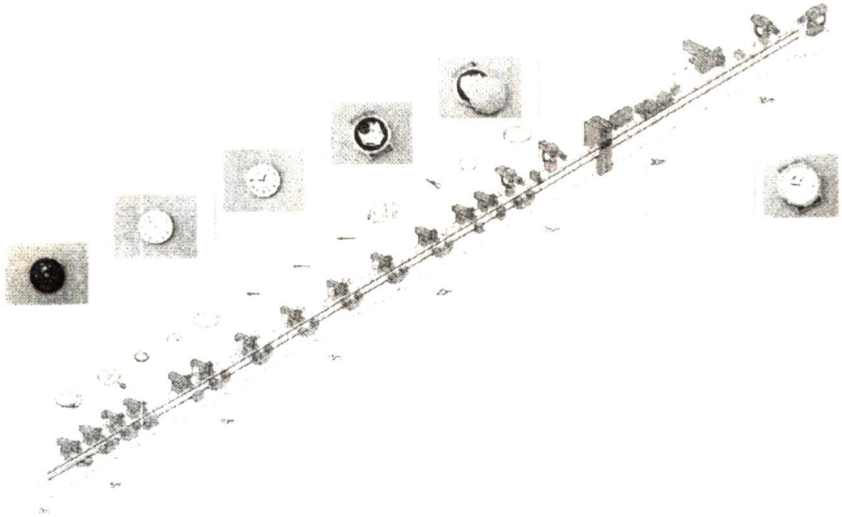

Fig.1. The automatic assembling system for wrapping of watches.

In this paper we describe the R&D situation of the experimental microfactory system in national project of *MITI*, the project about which started in 1994.

2. THE EXPERIMENTAL MICROFACTORY SYSTEM

Fig.2 shows the image of the experimental microfactory system consisting of three units; processing, assembling and conveyance unit. The specifications of the system are described in Table 1.

Consider manufacturing a gear train which includes gears sub-millimeter in diameter. Some of them are firstly made in the processing unit and are transported to the assembling unit by the conveyance devices to be assembled by micro-arms. Some other parts can be provided from the part-supply station to the unit.

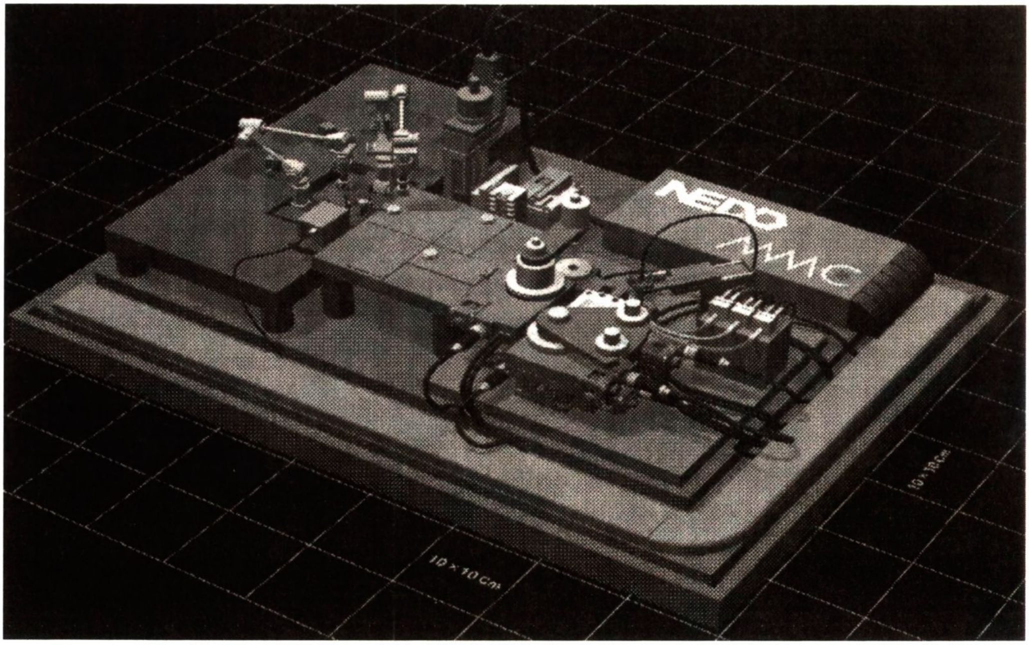

Fig.2. The image of the experimental microfactory system.

Table 1. The specification of the microfactory system.

Total size	:desktop, about 50x50x50 cm^3
Function	:Processing, Assembling, Conveyance, Pumping of Solution, Environment recognition, Holding and Adhesive spreading
Working area	:1 cm^3
Object size	:<10 mm
Object weight	< 2 g

Two approaches can be considered here as methods to miniaturize the manufacturing system. One is to develop new manufacturing method applicable to miniaturization. The other is to reduce the size of the instruments themselves in a conventional manufacturing system. Both approaches have been investigated in R&D of the experimental microfactory system : the first is for processing and conveyance unit and the second for assembling unit. The features of each of the units are described below.

2.1. Processing unit

In the processing unit, the micro-gears are processed in way of the electrochemical machining. This unit is consist of electrochemical machining device, micro-pump and the recognition device.

The electrochemical machining method is used in this unit. The photograph of the electrochemical machining device is shown in Fig. 3. The device has a probe, a sample and a reference electrode are put in electrolytic solution, and they are connected to a potentiostat. When a voltage is applied between a probe tip and sample surface in the state of non-contact and closely, etching or deposition is occurred according to direction of the applied voltage. The method is suitable to reduction of the system size, because of reasons as follows:

a) Both etching and deposition are possible only by changing the direction of applied voltage.

b) The material is supplied from atmosphere in deposition processing.

c) The vacuum system, which becomes the factor of the enlargement of the device, is not necessary.

d) Various metals can be processed, by exchanging the processing solution.

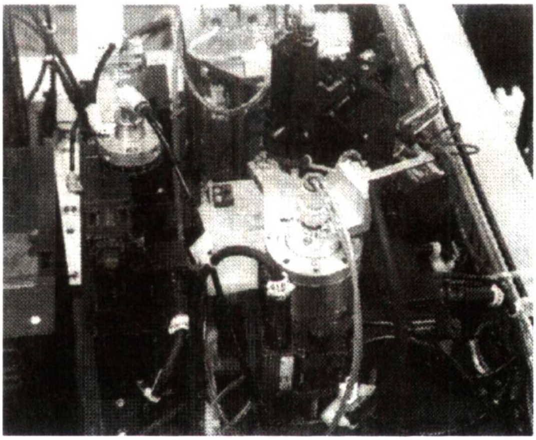

Fig.3. The electrochemical machining device.

The target of the resolution is 20 micron processing area is 5 x 5 mm^2 by using precise stage and the depth of processing is more than 300 microns: Fig. 4 shows the photograph of the gear pattern on Cr substrate by this method.

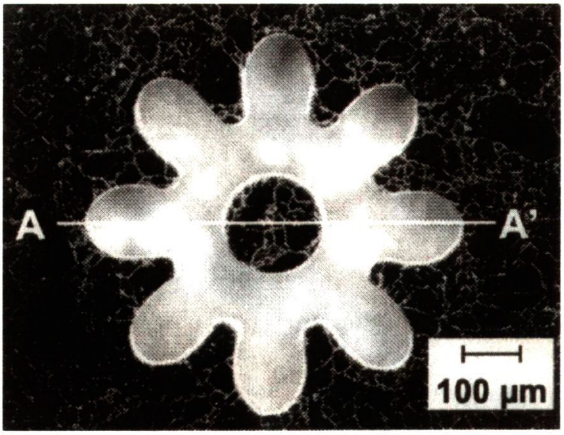

Fig.4. The gear pattern by the electrochemical machining.

2.2. Assembling unit

The assembling unit is composed of 2 micro-arms, precise stage, and several working tools. We have been trying to reduce system size by miniaturizing component's size with keeping the style of conventional assembling system. Fig. 5 shows a micro-arm. The size of a arm is 100 mm. As the arm has 7 degrees of freedom by using 7 ultrasonic micro-motors, it can move flexibly and the resolution of actuating is about 20 micron. The maximum of parts weights is 2 g. There are two kinds of holding devices and adhesive device as working tools in the unit. It is necessity that these devices must be light and they must not occur vibration not to disturb micro-arm's motion. So, one of the holding device is a vacuum chuck with a scrolled typed pump. The other holding device is a electro-magnetic chuck. It is used to hold magnetic materials. The adhesive device is made of Si and glass. The weight of the device is about 2.5 g (include the connector). The device is driven by laser-light and the minimum volume of pumping is about 0.5 nl. Therefore, it can coat adhesion on narrow area. It is very important that a stage is driven precisely to assemble micro-parts, The micro-servo-actuator has been developed to drive the assembling stage precisely. And the actuator is used to position a recognition device. The actuator has resolution of 0.5 μm in positioning. The recognition device is used for investigation of the assembled parts in narrow space. The device has image guide and it can swing the tip driven by SMA actuator.

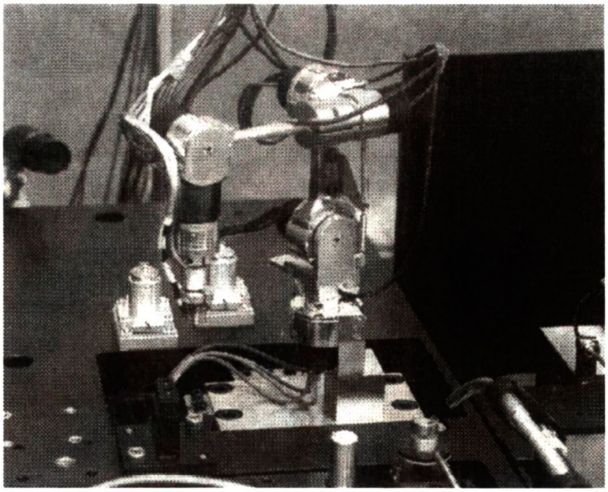

Fig. 5. The micro-arm.

2.3. Conveyance unit

The conveyance unit is constructed by micro-actuator array. The size of a micro-actuator is about 1 mm^2. The actuators are electromagnet, and each actuator can be operated individually. Therefore, the two-dimension conveyance can be accomplished if individual actuator is controlled properly. Permanent magnet was used for a mover to carry the parts of products. The CCD monitor that is put over the unit takes a shape image of the mover, the position of the mover is calculated by the image reader and the mover is conveyed by continues driving of each actuators. As the mover is round shape and a part is put on the center of the mover, the relative position between the part and edge of the mover doesn't change even if the mover is rotated. Therefore, the part can be positioned precisely at the positioning wall, which is placed at the end point of carrying. The maximum carrying mass is expected to be 1 g and the maximum carrying velocity is expected to be 30 mm per second. Fig 6 shows conveyance unit. The prototype device has 12800(40 x 40 x 8) actuators. The size of the unit is about 160 x 160 mm^2. The actuator is covered by polyimide film to slide a mover.

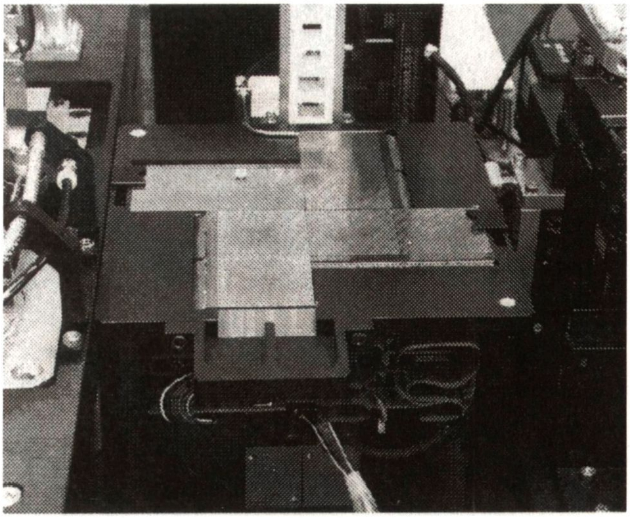

Fig.6. The conveyance unit.

3. CONCLUSION

We have been developing the microfactory system in R&D project of *MITI*. The experimental system, which consists of processing unit, assembling unit and conveyance unit, will be achieved in fiscal 2000. Until now, we have confirmed by prototype devices and simulations that each device performs its function in the system. Through this project we will investigate technological possibility of "Microfactory" and will make clear the problems to be solved in realizing it.

ACKNOWLEDGMENTS

A part of this work was performed under the management of the Micromachine Center as a part of the Research and Development of Micromachine Technology supported by *NEDO* (New Energy and Industrial Technology Development Organization) The authors wish to thank these agencies for their support of this research.

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MULTIPLE DISTRIBUTED MICROMACHINE SYSTEM

Koji Namura

Using micromachine technology, we have developed the second prototype of a multiple distributed micromachine system. The developed micromachine is the world's smallest machine (width: 9 mm, length: 5 mm, height: 6.5 mm, weight: 0.52 g) that can travel in both the horizontal and vertical directions. This paper gives an overview of the prototype and its travel and connection/disconnection performance. The following conclusions were obtained: (1) The developed micromachine is able to travel freely on a horizontal plane. (2) Ten connected micromachines can move vertically around a small tube. (3) Automatic connection and disconnection are realized by newly developed microconnectors.

1. INTRODUCTION

Three micromachine systems for the maintenance of power plants have been developed in the second stage of *MITI's* micromachine project, which started in 1996. One of these systems employs chain-type micromachines for the inspection of the outer surfaces of tube banks. The micromachine must be small enough to enable it to travel through the narrow spaces between the tubes in the system. Therefore, it is difficult to equip it with many functions. On the other hand, it must also be able to cover a certain working area and have a range of functions in order for it to achieve meaningful tasks. To solve these conflicts, a multiple distributed micromachine system has been proposed [1]. In this system the necessary functions are distributed between many micromachines (component micromachines) and the task is carried out cooperatively by the micromachines which gather and are connected to each other at the desired place. The second prototype of the system was developed using micromachine technology. This paper gives an overview of the prototype and its travel and connection/disconnection performance.

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2. SYSTEM OVERVIEW

In order to verify the concept of the chain-type micromachine system, a platform for the system has been developed (Fig. 1). The system includes such key requirements as movement in narrow spaces, automatic connection and disconnection, and vertical movement of multiple connected micromachines around a tube. The system has tube banks 22 mm in diameter and narrow spaces (10 mm) between tubes. Therefore, the size of the component micromachines should be less than 10 mm. The system has been designed to connect ten 9 mm wide component micromachines with a connector on each side.

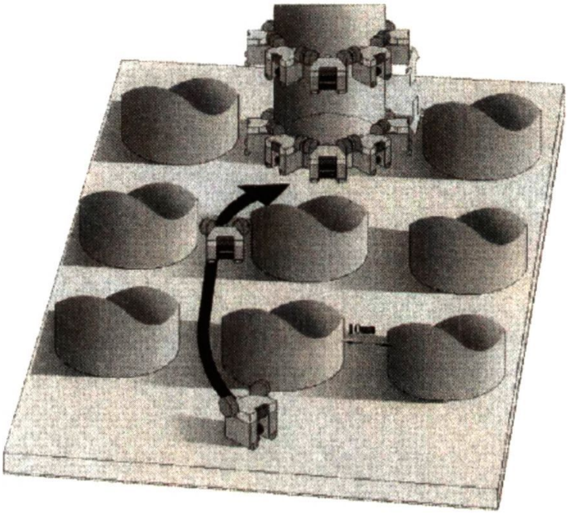


Fig. 1. Schematic view of the system.

A new structure composed of functional blocks was proposed for easy assembly. The component micromachine consists of 4 functional devices, a driving device, a traveling device, microconnectors and the flaw detection device shown in Fig. 2. Each device also has functions of frame and body.

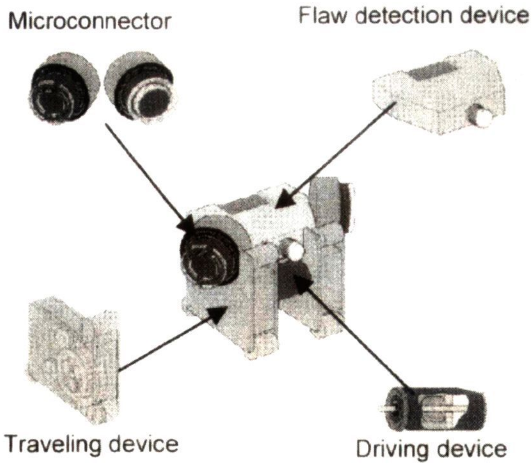


Fig. 2. Component micromachine structure.

3. OUTLINE OF PROTOTYPE

The newly developed micromachine prototype consists of 2 driving devices, 2 traveling devices, 2 microconnectors, and a flaw detection device (Fig. 3). It is 9 mm in width, 5 mm in length, 6.5 mm in height, and its weight is 0.52 g.

The driving device is a radial-gap cored electromagnetic motor. It consists of a stator with 50-turn coils fabricated using high-aspect layering technology and a rotor with a permanent magnet. It is 1.6 mm in diameter and 2 mm in length and rotates at 40,000 rpm. Its external appearance is shown in Fig. 4.

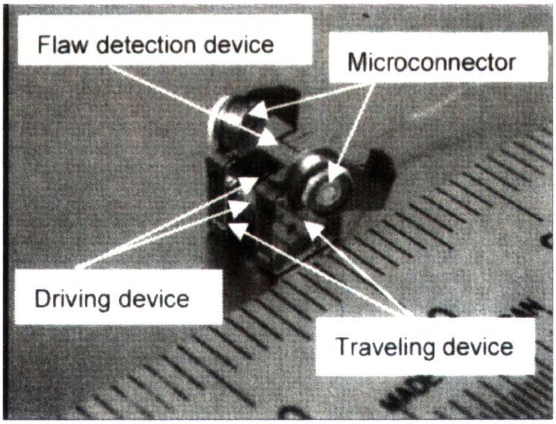


Fig. 3. Prototype of component micromachine.

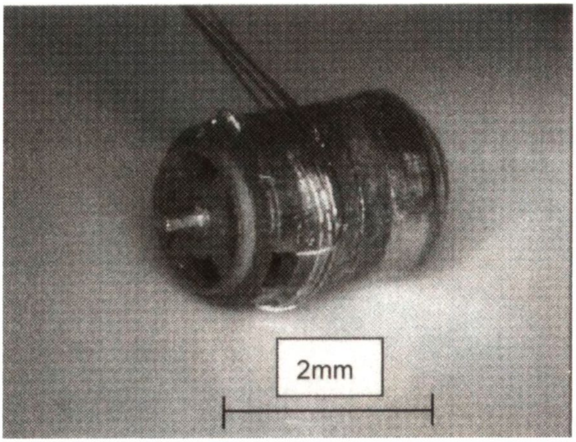


Fig. 4. Driving device.

The traveling device has a micro-scale reducer [2] and 3 magnetic wheels (Fig. 5). Fig. 6 shows a photograph of the assembled planetary gear system. It is 1.5 mm in width, 5 mm in length, 5 mm in height. Since a high reduction ratio (1/201) and compactness are important, a 3K-type mechanical paradox planetary gear system fabricated by micro electro-discharge machining (*EDM*) was chosen.

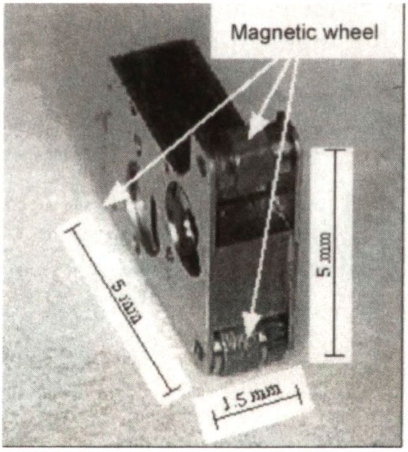


Fig. 5. Traveling device.

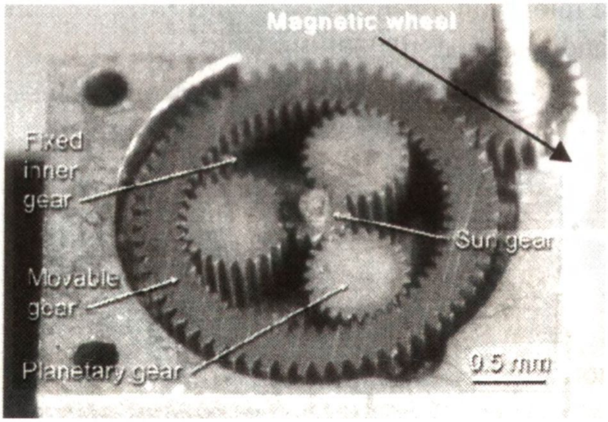


Fig. 6. Planetary gear system.

The microconnectors [3] establish mechanical and electrical connections with adjacent component micromachines. They are approximately 2.5 mm in diameter and 2 mm thick, and each connector automatically joins and separates when it is given external commands. The microconnector has a new structure, in which the terminals are supported by a spiral spring and a permanent magnet is actuated by an electromagnet, shown in Fig. 7. A guide, tapered and cantilever terminals were fabricated by deep X-ray lithography. The permanent magnets allow the microconnectors to remain connected without an energy supply.

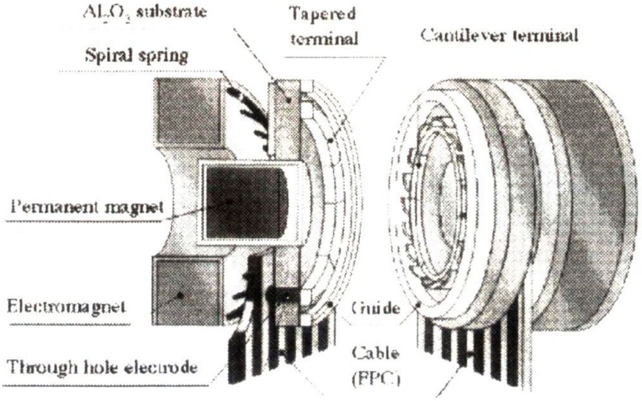


Fig. 7. Microconnectors.

The flaw detection device is located on the top of the traveling devices and the microconnectors are mounted on it. However, a flaw detection sensor was not installed in the prototype.

4. BASIC PERFORMANCE

To test the traveling performance, a component micromachine was driven on a horizontal plane. The component micromachine's movement was evaluated by measuring the positions of two marks on top of the component micromachine by a camera system. Fig. 8 shows an example of the trajectories drawn by the component micromachine. Fig. 9 shows the radius of turn as a function of the difference in rotational speed between the wheels on both sides. These figures indicate that the component micromachine is able to travel freely on a horizontal plane, although this was said to be difficult for wheel-driven micro-

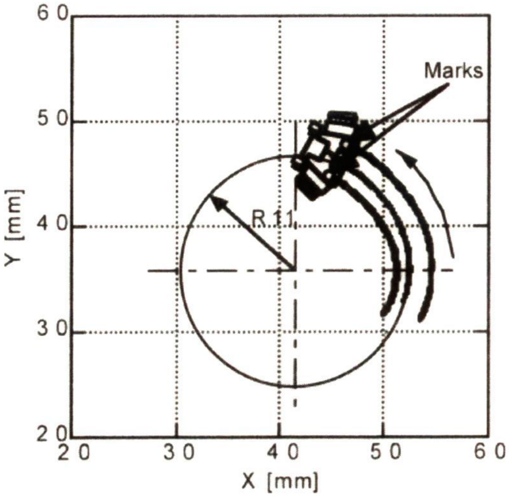


Fig. 8. Trajectory of micromachine.

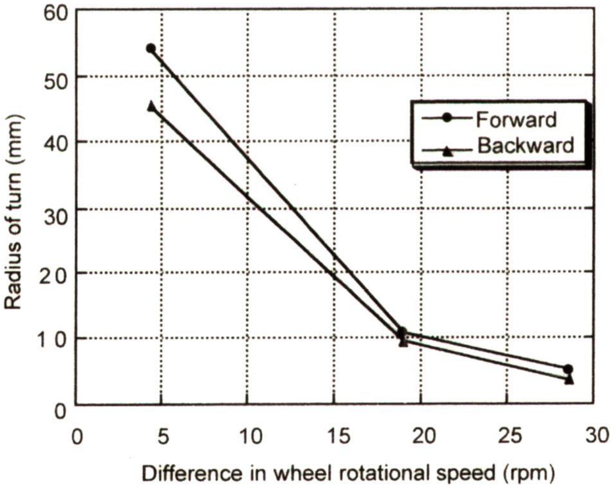


Fig. 9. Relationship between difference wheel rotational speed and Radius of turn.

machines. This was achieved because the magnetic attraction between the magnetic wheels and the plane provides strong traction.

To examine the connected movement, ten component micromachines, three of them driving micromachines with driving devices and the others connecting

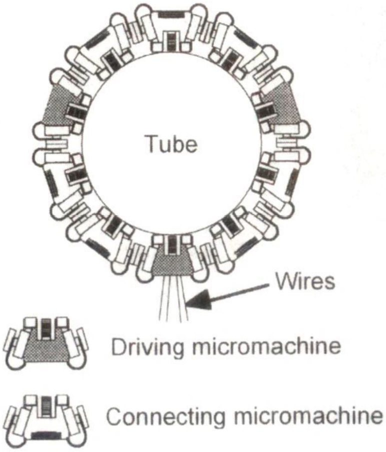
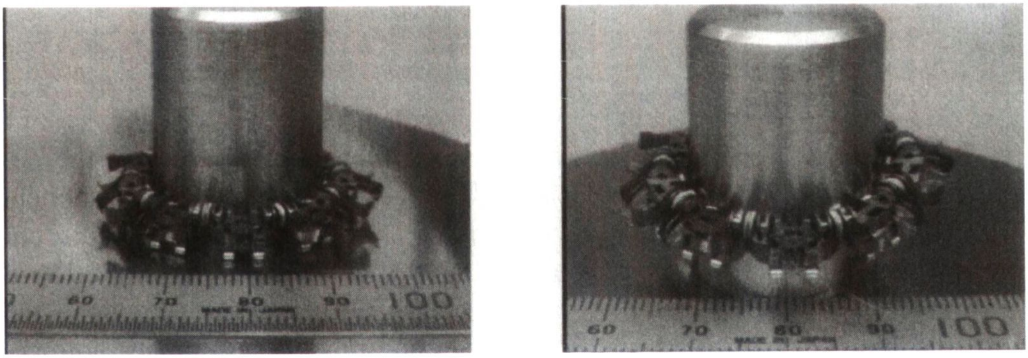


Fig. 10. Machine arrangement.



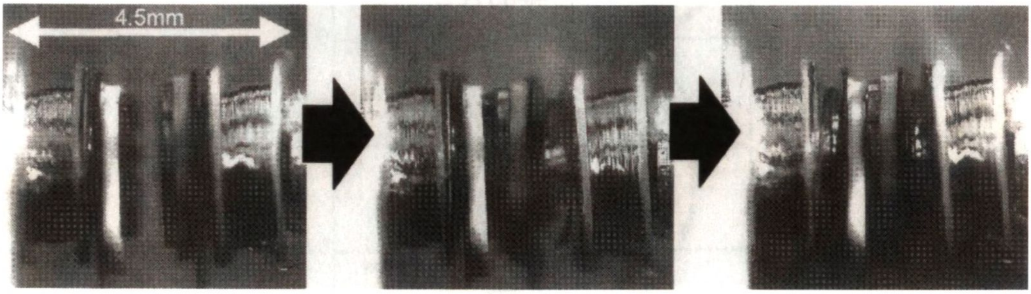
a) Lower state

b) Upper state.

Fig. 11. Connected movement.

micromachines without driving devices Fig. 10, were connected and were driven vertically around a small tube. Fig. 11 indicates the connected movement.

To examine the connection/disconnection operations, a model was fabricated in which three component micromachines were connected with two pairs of microconnectors. It was established that by energizing the electromagnets, they could automatically be connected and disconnected and that when they were connected, they could be energized via the microconnectors. Fig. 12 shows enlarged views of the microconnector's movements when they are connected.



(a) Disconnected state (b) Excited state (c) Connected state

Fig. 12. Movements of microconnectors.

5. CONCLUSION

The structures, specifications, fabrication methods and functions of the devices used in component micromachines has been described. The component micromachines were tested regarding their movement and connection/disconnection operations. The following results were obtained: (1) The developed micromachine is able to travel freely on a horizontal plane. (2) Ten connected micromachines can move vertically around a small tube. (3) Automatic connection and disconnection are realized by newly developed microconnectors.

The next task is to improve the performance of the component micromachines. The aim is to complete a prototype system by the end of this year in which ten connected component micromachines can detect flaws while moving vertically around a small tube.

ACKNOWLEDGEMENTS

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IN-PIPE WIRELESS INSPECTION MICROMACHINE

Nobuaki Kawahara[1]

We have been developing an In-Pipe Inspection Micromachine for inspection on the inner surface of thermoconduction tubes of power plants, in the collaboration with DENSO, Toshiba and SANYO under the project. The machine consists of several devices, CCD camera for inspection, actuator for locomotion, communication circuit for control, microwave antenna and photovoltaic device for energy supply and communication, and so forth. Through the project, the technologies of the component devices and the system have been developed. Several prominent results were also obtained on the both technologies. As for the device technologies, the component devices have been miniaturized and integrated. As for the systematization technologies, the functions, simulation, packaging and assembling of the system have been studied.

1. INTRODUCTION

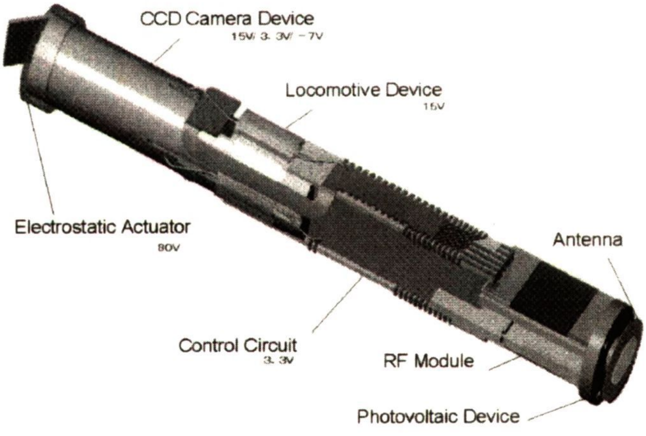

Fig.1. System image of wireless micromachine for inspection on inner surface of tubes.

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As a prototype of the system, we developed a wired in-pipe inspection micromachine which moves in a curved pipe and detects cracks in the pipe [1]. With a diameter of 5.8 mm and an overall length of 20 mm, it fits inside 8 mm piping, and is inertia-driven [2] while searching for cracks in pipe walls using an eddy current sensor. Through the development of the prototype micromachine, problems unique to micro technology were identified. The biggest problem was wiring for the power supply and signal monitoring, which is described in detail in our previous paper [3]. Therefore, we started the development of a wireless in-pipe inspection micromachine shown in Fig. 1.

The machine consists of CCD camera for inspection, actuator for locomotion, communication circuit for control, microwave antenna and photovoltaic device for energy supply. The machine moves in a curved pipe at 20 mm/sec by the actuator, inspects the inside of the pipe and transmit the observation data to a host computer. The required power of 650 mW is provided from the outside via microwaves and light. Although the system will be completed in 2001, the R&D current status of the component devices and the systematization are discussed in this paper.

2. DEVICE TECHNOLOGIES

2.1. CCD micro camera

The CCD camera has a mirror with an electrostatic actuator and a motor. When the mirror is pushed up, the camera takes the picture ahead. When the mirror is pushed down to 45 degree and rotated, the camera takes the pictures of surrounding pipe in detail. The CCD micro camera having 100.000 pixels consists of four technological fields of development [4]: sight adjusting mechanism of focusing and mirror rotation, designing micro CCD module for wireless transmission, three dimensional packaging of LSI's and discrete elements, and glass press molding method of micro lens. So far all the technologies have been integrated to achieve 9.2 mm diameter CCD micro camera. On the top of this camera adjusting mechanism electrostatic actuators of three degrees of freedom are mounted. Aspherical catadioptric lens of 3 mm diameter as a focusing mechanism inside is formed altogether with its cylinder by glass press molding method, to realize better optical characteristics after trimmed by FIB. Through this lens images are captured with CCD, its signals are processed by three dimensional packaged LSI block of 4.4 x 5.2 x 11.5 mm.

2.2. Locomotive mechanism

We have developed a new actuator whose displacement is larger compared with the piezoelectric stacked actuator [7]. This mechanism enlarges the displacement of the actuator but reduces the generating force. Therefore, the actuator has multi-layered structure, which controls the generating force by the layer number.

2.3. Control circuit

The control circuit consists of a voltage regulator and a voltage monitor, a system control gate-array and a drive circuit of the locomotive mechanism. The voltage monitor detects the output voltage of the RF module and sends the data to the gate array. The gate-array converts the data to digital and send it to the RF module.

The gate-array also generates a timing signal to generate the saw-toothed wave voltage for the locomotion. The timing signal controls the direction and the speed of the robot according to the host command. The gate-array controls the CCD and it's sight adjusting mechanism of focusing and mirror rotation. The gate-array also converts the data of the CCD to digital and sends it to the RF module.

The drive circuit generates a saw-toothed wave voltage from DC voltage supplied from the voltage regulator. In order to make the circuit compact, we developed a simple drive circuit [6]. The circuit consists of four analog switches, two resistors, and the PZT actuator used as a capacitor. In this circuit, the combination of the PZT actuator and resistors works as CR circuit to generate the saw-toothed wave voltage. The gate array controls switches, and generates forward and backward voltage.

2.4. RF module

The RF module, as shown in Fig. 2, consists of a stacked patch antenna, two rectifying circuits, a communication circuit and a photovoltaic device formed on the antenna. The antenna receives two frequencies of microwaves and isolates them. The rectifying circuit converts the microwave for energy supply (22 GHz) into direct current. The communication circuit receives the host command and answers the voltage condition of the robot and the image data of the CCD.

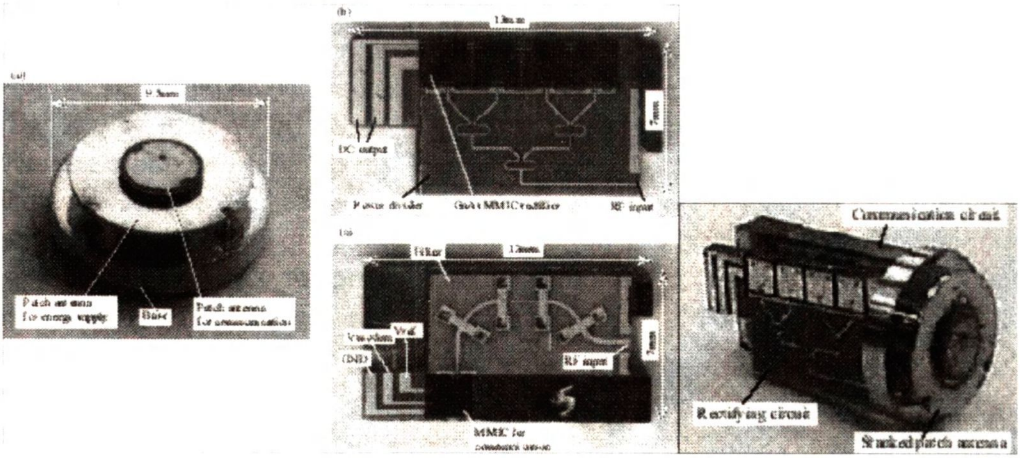

Fig. 2. RF module (Right) and It's components: (a) Micro patch antenna; (b) Rectifying circuit; (c) Communication circuit.

2.5. Photovoltaic device

In order to supply enough energy to drive the specific devices in the experimental wireless inspection microsystem, it is necessary to increase the output power and voltage per unit area because the available area and shape are restricted to the system's optimum design.

Accordingly, We use a high intensity laser as a light source and the tandem structure of unit cells in an integrated type photovoltaic device. Each cells in the tandem structure has to be designed to match the top cell's current with bottom cell's current under penetrated monochromatic light incident through the top cells. By using theoretical analysis, the optimum design of the tandem photovoltaic cells for a laser of 532 nm wavelength was achieved. Consequently, the maximum output power P_{max} has been improved about 180% compared with that under white light illumination.

3. SYSTEMATIZATION TECHNOLOGIES

3.1. Packaging

Packaging is inevitable for the microrobot, because the size of the robot is limited by the diameter of the pipe, 10 mm. And total weight of the microrobot should be light, because the power of the micro locomotive mechanism is limited. We have used three different packaging technologies in photovoltaic device, CCD camera device and control circuit. In the packaging in photovoltaic device, three-dimensional micro-wiring method utilizing a dual wavelength laser CVD was applied. In the packaging in CCD camera, three dimensionally packaged LSI blocks are connected by MID. As for the packaging in control circuit, to make the control circuit compact, we used a flip chip assembly for the gate array and other eight LSIs. The gate array is made of 0.35 microns CMOS: the pad pitch is 120 microns and the pad size is 88 microns, which is shown in Fig. 3. Small stud bumps whose diameters are approximately 50 microns are formed on the each pad of the bare chips. The bumps are bonded on a fine pitch 6-layered printing circuit board (*PCB*) by using an anisotropic conducting paste (*ACP*). The *ACP* is composed of heat-hardening resin and many conductive particles. One of the advantages of the *ACP* is that the contacts between bumps and PCB are done by heating with low stress. The chips are precisely aligned, mounted and heated on the *PCB* by a chip bonding machine.

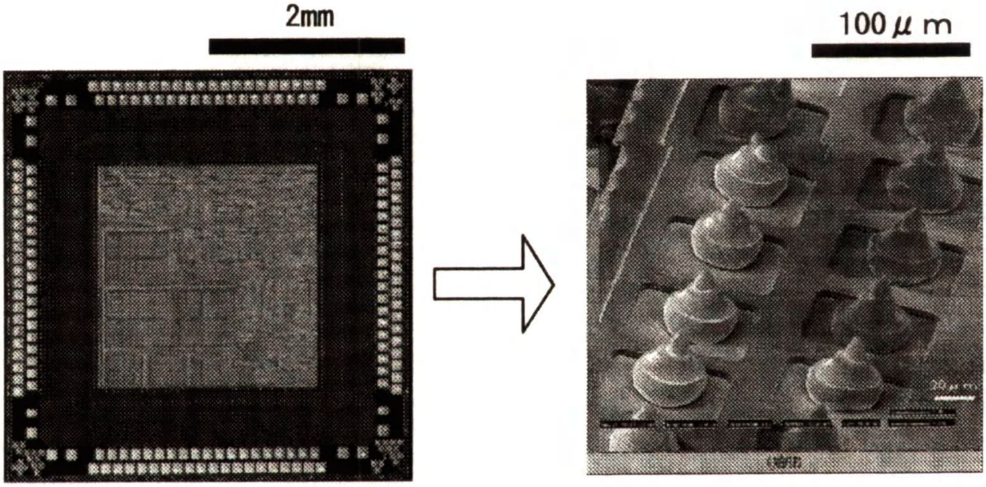

Fig. 3. Gate array (0.35 μm CMOS) and 50 μm stud bumps formed on the pads.

3.2. Developed proto-type systems

We are now developing the advanced wireless in-pipe inspection system shown in Fig. 1. In our previous work, we developed a wireless energy supply method utilizing microwave [5]. We also developed a 15 mm diameter in-pipe locomotive mechanism whose power was supplied from outside by microwave [6].

As proto-types of the system, we have developed three different systems. One of the systems is shown in Fig. 4, as called A-type. The system consists of the locomotive mechanism, the control circuit and the RF module. The A-type moves in the pipe of 10 mm diameter, receives the commands from the host, transmits the voltage data of the RF module to the host and receives microwave energy from the host.

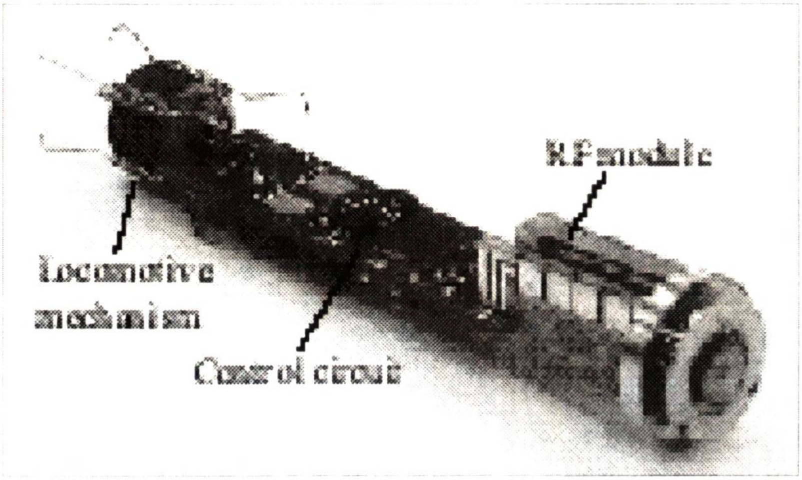

Fig. 4. Developed proto system: type-A.

ACKNOWLEDGMENTS

A part of this work was performed under the management of the Micromachine Center as the Industrial Science and Technology Frontier Program (*ISTF*), Research and Development of Micromachine Technology of MITI, supported by New Energy and Industrial Technology Development Organization (*NEDO*).

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MICROMACHINED SILICON SENSORS

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This paper reviews novel silicon micromachining technology and sensors developed in Yokogawa Electric Corporation. Two types of pressure sensors are described: a highly stable and accurate resonant sensor fabricated using special vacuum encapsulation technology: and an integrated pressure sensor with twin diaphragms and micro over-range protection structures. Also described are silicon bolometers and micro variable infrared filters for infrared spectroscopy of gas analyses and silicon microforce sensors.

1. INTRODUCTION

Yokogawa found potential uses for silicon micromachining technology in the mass production of low-cost yet high-performance silicon sensors and started to develop such sensors at the end of 1980 in response to advancements in the silicon micromachining technology used in the electronic IC process. The first product from this development project was a high-precision resonant silicon pressure sensor, which was rolled out onto the market in 1992 as a series of industrial deferential pressure transmitters under the name of DPharp. Conventional transmitters employing piezo resistive pressure sensors are still being produced. Yokogawa is now adopting the silicon micromachining technology for next generation of pressure sensors, and optical micromachining sensors and actuators for infrared spectroscopy application.

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2. PRESSURE SENSORS

2.1. High stability and accuracy of resonant pressure sensors

Differential pressure transmitters are field instruments widely used for measuring flow rates, pressures, liquid levels and so on. Highly stable and accurate resonant pressure sensors were developed for use in differential pressure transmitters. Fig. 1 shows a resonant pressure sensor excited electromagnetically and an SEM cross-sectional view of a resonator [1-2]. The resonator consists of H-shaped dual bridges that are connected to each other at their centers and vacuum-sealed inside the same H-shaped microcavity on the surface of a diaphragm. The resonator vibrates in a vacuum environment independent of the external fluid. As the resonator and microcavity are extremely small, the sensor can detect at a higher sensitivity the deformation of the diaphragm due to the applied pressure as well as withstand a higher pressure. One of the bridges is an excitation bridge and the other is a detection bridge. The resonator is excited by the Lorenz force caused by an external magnetic bias field and an alternating current applied to the excitation bridge. Fig. 2 shows the fabrication process. The resonator is formed of single-crystal silicon. The resonator and substrate are isolated by p/n junctions. The resonator is made of heavily doped p-type silicon, and the other areas of n-type silicon. At the vacuum sealing stage, the wafers are put in a silicon epitaxial growth reactor to grow n-type silicon over the wafer. Hydrogen carrier gas, which remains in the microcavity after sealing, is released by diffusing it through the silicon crystal in a high-

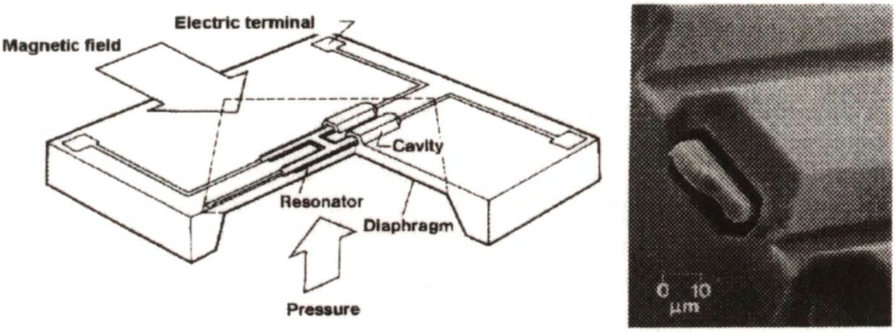


Fig. 1. Structure of silicon resonant pressure sensor (left), and, cross-sectional view of a resonator and a vacuum cavity chamber fabricated on the silicon diaphragm.

temperature purified nitrogen furnace. The cavity pressure after the hydrogen is removed falls below 1 Pa. This pressure sensor shows a long-term stability as high as ±0.01 % of full scale per year or even superior.

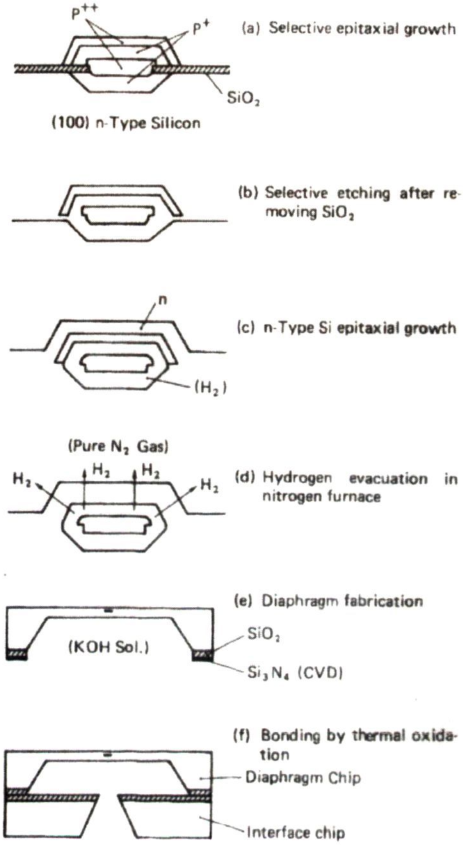


Fig. 2. Fabrication process of resonator and sensor.

2.2. Pressure sensors with twin diaphragms and micro over-range protection structures

Pressure sensors using a single-crystal silicon diaphragm have demonstrated excellent mechanical stability and have been produced using the same fabrication technology as that for silicon integrated circuits. However, to use single-crystal silicon sensors for differential pressure transmitters, they must be able to withstand a high static pressure and a high differential over-range pressure. Therefore, conventional silicon sensors for differential pressure measurement need to be mounted in a strong high-pressure vessel, and the output terminals need to be hermetically sealed. Also, a complex mechanical structure is required to protect the silicon diaphragm from a high differential pressure [3]. These structural requirements lead to an increase in costs.

See also our past reports for the first attempt to fabricate a sensor with a micro over-range protection structure [4-5].

The following describes a sensor, which has two diaphragms with piezoresistors working complementarily to each other due to the respective pressures. This structure has improved sensor linearity, and reduced errors caused by changes in ambient temperature and static pressure. Fig. 3 shows a cross sectional view of the sensor. Fig. 4 shows the fabrication process of the silicon sensor chip. The substance to be measured passes via two openings in the pyrex glass base. The glass base and the silicon sensor chip are bonded using the anodic bonding method. The sensor has two diaphragms which work complementarily to each other by applying differential pressure. The substance is led through the gaps on both sides of the diaphragms via lateral openings that are formed inside the silicon sensor chip. Piezo gauge resistors are positioned on the side of each diaphragm.

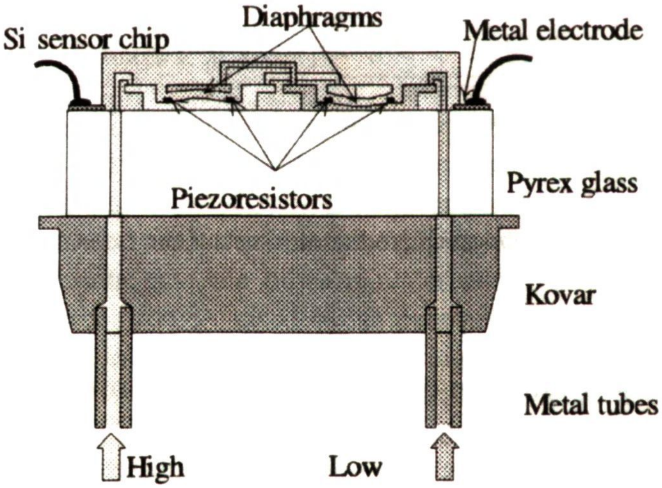


Fig. 3. Cross sectional view of the sensor.

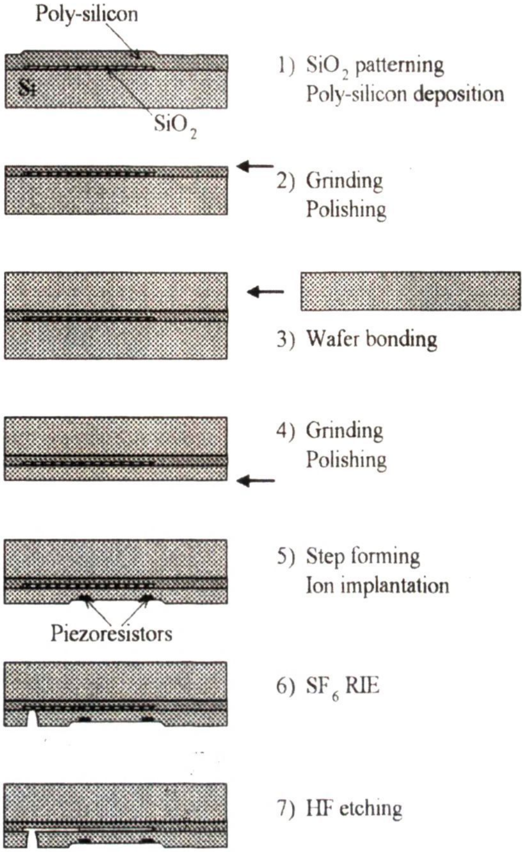


Fig. 4. Fabrication process.

Excess pressure causes the diaphragms to come into contact with the back planes, thus preventing the diaphragms from fracturing. The sensor is also a high-pressure vessel, and the electrical feed through of the silicon surface and the pyrex glass are hermetically sealed with unique bonding structures. The ion-implanted layers are formed as piezoresistors and p-type leads on the silicon surface, and the p-type leads are connected to the electrodes that are formed on the glass surface. The anodic bonding and annealing process gain ohmic contacts.

Fig. 5 shows the output signal of a sensor covering ±100 kPa. The output signal saturation indicates that either diaphragm has come into contact with the back plane. Fig. 6 shows the result from testing long term stability. The zero drift after use for a long term was observed to be less than 0.01 %.

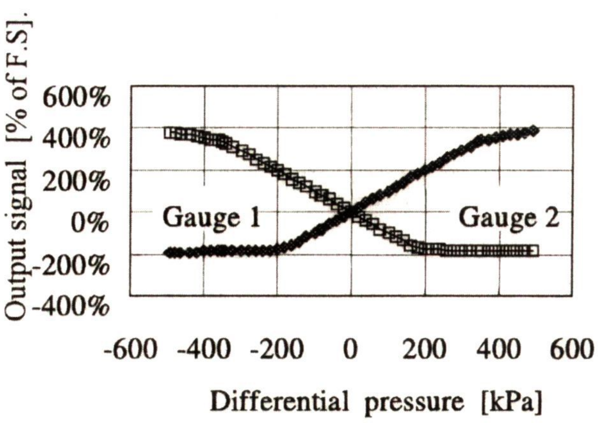


Fig. 5. Output signal of the sensor.

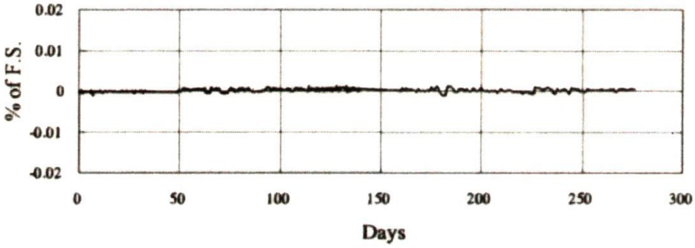


Fig. 6. Zero-point long -term stability.

3. SILICON BOLOMETERS AND MICRO VARIABLE INFRARED FILTERS FOR CO_2 MEASUREMENT

We have developed silicon bolometers fabricated on an SOI wafer using bulk micromachining and also developed a micro variable infrared filter, and have investigated the bolometers' capability of measuring CO_2 concentration when used in a *Non-Dispersive Infra-Red (NDIR)* system [6-7]. Two bolometers were combined with a micro variable infrared filter adjusted to two different wavelength ranges: the CO_2 absorption band and reference band. The two wavelength *NDIR* system having these bolometers and filter elements with a conventional infrared source was able to measure the concentration of CO_2

with the measurement reproducibility 3σ of ±3.6% of the measured value or less between the concentrations of 0 ppm and 5000 ppm.

3.1. Non-cooled micro bolometers

The bolometer is designed to obtain a maximum specific detectivity *D** by optimizing the structure and concentration of boron in the silicon. Highly doped silicon can absorb infrared rays in a wide band by free carrier absorption. Therefore, the concentration of boron is set at $1\text{x}10^{20}/\text{cm}^3$. This bolometer is sensitive for wavelengths between 3.5 μm and 8.5 μm at half maximum. The total of blackbody absorption at 500 K is 48%. The temperature coefficient of resistance (*TCR*) is 0.2°/a/K at 300 K. In order to minimize the heat capacitance and thermal conductance, a thermally isolated structure is formed so that highly boron doped single-crystal silicon is suspended from the substrate. The bolometer is fabricated on an SOI wafer by bulk micromachining. The performance of the bolometer is tested in a vacuum. By measuring voltage and current, the average thermal calculated to be $1\text{x}10^{-5}$ W/K. The calculated heat capacitance is $3\text{x}10^{-7}$ J/K. This bolometer has a measured specific detectivity *D** (500 K, 10 Hz, 1 Hz) of $1.1\text{x}10^{8}$ $\text{cmHz}^{1/2}/\text{W}$.

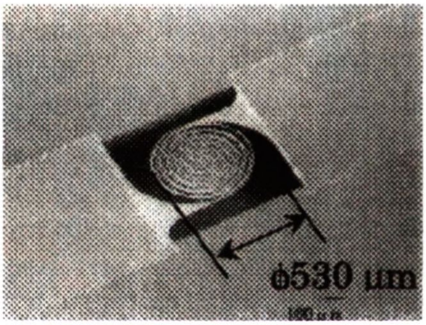


Fig. 7. SEM photograph of bolometer.

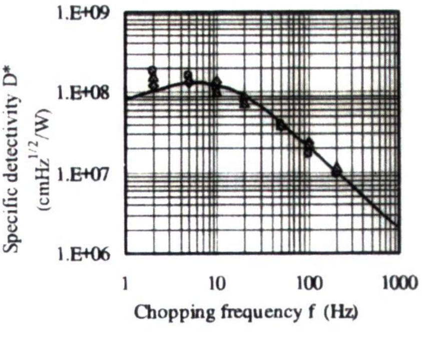
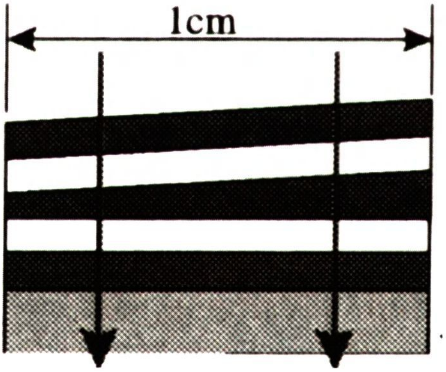


Fig. 8. Comparision between calculations (line) and measurements(points) of spectral *D** of the bolometer (L = 10 mm, w = 10 μm, d = 1.7 μm, V_b = 9.0 V).

3.2. Micro variable infrared filters

The filter of a dielectric multiple layer membrane is composed of three parts: two sets of $\lambda/4$ type multiple layers and a spacer type layer. The value λ, is a center wavelength of the filter, $\lambda/4$ indicates the optical thickness nd, where n is the refractive index and d is the film thickness. Such filters are called single halfwave (*SHW*) type filters. The five-layer SHW filter is defined as follows. These filters consist of dielectric coating materials deposited onto substrates in a vacuum.

Generally, the selective infrared linear variable filters consist of ramp film thickness layers. However, we adopted a structure that transforms the center wavelength by changing the thickness of only the spacer layer in the five-layer *SHW* filter. The *MVIF* experimentally produced using the slit shutter sputtering system offers continuous wavelength coverage from 3.8 μm and 4.3 μm. This wavelength range includes infrared absorption by CO_2. We adopted a structure that transforms the center wavelength by changing the thickness of only the type spacer layer in the five-layer *SHW* filter as shown in Fig. 9. The size of the *MVIF* is 1 cm^2. The spectrum transmission of the *MVIF* measured by a spectrometer is shown in Fig. 10. The experiment results agree with the simulation results for the spectrum transmission characteristics. The linearity of the transmitted bands for different wavelengths at different measurement positions is within 1 %. The cause of the 1 % error is dispersion of the film thickness. This linearity satisfies the condition mentioned previously (<2%).



$Si(\lambda 4):d$ = 272 nm
$SiO_2(\lambda/4):d$ = 670 nm
$Si(\lambda):d$ = 970 nm-1100 nm
$SiO_2(\lambda/4):4$ = 670 nm
$Si(\lambda/4):d$ = 272 nm
Sapphire:d = 0.5 nm

R: λ = 3.8 μm M: λ = 4.25 μm

Fig. 9. Schematic diagram of MVIF.

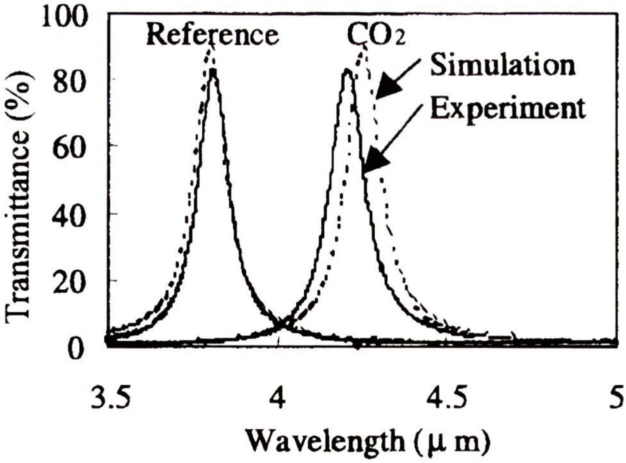


Fig. 10. Spectrum transmission characteristics of MVIF.

3.3. NDIR system and conclusions

The prototype CO_2 sensor was designed with two micro bolometers: an MVIF and an infrared source. Signal output R of the bolometer for the reference wavelength (λ = 3.8 μm) and signal output M of the bolometer for the CO_2 measurement wavelength (λ = 4.25 μm) were measured at five points of CO_2 gas concentration in the range between 0 ppm to 5060 ppm. The relationship between the concentration of CO_2 and the signal of M/R which was standardized in M/R at the 0 ppm concentration is shown in Fig. 11. The measurement reproducibility 3 σ was shown to be within ±3.6% of the measured value. These results demonstrated the possibility of microfabricated CO_2 sensor for consumer and commercial applications.

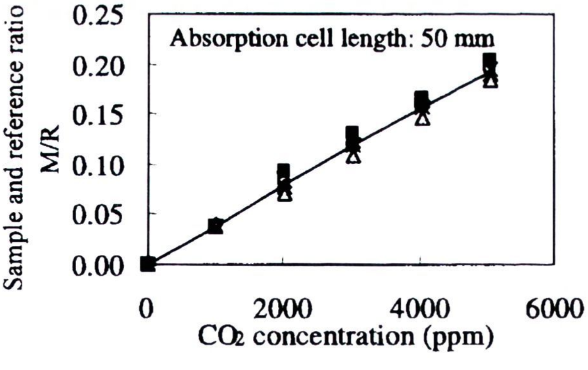


Figure 11. Measurement results of CO_2 concentration signal output R of the bolometer for the reference wavelength (λ = 3.8 μm) and signal output M of the boiometer for the CO_2 measurement wavelength (λ = 4.25 μm). M/R is standardized y M/R of 0 ppm.

4. FORCE SENSORS

In line with the recent development of micromachines, various microactuators have been developed. In general, the smaller the actuator, the smaller the force the actuator generates; however, the smaller the force, the more difficult it is to measure. Instruments suitable for this are currently unavailable. We developed a probe sensor for measuring very small forces, employing a semiconductor shear strain gauge sensor on cantilever [8]. The probe thus developed demonstrates high sensitivity and stability as it was created by forming the stress concentration part and the strain sensor on the same silicon crystal using high-quality raw materials including single-crystal silicon. Using the finite element method (*FEM*), we invented a probe structure in which a very small force effectively generates strain on the sensor. We also developed a semiconductor micromachining process including an inducted coupled-plasma deep-trench etching method to manufacture the probe, and built a calibrator for the probe, based on an electronic balance. In preliminary experiments, we successfully measured the force with a resolution as small as 0.01 mN, exactly as specified by the design. In the future, we are aiming to develop a superior probe with 1 μN resolution.

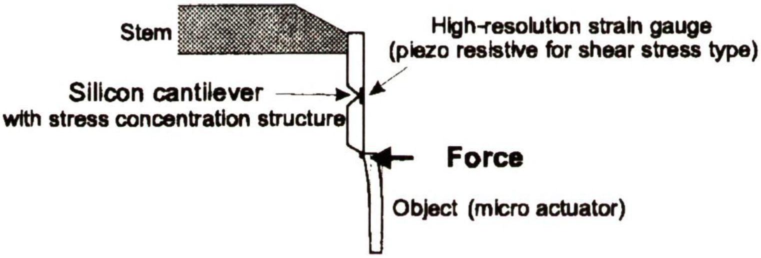


Fig. 12. Basic design of micro force sensor probe.

Fig. 12. shows the basic design we formulated for equipment to measure small forces. The probe was developed as follows. First, the dimensions of the probe were approximately calculated from the properties of the raw material. Next, a shape that could actually be manufactured was designed. The resulting properties of the probe were estimated by the *FEM*, and the dimensions of each part were optimized. A photograph of the force probe is shown in Fig. 13. The fabricated probe was evaluated with a probe calibrator. Fig. 14 shows the

force dependence of a standard probe of 0.1 N range, its output and the deformation at the tip of the probe. The results of the experiment fall within 30% deviation of the theoretical values obtained by the *FEM*. The relationship between the force and the probe output suggested that a 1 μN resolution is achievable.

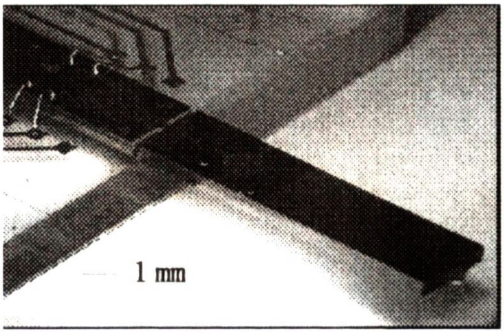


Fig. 13. Standard force probe.

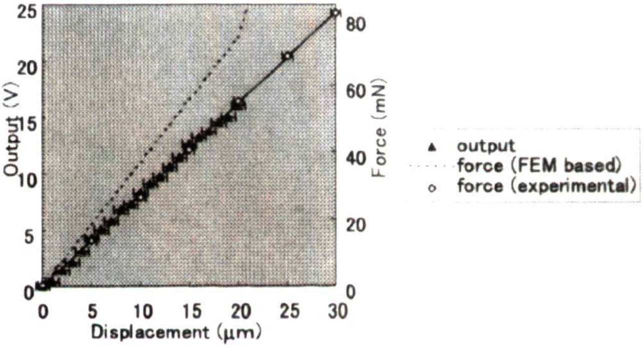


Fig. 14. Dependence characteristics of standard force probe.

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APPLICATIONS OF DEEP X-RAY LITHOGRAPHY

Yoshihiro Hirata[1]

We developed the LIGA process using a compact synchrotron radiation (SR) source and ceramics micro fabrication process. These processes realized an array of lead zirconate titanate (*PZT*) rods whose cross section is 25 μm and was applied to manufacture piezocomposite for high resolution ultrasonic diagnosis for the first time. We also developed microconnector by the LIGA process.

1. INTRODUCTION

Nowadays, micromachining technology has attracted the attention because many applications are expected. The LIGA process, which is composed of deep x-ray lithography (*DXL*), electroforming and molding, is one of the most promising technology. We also recognized the future of this process to start studying it using our own SR source, named "NIJI-III", several years ago.

2. DXL [1]

Our *DXL* system is unique. We perform lithography using "NIJI-III" as SR source. This is a superconducting type compact SR source and the circumference is only 19 m. NIJI-III was designed for ULSI fabrication and its peak wavelength is 5Å. In general, SR with wavelength between 2 and 3Å is said to be suitable for *DXL*. However, the intensity of SR under 3Å from NIJI-III is about 1% of that from the SR sources normally used for the LIGA process. Therefore a sensitive resist had to be developed.

The developed resist is made of a copolymer of methyl methacrylate (*MMA*) and methacrylic acid (*MAA*) and its sensitivity is 10 times higher than that of PMMA, which is usually used in the LIGA process. The accuracy is worse than

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that of PMMA, but 0.16 μm per 100 μm height. It is good enough for many applications. As the result, the exposure time using a compact SR source is on the same order as that of PMMA using with normally used SR source.

The mask is composed of a 2 μm -thick SiN membrane and a 5 μm - thick WN absorber, which is patterned by ECR-etching. The substrate is cooled to (-30°C), and the side etching is suppressed to under 0.2 μm.

3. APPLICATIONS

3.1. Piezocomposite transducer for medical diagnosis [2-4]

Medical ultrasonic diagnosis has been widely used because of its weak influence on patients, ability of blood flow measurement, and real time measurements. The improvement of the resolution is always required, therefore many techniques are being studied. To achieve this, in particular, the changing of the transducer material from piezoelectric ceramics like PZT to 1-3 piezocomposite as shown in Fig. 1 is a thorough idea. However, by the conventional dice-and-fill method, it is impossible to fabricate PZT rods which are small enough to make the composites behave like homogeneous materials.

We applied the LIGA process and developed a mass-production process (see Fig.2), and made piezocomposite for high frequency industrially available for the first time. The size of PZT rods was realized to be 25 μm. It is one-fifth of the size realized by conventional methods. There is characteristic point in removing the acrylic mold. In the conventional *lost wax* method, a burn-out process is usually used to remove the plastic mold. However the fine PZT rods with a high aspect ratio, topple during this process. Therefore, we adopted the plasma etching.

The properties were measured by making the test probe for 10 MHz. The pulse width was recognized to be one-third shorter than that of PZT probe, and

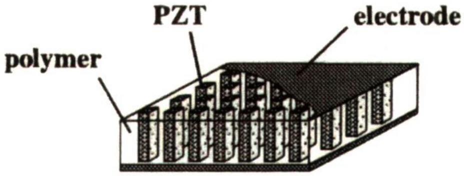


Fig.1. Schematic view of piezocomposite.

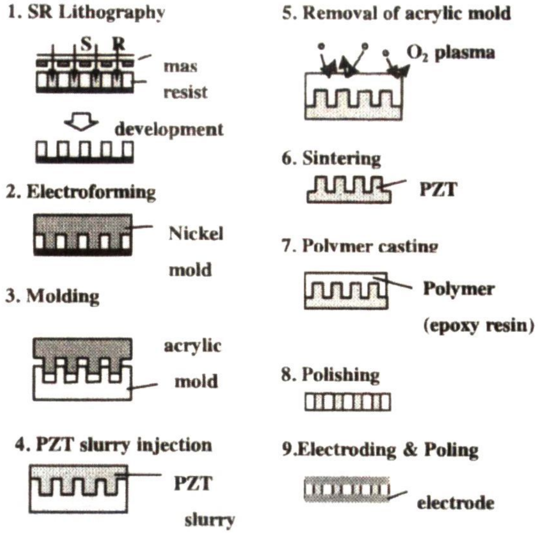
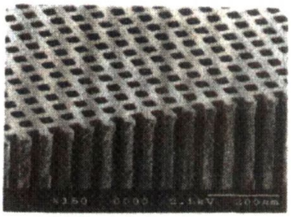
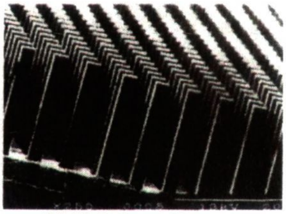


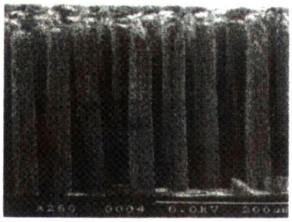
Fig.2. Brief fabrication process of piezocomposite.



(a) Resist structure.



(b) Nickel mold insert.



(c) As-sintered PZT rods array.
(25 μm square, 250 μm height)

Fig.3. SEM photographs.

the sensitivity was 3 times higher than that. The developed piezocomposite is thought to contribute to the improvement of the resolution.

3.2. Microconnector [5-7]

Micromachines must operate in a group because the power of an individual micromachine is low and its functions are limited by its size. One example is the chain-type micromachine system shown in Fig. 4, one of MITI's micromachine projects. To realize this chain-type micromachine system, small connec-

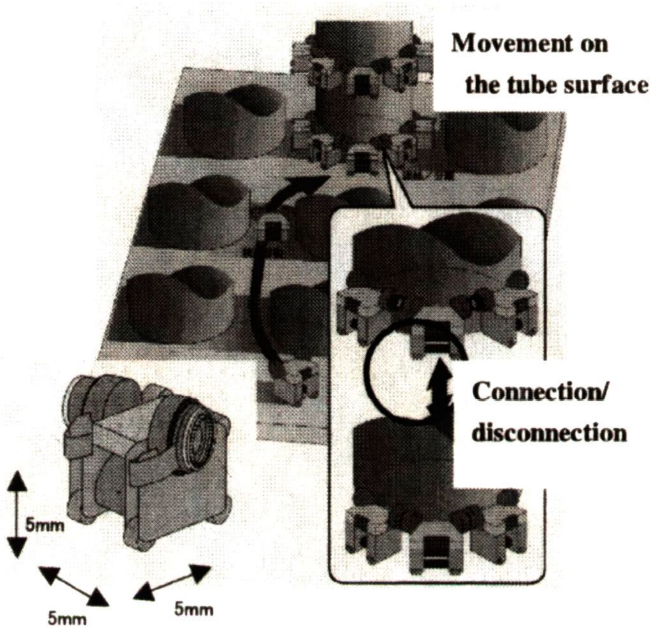


Fig.4. Schematic view of the system for inspecting on the outer surface of tubes.

Table 1. Reguirements of the microconnector.

Connection/Disconnection	Automatic
Connectable Distance	> 500 μm
Thickness	< 2 mm
Diameter	< 2.5 mm
Electric line	7
Current	500 mA (max. 150 mA/line)

tors having a large positioning margin and an automatic connection/disconnection function are necessary. The requirements for the microconnector are summarized in Table 1.

3.2.1. Concept and design:

The schematic configuration of the microconnector is shown in Fig. 5. In order to achieve automatic connection/disconnection, a large positioning margin is required. Thus, we arranged the terminals and tapered guides cylindrically. Furthermore, to generate rectification force, the guides of one side of the connector are concentric double rings, and the permanent magnet is installed in the center of connector. To decrease the load of the actuator, the terminals were coated with Au, and the contact force of the terminals was designed to be 0.5 mN, which is the minimum value for stable electrical contact between Au and Au.

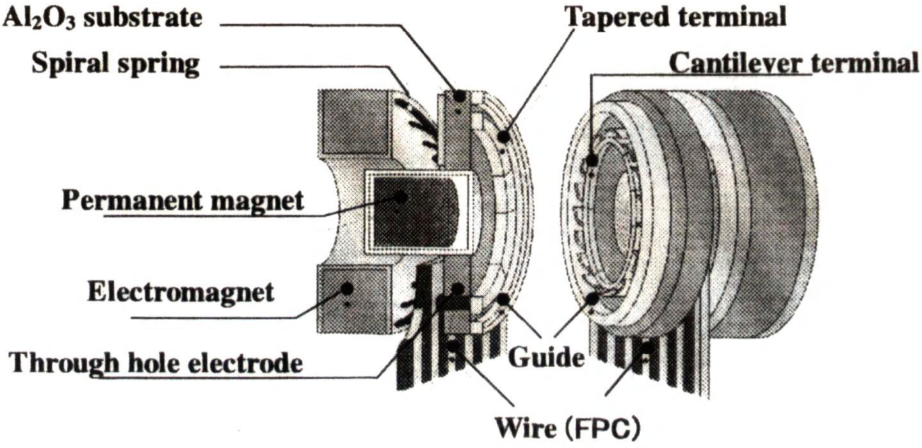


Fig.5. Schematic view of the microconnector.

3.2.2. Fabrication process of electrical terminals and guides:

We fabricated the terminals and guides using DXL and electroforming to achieve high accuracy and a high aspect ratio.

The cantilever terminals were fabricated using a one-layer sacrificial process, as shown in Fig. 6. The 3- µm-thick sputtered titanium (Ti) on the Al_20_3 substrate is the electroforming electrode and the sacrificial layer. The width of the cantilever terminal is 7 µm, and the height and the length of that is 80 µm

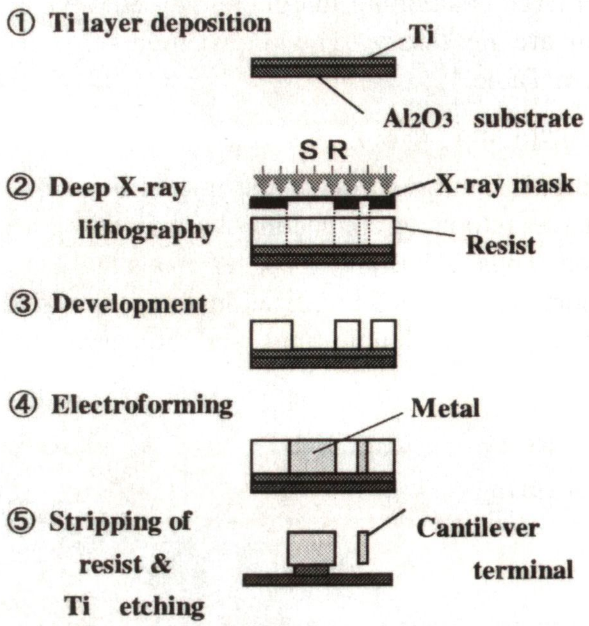


Fig.6. Flow of one-layer sacrificial process for cantilever terminals.

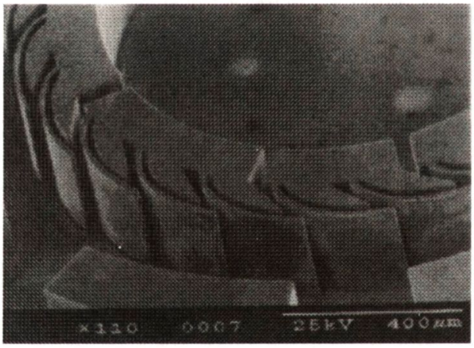


Fig.7. SEM image of the cantilever terminals.

and 250 μm, respectively. Therefore, when the Ti layer under the cantilever is removed by wet etching, that under the anchor area still remains. Fig. 7 shows the cantilever terminals and guides. A fabrication accuracy is less than ±0.5 μm was achieved.

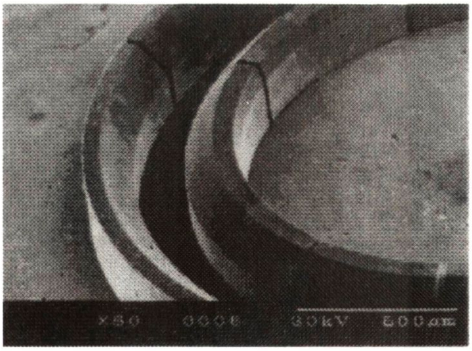


Fig.8. SEM image of the tapered terminals.

Tapered terminals and guides for smooth connection with the microconnectors were fabricated by micro-electrodischarge machining (μ -EDM) combined with a LIGA-like process. Fig. 8 shows the fabricated structures of tapered terminals and guides.

3.3.3. Electric properties of microconnector:

An electrical contact at each terminal of the microconnector was achieved. The connection resistance of the microconnector through the FPC is approximately 3.6 Ω/line. The breakdown voltage is 370 V(DC) at atmospheric pressure in the air. This is enough to drive the device mounted on the micromachine.

We demonstrated the automatic connection/disconnection of the microconnectors, when the gap is between 300 μm and 800 μm. The margin of the alignment angle during automatic connection/disconnection was achieved ±5 degree when the initial gap was 500 μm.

4. CONCLUSION

We also developed micro array type electron multiplier and microactuator for hard-disk-drive. I think one of the most important breakthrough point for industrialization of LIGA applications is decreasing the process cost, especially for manufacturing the metallic parts. We eager to solve that problem and make many LIGA applications industrially available.

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DETECTORS OF UV AND INFRARED RADIATION OBTAINED USING SILICON MICROMACHINING

Lech Dobrzański [1]

Technology of the surface silicon micromachining developed in ITME comprises fabrication of a porous silicon as a sacrificial layer. This is needed to suspend device over a cavity and thermally isolate sensing element from the heat sink. Two types of devices have been fabricated and characterised: a bolometer and a termopile. It has been demonstrated that detectivieties of devices are on the level of 10^{8}cmHz$^{1/2}$/W and in a case of a bolometer LF noise limits device performance. This devices have been described in detail in Refs. [1,2]. Detectors of the UV light on GaN are additionally presented.

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INTEGRATED INSTRUMENTS FOR TOTAL CHEMICAL ANALYSIS

Jan Dziuban[1]

Previous works on silicon micromachined devices started in the Institute of Microsystems Technology (ITM) of the Wrocław University of Technology (WUT) in late 80's, although some fundamental technological works on silicon anisotropic etching for three-dimensional structures fabrication were done in mid 70's. Our Institute was the first in Poland recognising a need of micromachined sensors and actuators investigations.

We have developed wide scope of the piezoresistive pressure sensors with single and double Wheatstone's bridge piezoresistors configuration. Some of them have been equipped in the unique „cut” piezoresistors.

First silicon rotating microturbines, gear-boxes and other movable micromachines ever developed in Poland, were developed by Silicon Micromechanics Group of ITM of WUT. In mid 90's The State Research Project on „Silicon Micromechanical Sensors” was founded. Our Group became a subsidiary of the Research Team headed by the Institute of Electron Technology of Warsaw. We were responsible for bonding and packaging methods.

Parallel to the mentioned above works we started in the mean time a new program on micro total analysis systems. In 1997, at Eurosensors XII in Warsaw, the integrated silicon-glass capillary column 15th meters long, fabricated on 3" wafer was presented. Afterward, the conception of an integrated gas analyser, elaborated in the close co-operation with EMAG - Katowice, has been presented. Own TCTs, sampling valves and MCM-like model of the integrated gas chromatograph have been developed and tested. Currently works on portable gas chromatograph are in progress under State Research Program "Mikrotas"

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In the lecture some of the most interesting past works will be shown. Newly developed components for analytical chemistry and microchemistry will be presented. A short sketch of recently discovered fast deep anisotropic etching of single silicon wafers and other materials will be presented. Samples of devices and short TV movie on our works will be shown.

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MICROSYSTEMS AND SENSORS IN THE ELECTRONIC DEPARTMENT OF MINING AND METALLURGY UNIVERSITY

T. Pisarkiewicz[1], S. Nowak[1] and P. Potempa[1]

Many measurements were performed investigating thin film semiconductor ozone sensors. Below one example of ozone sensor characteristics is shown.

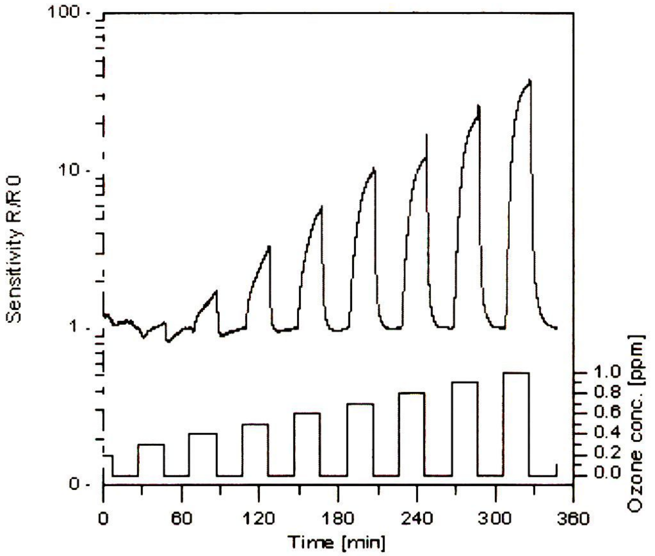

Fig. 1. Ozone sensor response to the variations of O_3 concentration for dry air. The sensing layer is a thin In_2O_3 film doped with 1at % of Fe.

As thin film gas-sensitive layers the following materials were used:
In_2O_3 (Fe)
In_2O_3 (Ce)

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Developed technology: DC and RF sputtering
Substrates: Corning 7059, alumina
Ozone conc. Variations: 0.01 ppm - 5 ppm.

Part of our activity was connected with analysis of gas sensor signals with the help of fuzzy logic.

Below a simple fuzzy model of the sensor is shown.

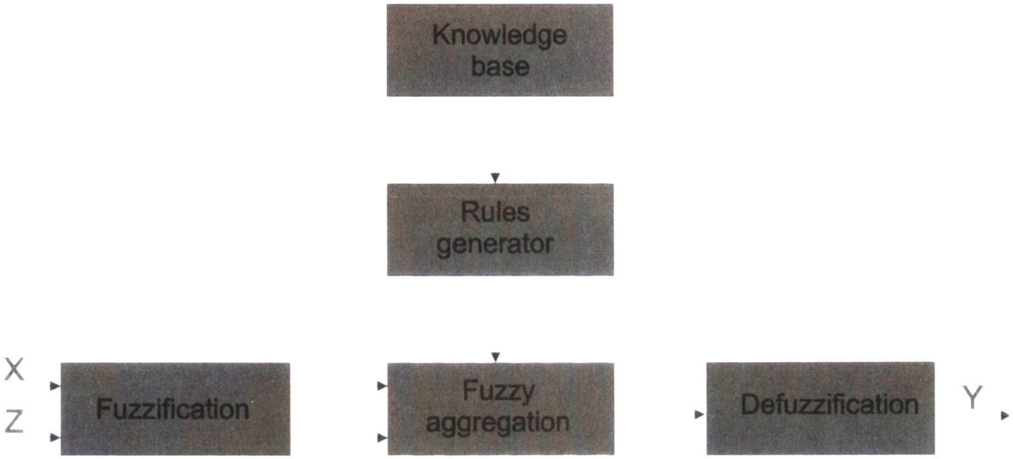


Fig. 2. **Application of fuzzy logic to gas sensor modelling.**

Developed fuzzy models:

- Mamdani model (linguistic variables in input and output)
- Takagi - Sugeno - Kang (*TSK*) model (output linguistic variables replaced with functions).

Learning of the model (membership functions, inference rules):

- Expert knowledge
- Genetic algorithms.

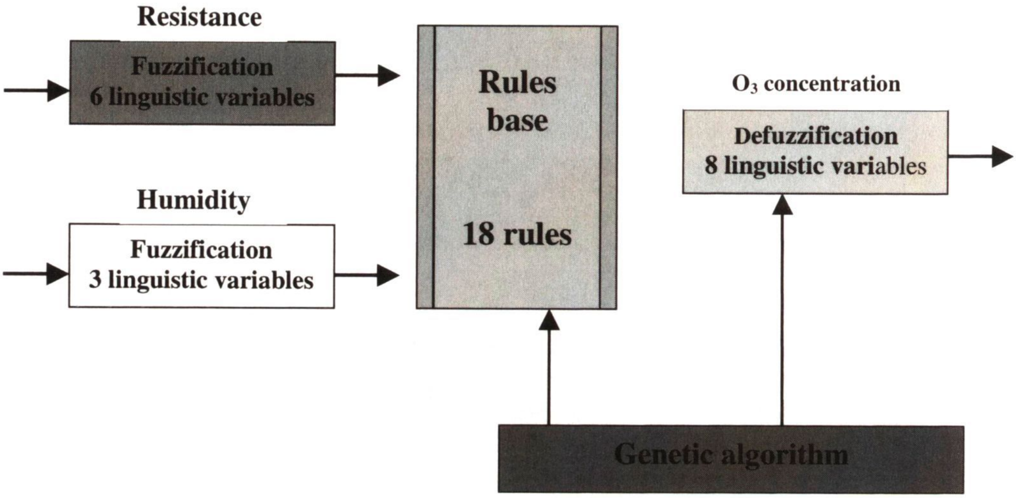
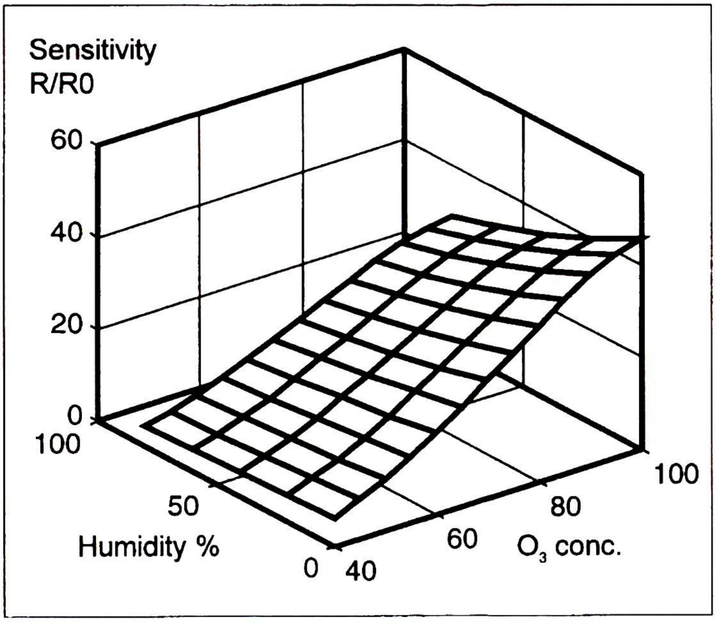


Fig. 3. Mamdani - type fuzzy model with the lecrning scheme.

The consequent of the interference rules and output membership function parameters were optimized.

a)



b)

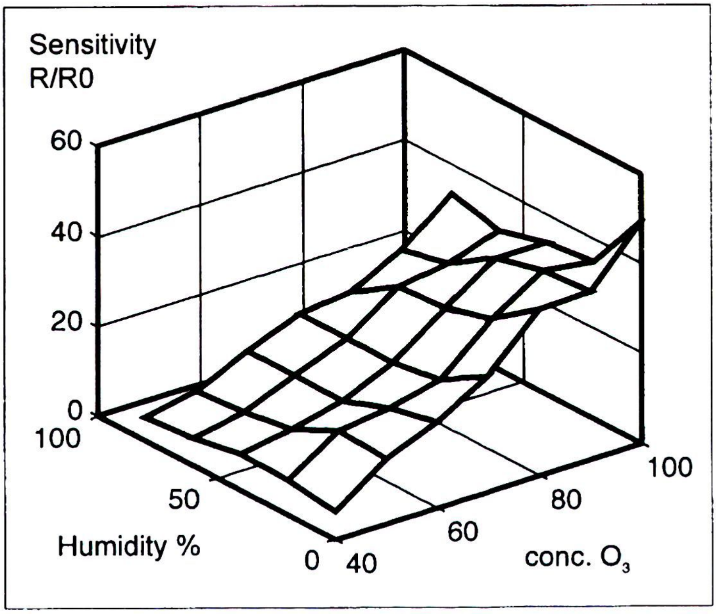


Fig. 4. Sensitivity of the ozone sensor vs. humidity and O_3 concentration (a.u.) - (a), variations and sensitivity approximated by the developed Mamdani model - (b).

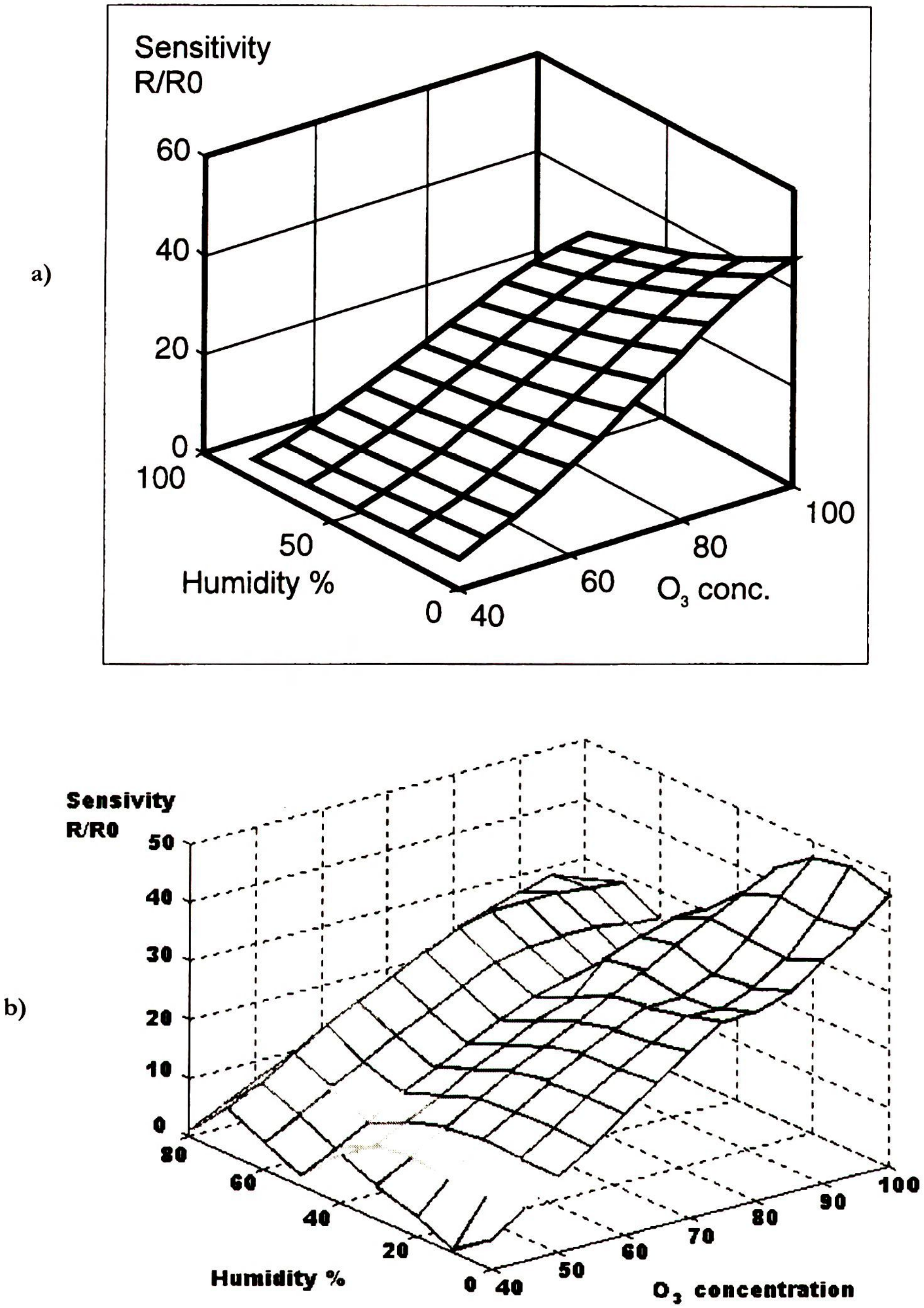


Fig. 5. Sensitivity of the ozone sensor vs. humidity and O_3 concentration (a.u.) - (a); variations and sensitivity approximated by the developed TSK model - (b).

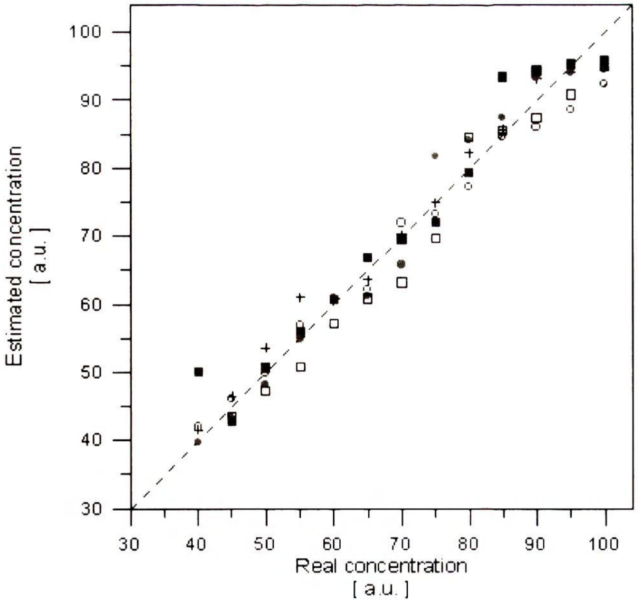


Fig. 6. Estimated vs. real concentration of ozone determined in the conditions of varying humidity by the Mamdani fuzzy model.

The models of the Mamdani type suffer from the poor extrapolation possibilities and hence more learning data uniformly distributed are needed. Model calculations with the help of genetic algorithms and *TSK* fuzzy sensor are in progress. However, the preliminary results indicate that the *TSK* model gives better approximation of the ozone sensor working in varying environmental conditions.

Recently developed rheotaxial growth and thermal oxidation technique (*RGTO*) enables fabrication of thin films with increased sensitivity to the gas atmosphere.

RGTO technique can be shortly described as follows:

- deposition of In - metal on a heated substrate (temp. exceeding melting point) by sputtering in argon atmosphere ⇒ discontinuous film, isolated droplets,
- oxidation of metal film in air at elevated temperature (450°C, 24 hrs), In_2O_3 oxide is formed ⇒ connections between grains are established.

For comparison of the properties of films deposited by different methods some In_2O_3 films were obtained by:

- RF sputtering of In target in Ar $+O_2$ atmosphere
- magnetron DC sputtering of In target in Ar $+O_2$.

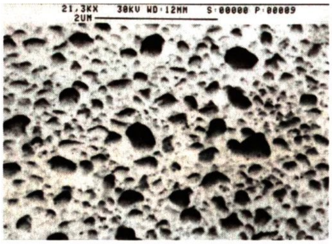
Surface morphology of the films deposited by *RGTO* technique varies during the deposition process as shown in SEM micrographs below.

SEM micrographs:

a)

metallic In surface

separate droplets with varying diameters



b)

RGTO In_2O_3

interconnected agglomerates

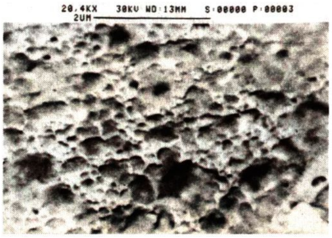


Fig. 7. SEM micrographs.

Variation of surface morphology can be also investigated by optical methods.

Due to intensive light scattering - measurements of optical transmittance and reflectance were performed in the hemispherical mode.

Spectrophotometer Perkin-Elmer Lambda 19 with integrating sphere was used.

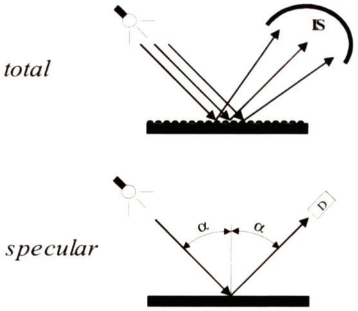
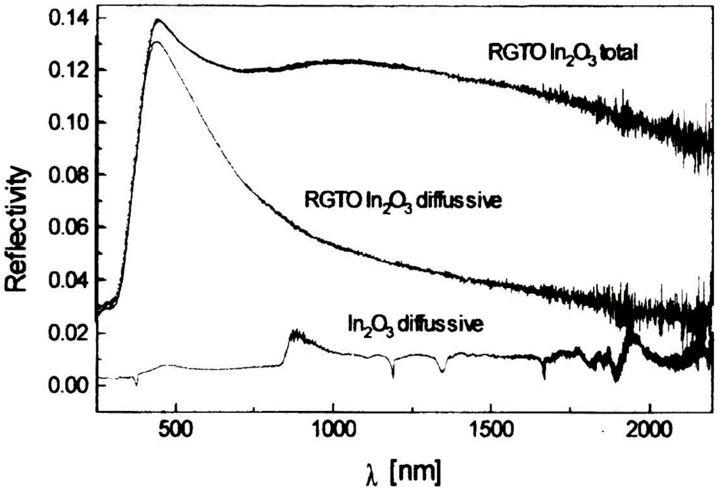


Fig. 8. Models of transmittance and reflectance measurements .

a)



b)

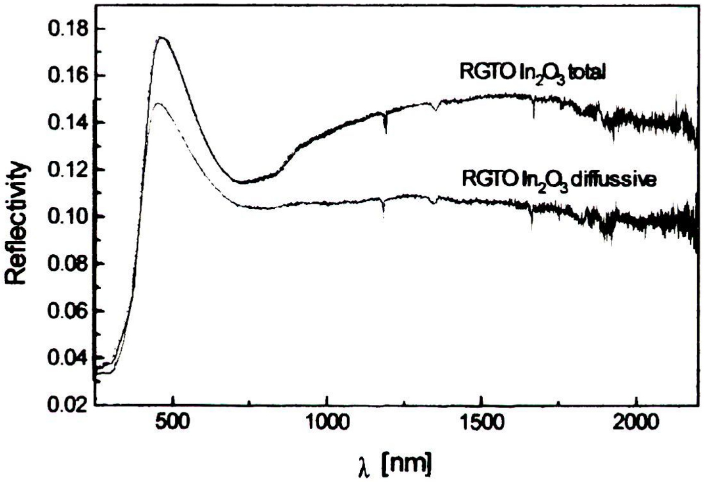


Fig. 9.Variations of the reflectivity for films deposited onto substrates kept at 156°C and room temperatures respectively are shown on figures below.

Model:

Θ - angle of incidence

σ - r.m.s. amplitude of surface roughness

$$1-\frac{T_{diff}}{T_{tot}} = exp\left\{-\left[\frac{4\pi\sigma\cos\ \Theta}{\lambda}\right]^2\right\}$$

Sensitivity to ozone was measured with varying O_3 concentration till ca 300 ppb.

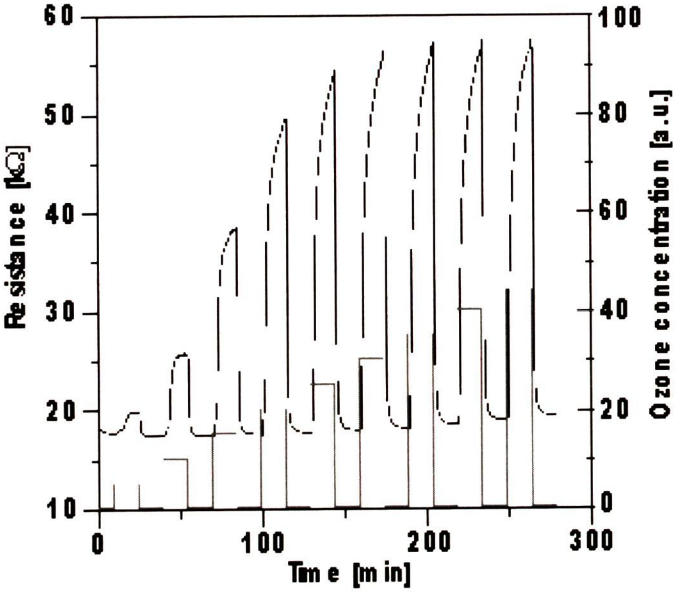


Fig. 10. Time variations of the ozon sensor resistance.

As compared to In_2O_3 films obtained by reactive sputtering, *RGTO* films exhibit better stability and shorter recovery times.

Many of the sensor structures were fabricated using the substrates manufactured by the low temperature cofired ceramics *(LTCC)* technology.

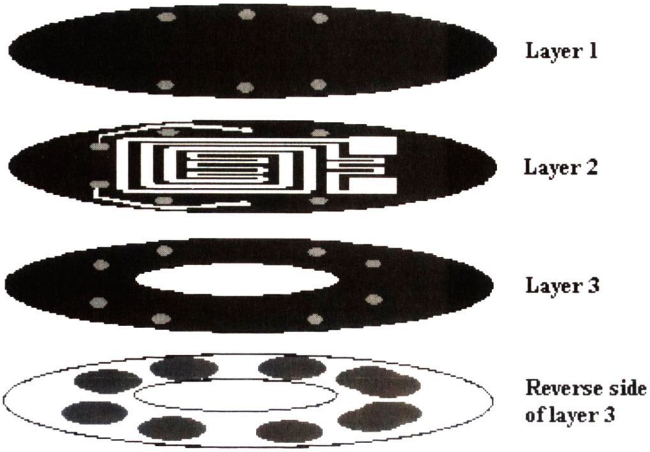


Fig. 11. Masks layouts for thin films deposition.

Specially developed fabrication procedure enabled obtaining of the ceramic structures with the upper surface suitable for deposition of thin films.

The surface of the upper layer of *LTCC* structure prepared in optimized conditions is shown on figure below (AFM micrograph).

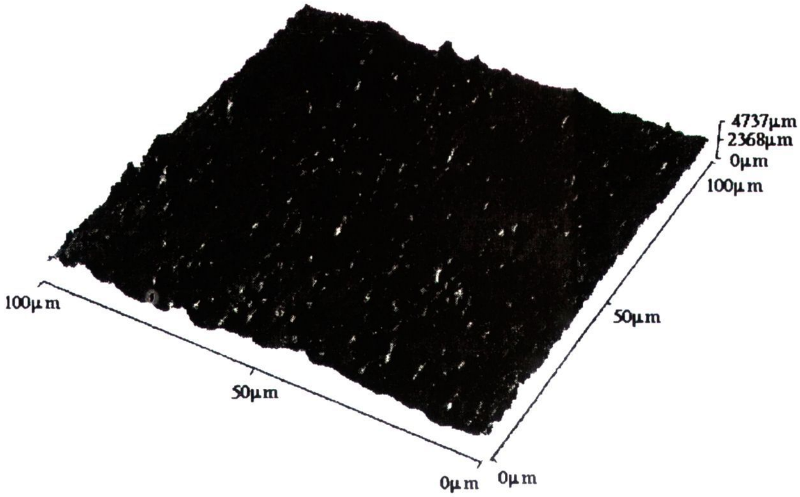


Fig.12. AFM microscope image of the upper layer of LTCC structure.

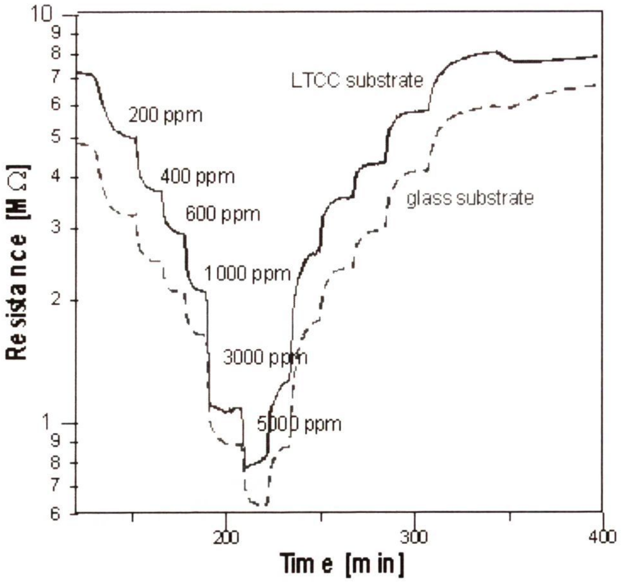


Fig. 13. The variations of sensor resistance with increasing and decreasing H_2 concentrations for the films deposited on both LTCC and Corning 7059 structures. The working temperature of the sensors was 350°C.

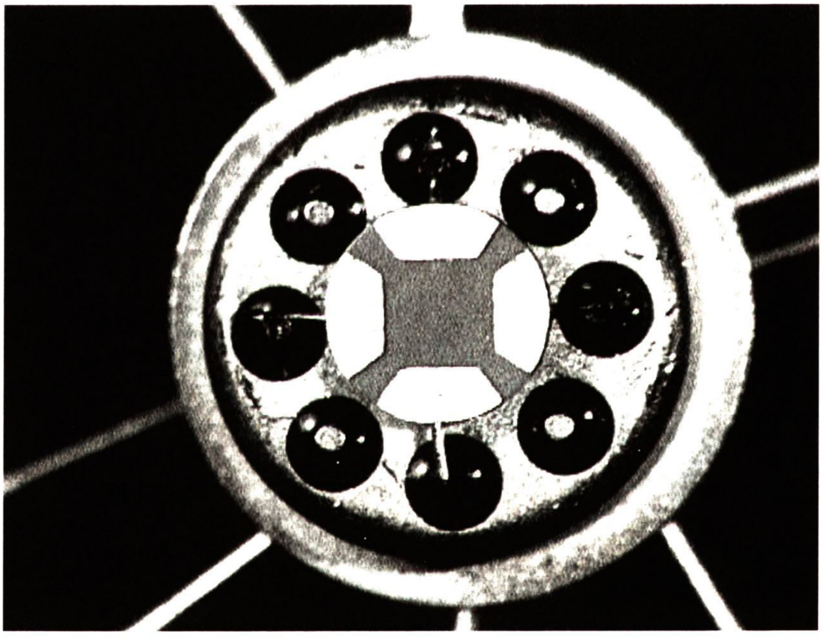


Fig. 14. The ready LTCC gas sensor in TO5 package.

Our recent activty is also directed onto fabrication of thin film gas sensors with substrates manufactured by micromachining. Typical design of the sensor is shown on the figure below.

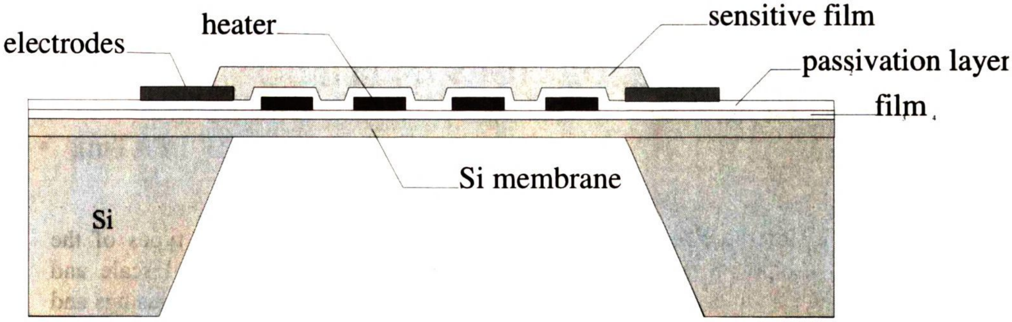


Fig. 15. Typical design of a gas sensor on substrate made by micromachining.

Recently we started also the manufacturing and investigation of solar cell structures based on indium -copper halcopyrites (*CIS*) heterostructures. Typical *CIS* solar cell structure is shown below.

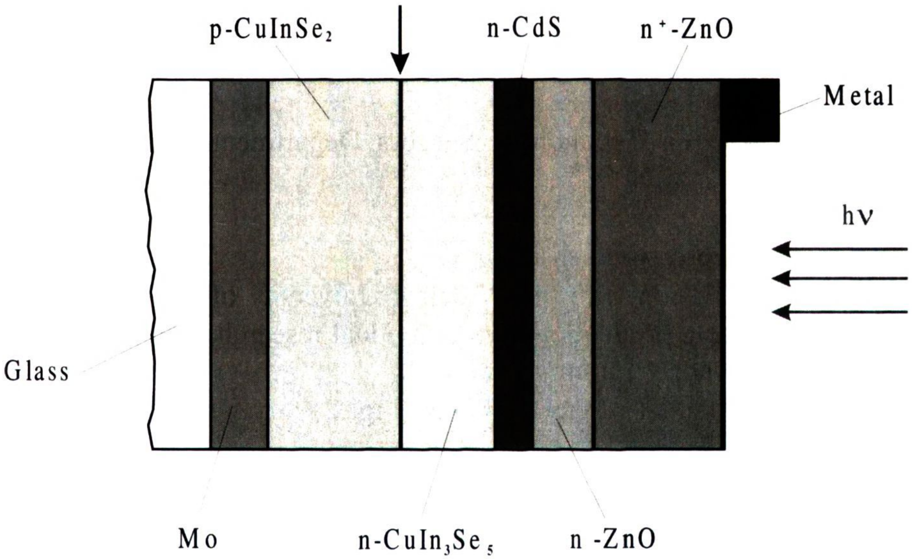


Fig. 16. A recently developed solar cell heterostructure.

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MODELLING, SIMULATION AND DESIGN OF MICROMECHANICAL DEVICES IN ITE

Jan M. Łysko [1]

R&D activity of the *ITE* Sensors Department is presented. Several types of the piezoresistive-type pressure sensors are already produced in the small scale and offered to the customers on the local market. Silicon structures' designs, housings and technology are still optimized to improve functional parameters of the devices. Other sensors are under research. Technological experiments and production are realized in cooperation with the *ITE* Technological Department. *PSFET* (Pressure Sensitive Field Effect Transistor) and *DPR* (Dew Point Detector) are both developed in cooperation with the Warsaw University of Technology. Capacitive and piezoresistive type acceleration sensors are the subject of the ITE individual research program, sponsored from the government founds. *ISE* (Ion Selective Electrodes) and m-*TAS* (Micro Total Analysis System) are the newly opened programs in the chemical sensor area.

FIELDS OF ACTIVITY

Institute of Electron Technology Sensors Department is involved in the following subjects :

- Piezoresistive pressure sensor -
    in cooperation with the Wrocław University of Technology
    small-scale production, two individual research projects (Fig.1 a, b)
- Piezoresistive acceleration sensor -
    one individual research project (Fig. 2)
- Capacitive acceleration sensor -
    one individual research project (Fig. 3 -5)
- ISFET - ion sensitive field effect transistor - (Fig. 6)
    in cooperation with the Polish Academy of Sciences (Fig.7)

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- PSFET - pressure sensitive field effect transistor -
  in cooperation with the Warsaw University of Technology (Fig.8)
- DPR - dew point detector -
- in cooperation with the Warsaw University of Technology
- ISE - ion selective electrodes -
- in cooperation with Polish Academy of Sciences and Warsaw University of Technology
- µmTAS - micro total analysis system
  in cooperation with the Warsaw University of Technology, Wrocław University of Technology and Polish Academy of Sciences
  multi-institution project sponsored by the government.

The following figures illustrate construction details, parameters and selected computer simulation results of the devices under research.

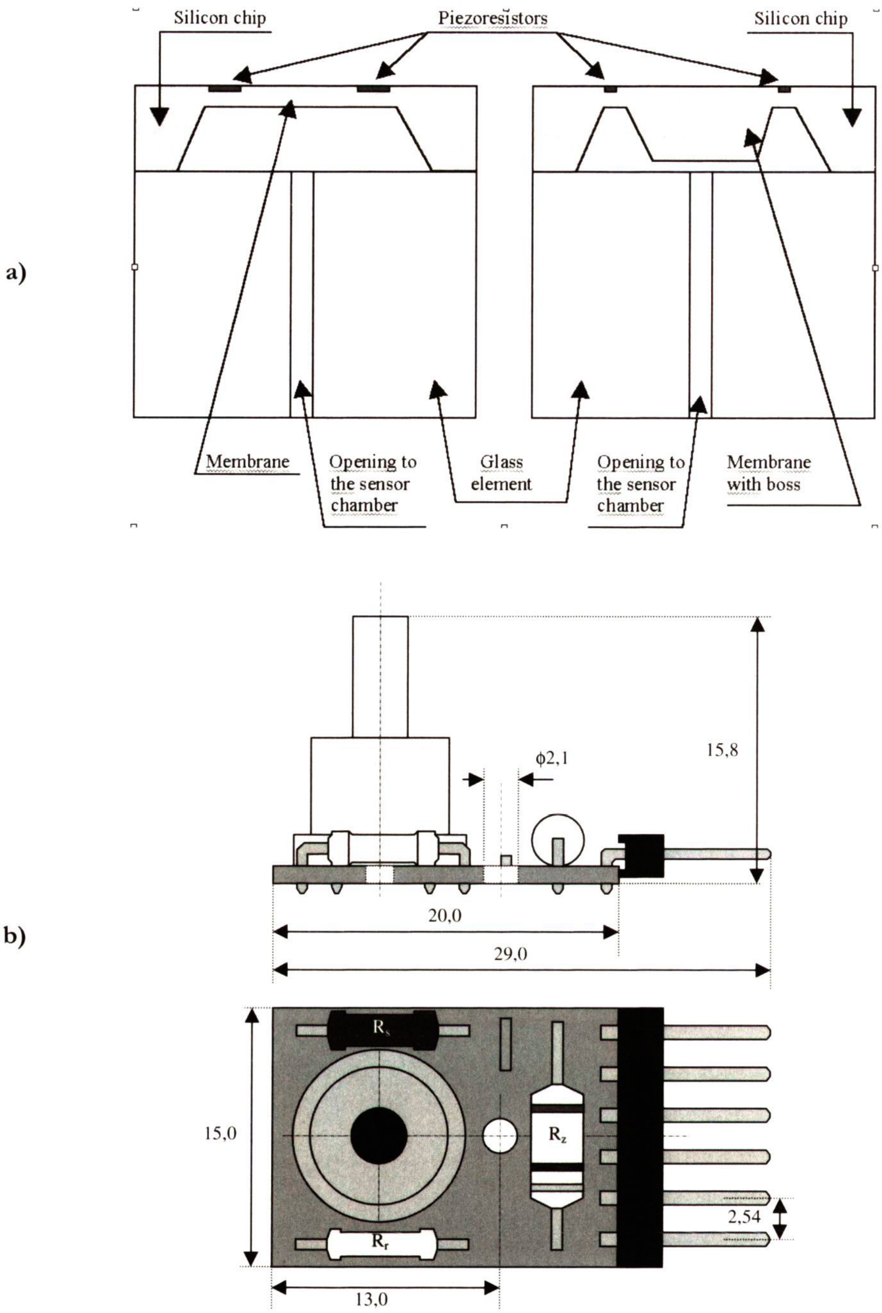


Fig. 1. Piezoresistive, silicon pressure sensor: a) schematic cross sections of the silicon-glass structures with the flat and bosset membranes, b) pressure sensor with the temperature compensation elements.

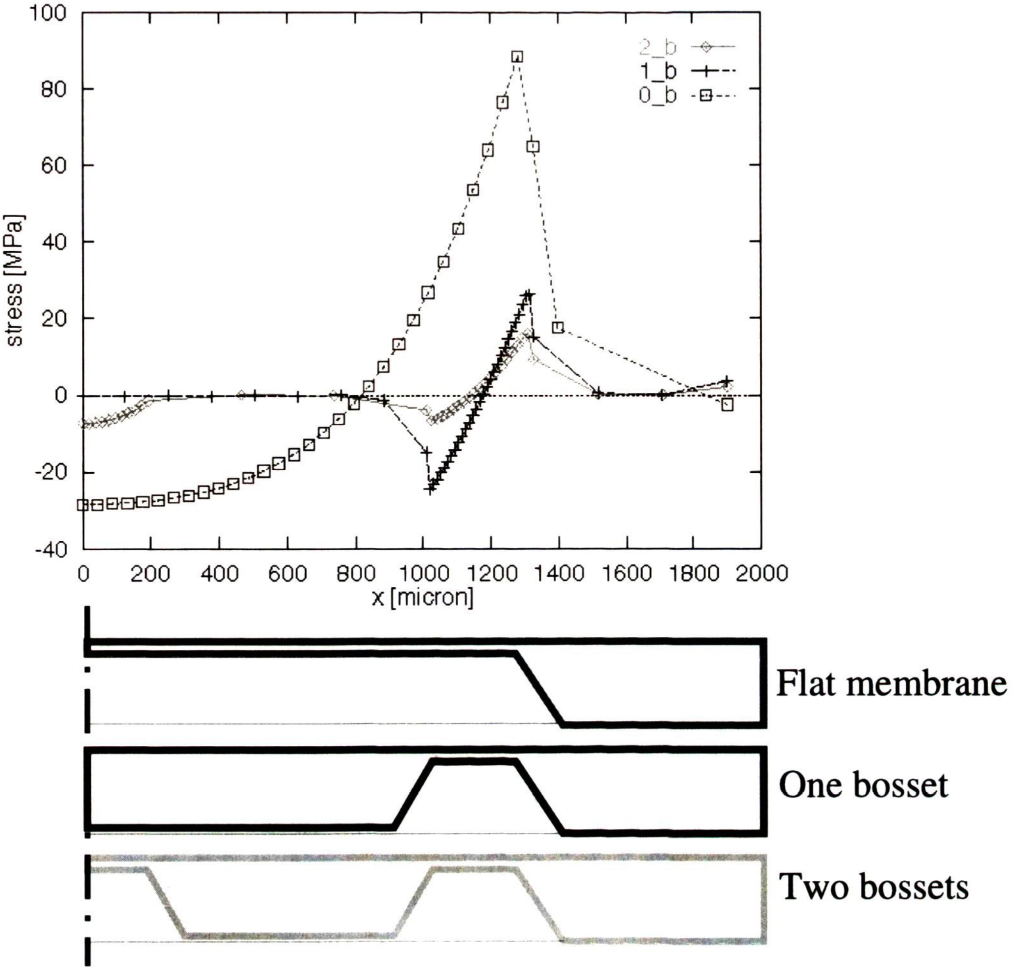
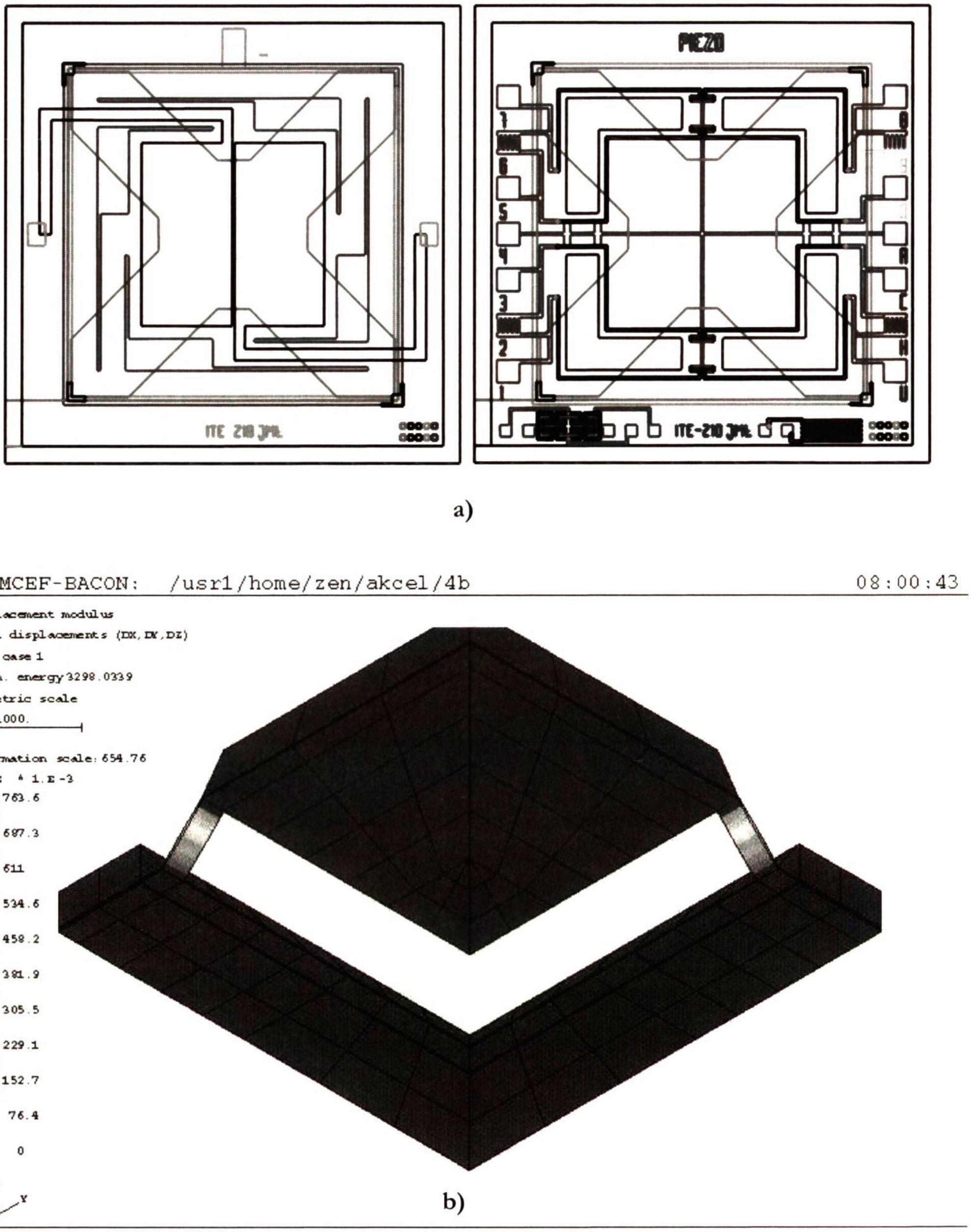


Fig. 2. Stress simulation results for the different piezoresistive pressure sensor membranes arrangement, SAMCEF® software.



```
SAMCEF-BACON:   /usr1/home/zen/akcel/4b                    08:00:43
Displacement modulus
Nodal displacements (DX,DY,DZ)
Load case 1
Poten. energy 3298.0339
Geometric scale
1000.
Deformation scale: 654.76
VALUE * 1.E -3
```

Fig. 3. Capacitive and piezoresistive acceleration sensors masks layouts - (a); simulation of the seismic mass deflection - SAMCEF® software - (b).

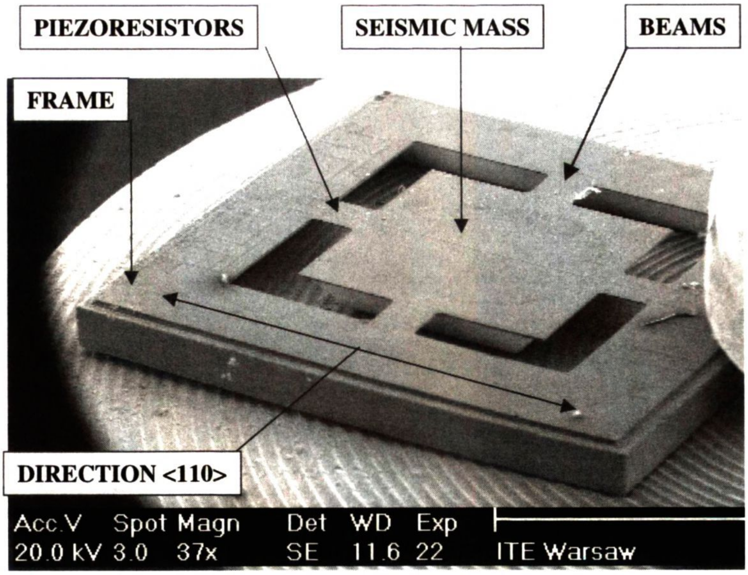


Fig. 4. SEM microphotograph of the silicon piezoresistive acceleration sensor chip.

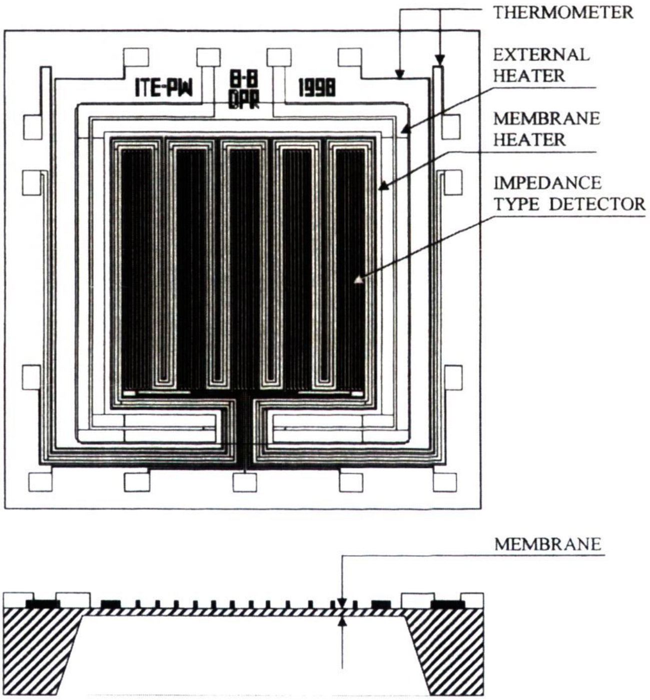


Fig. 5. Dew point detector masks layout and schematic cross section.

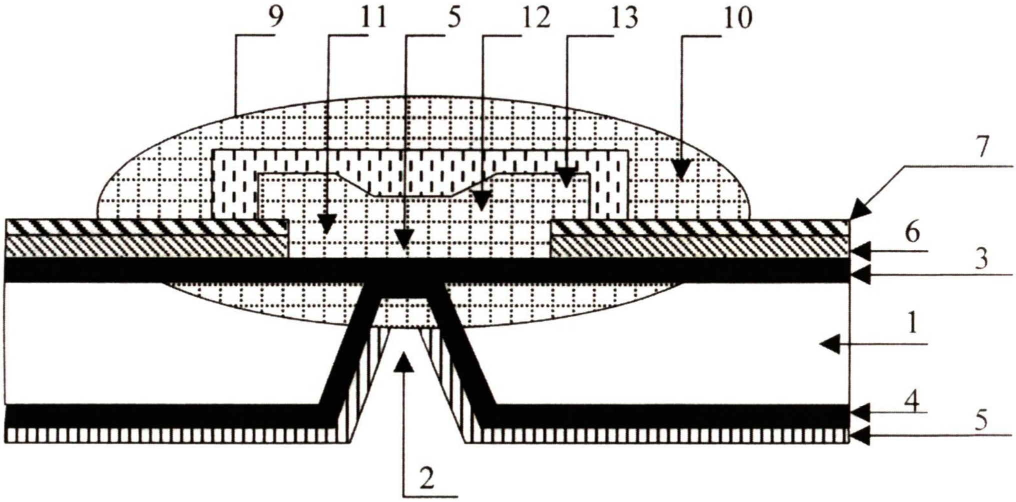


Fig. 6. Ion selective electrodes with beck side contact (BSC) for chemical sensing - schematic cross-section:

silicon substrate /1/
back side contact /2/
conductive, doped areas /3/ i /4/
aluminum layer /5/
silicon dioxide SiO_2 layer /6/
silicon nitride Si_3N_4 layer /7/
poliHEM layer /9/
ion selective membrane/10/
gold Au layer /11/
silver Ag layer /12/.

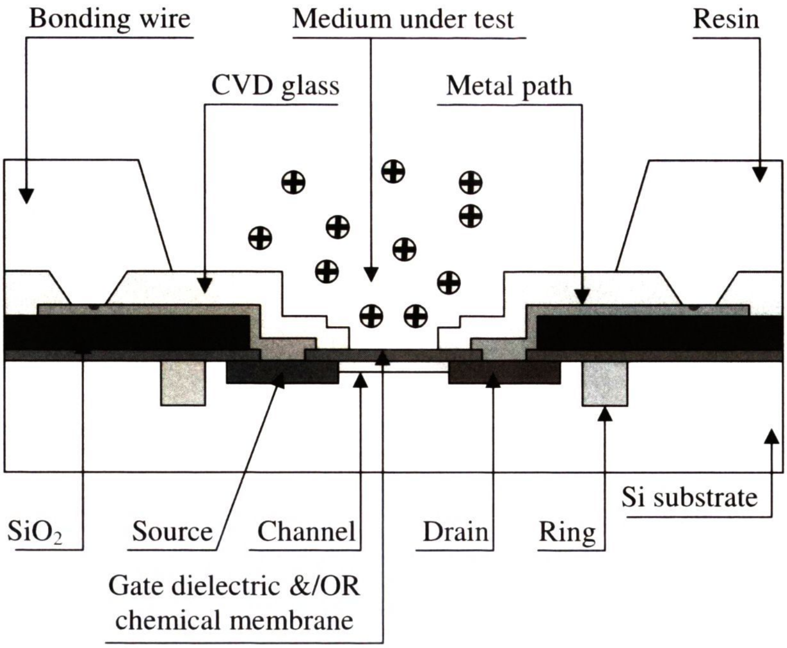


Fig. 7. ISFET - ion sensitive field effect transistor - cross-sectional view.

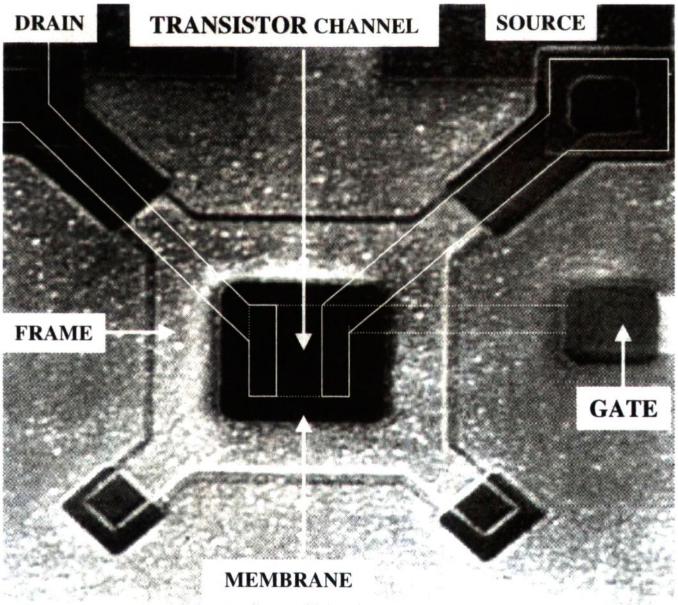


Fig. 8. SEM microphotograph of the PSFET- pressure sensitive field effect transistor silicon structure.