Micro Industry Equipments*

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Advanced states of art of MEMS (Micro Electro Mechanical Systems) technology have been applied to micro industry equipments. These are electrostatically levitated ring rotor gyroscope and micro energy source for self moving machines like robots, maintenance systems used in narrow spaces, components for multi-column electron beam lithography and multi-probe data storage, micro gas control systems, micro/nano mold, micro contactor and thermal RF relay for LSI testing and nano-instruments which performs high sensitivity and spatial resolution.

Key Words: Valve, Flow Control, Energy Conversion

1. Introduction

MEMS (Micro Electro Mechanical Systems) are fabricated by a silicon micromachining based on photolithography and have been applied to key components of industry equipments. This technology facilitates to integrate different components such as micro/nanostructures, sensors, circuits, actuators and energy sources. By combining different technologies sophisticated systems like electrostatically levitating rotational gyroscope, array microstructures like multi-column electron beam lithography system, extremely small nano-instruments could be realized.

In the following, there are three topics. The first topic is key parts of robots such as sensors for motion control, micro energy sources and distributed actuators. The second topic is the production equipments for high throughput electron beam lithography, precise gas control and molding. The third topic is testing and measurement equipments which take an advantage of small size.

2. Key Parts of Robots

2.1 Sensors for motion control

2.1.1 Electrostatically levitated spherical 3-axis accelerometer Spherical 3-axis accelerometer has been developed⁽¹⁾. As shown in Fig.1 1 mm diameter

spherical proof mass (ball) made of silicon is electrostatically levitated inside a shell with closed-loop control. The principle of the levitation is based on a capacitive displacement sensing and an electrostatic actuation. The three-dimensional patterning of the electrode was performed on the ball. Narrow ($4\ \mu\text{m}$) gap between the silicon ball and the electrodes was made by sacrificial etching of poly-Si through gas permeable porous shell utilizing XeF_2 gas.

2.1.2 Electrostatically levitated ring rotor gyroscope Silicon rotational gyroscope has been devel-

Fig. 1 Electrostatically levitated spherical 3-axis accelerometer

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Fig. 2 Principle, structure and picture of the electrostatically levitated ring rotor gyroscope

oped for the purpose of motion control and navigation (Fig. 2)⁽²⁾. A 4 mm diameter silicon ring which is electrostatically levitated by digital control using capacitive position sensing and electrostatic suspension were rotated at 12 000 rpm. The rotation is based on the principle of variable capacitance motor. A 5 μm radial gap between the ring rotor and electrode was formed using deep RIE (Reactive Ion Etching) and the rotor is held between two glasses which have electrodes (z , θ , ϕ control electrode in Fig. 2). The function as a high performance 2 axes gyroscope of which precision is $0.2 \text{ deg}/\sqrt{\text{h}}$ and 3 axes accelerometer was successfully demonstrated.

2.2 Micro energy sources

2.2.1 Micro gas turbine engine electrical power generator Small size but large output power and large capacity energy sources are required for moving machines such as robots and wheel chairs. For this purpose studies aimed at MEMS gas turbine electrical power generators have been made⁽³⁾. Silicon micro air turbine has been fabricated for the purpose of rotation test of the turbine and as a polarization modulator needed for surface infrared adsorption spectroscopy as well⁽⁴⁾. The structure was fabricated using the deep RIE and is shown in Fig. 3. An air bearing is used and the rotational speed of 40 000 rpm was achieved. Micro turbine blades were fabricated using refractory materials as Si_3N_4 (Fig. 4)⁽⁵⁾ and SiC ⁽⁶⁾ to be used

Fig. 3 Silicon micro air turbine

Fig. 4 Si_3N_4 micro turbine

for combusting gas turbine engine.

2.3 Distributed actuators

2.3.1 Maintenance system in narrow space (active catheters) Soft and flexible motion can be performed using distributed actuators. Multi-link active catheters which can be steered in blood vessel have been developed for minimal invasive diagnosis and therapy. Distributed shape memory alloy (SMA) coils are utilized for the actuation in multi-degrees of freedom.

The active catheter which has bending, twisting, extending and stiffness control functions is shown in Fig. 5⁽⁷⁾. The SMA coil and a stainless steel liner coil are connected by electroplating of nickel and acrylic resin. This novel method enables low cost batch assembly and small outer diameter (1.4 mm). Small diameter (0.5 mm) SMA active guide wire was also developed⁽⁸⁾.

Sensors used at the end of the active catheters

were developed to facilitate the navigation control of the catheter. One is a forward-looking ultrasound imager⁽⁹⁾ and the other is a three axes magnetic field sensor to detect the position and the direction of the catheter tip.

Fig. 5 Active catheter which can not only be bent but also twisted and extended

Fig. 6 Tactile display for blind people

2.3.2 Tactile display for blind people Two SMA actuators and a magnetic latch mechanism are arrayed to be used as a tactile display for blind people as shown in Fig. 6⁽¹⁰⁾. Because of the latch mechanism not only power dissipation and heat generation are reduced but also each data for the matrix can be written successively. The batch assembly using the electroplating was also applied to the construction of the tactile display.

3. Production Equipments

3.1 Multi-column electron beam lithography

Multi-column electron beam lithography system as shown in Fig. 7 is being developed for high throughput sub- $0.1\mu\text{m}$ LSI production. Components that are electron field emitter, electrostatic lens, glass with electrical feedthrough, monolithic XYZ stage have been developed as below. The system in Fig. 7 can be also applied to multi-probe data storage systems^{(11)–(13)} for non-contact

Fig. 7 Principle of multi-column electron beam lithography system

Fig. 8 Diamond micro-thermionic electron field emitter

recording and reading.

3.1.1 Electron field emitter Diamond micro-thermionic electron field emitter is shown in Fig. 8. Electron is emitted from the diamond apex fabricated on a diamond heater⁽¹⁴⁾. For the purpose of the field emitter carbon nano tubes (CNT) was grown at silicon tips as shown in Fig. 9⁽¹⁵⁾. After forming the silicon tips 4 nm Fe film was deposited for catalyst and CNT was grown by hot-filament CVD. High electric field applied by negative substrate bias voltage was necessary to enhance the growth of the CNT at the apex. The threshold voltage for electron field emission was reduced owing to the CNT (Fig. 10).

Fig. 9 Fabrication process and photograph of carbon nano tube electron field emitter grown at a silicon tip

Fig. 10 Electron emission characteristics of CNT/Si tip and Si tip

3.1.2 Electrostatic lens Array of field emitter with integrated electrostatic lens has been developed for electron extraction and focusing⁽¹⁶⁾. The structure and the emission characteristics are shown in Fig. 11. The tip-gate leakage current caused after 1 hour operation because of

Fig. 11 Electron field emitter with electrostatic lens

Fig. 12 Pyrex glass with electrical feedthrough

the insufficient insulation of the oxide layer between the emitter and the silicon gate. Simulation assuming a small emitter tip showed focused spot size of approximately 40 nm.

3.1.3 Glass with electrical feedthrough High density feedthrough made in a glass provides electrical interconnections to the backside of the glass. The integrated circuit chips and the MEMS devices can be fabricated separately because both can be electrically connected using the feedthrough. The fabrication method of the feedthrough in the glass is shown in Fig. 12⁽¹⁷⁾. Holes are made in a glass by femtosecond laser drilling and the holes are filled by electroplated copper. The leveling (polishing) process to remove the over-plated copper are eliminated by the following through-hole auto-filling

technique. The end point of the electroplating is detected electrically using the metal on the glass and the electroplating is carried out using a bipolar pulse current for alternative dissolving and plating of copper.

Deep RIE is needed to make many through-holes simultaneously on a large glass wafer. However the etching rate of the glass RIE is small (0.5 $\mu\text{m}/\text{min}$). Large diameter wafers must be thick otherwise they are broken during handling. The process to make electrical feedthrough on a large diameter glass wafer was developed as shown in Fig. 13⁽¹⁸⁾. After making holes in a glass by deep RIE (a), the holes are filled with an electroplated metal (c). The glass is bonded to the handling wafer which has grooves and Ge on the surface (d). The glass is ground and polished until the feedthrough metal is exposed (e). After a

Fig. 13 Feedthrough process on a large glass wafer

Fig. 14 Detaching from a handling wafer by etching Ge at the surface of the handling wafer (A: before etching, B: during etching, C: after etching)

device is anodically bonded (f), the handling wafer is delaminated by etching the Ge at the interface. Hot (80°C) H_2O_2 is used to etch the Ge. Owing to the grooves made on the handling wafer the Ge etchant can penetrate deeply and hence the detaching could be carried out quickly as shown in Fig. 14.

3.1.4 Monolithic XY stage Monolithic XY stage is needed for the wafer motion in Fig. 7. A new planer fabrication method of multi-layer piezoelectric actuator was developed. Grooves are made in a PZT (lead zirconium titanate) plate by dicing and they are filled with electroplated nickel. Next the metal electrodes are connected alternatively. The XY-stage shown in Fig. 15 (bottom) has the planer multiplayer piezoelectric actuators and displacement enlarging mechanisms in a PZT plate⁽¹⁹⁾. The mechanisms are fabricated by cutting the PZT plate using femtosecond laser. The monolithic stage which have 6 degrees of freedom ($X, Y, Z, \theta, \varphi, \psi$) was fabricated by making the grooves on the both side of the PZT plate. The actuator can bend like a bimorph actuator and lift up the stage for Z motion.

Fig. 15 Multi-layer piezoelectric actuator by planer fabrication (top), monolithic XY stage (middle) and the principle of the X motion (bottom)

3.2 Precise gas control

3.2.1 Anti-corrosive integrated mass-flow controller Integrated mass-flow controller which has valve and thermal mass-flow sensor and enables fine gas control has been developed⁽²⁰⁾. Figure 16 shows an anti-corrosive integrated mass flow controller made of stainless steel and AlN⁽²¹⁾. The operation as the anti-corrosive integrated mass-flow controller in chlorine gas was successfully demonstrated. Bakable pneumatic micro valve for reactive gases⁽²²⁾ and capacitive vacuum pressure sensors which have thin diaphragm and vacuum cavity⁽²³⁾ were also developed.

3.3 Micro/nano molding

3.3.1 SiC microstructures for glass press molding Silicon carbide (SiC) microstructure can be used as a mold to form glass parts by pressing. This takes advantages of the hardness and heat-resistance of the SiC. The deep reactive ion etching of the SiC can be carried out using O_2 and SF_6 as etching gas⁽²⁴⁾. The SiC microstructures can be also fabricated by SiC CVD on a micromachined silicon wafer as shown in Fig. 17⁽²⁵⁾. The SiC surface is ground and bonded to a SiC ceramic plate by reaction bonding using a metal thin film.

3.3.2 Nano-imprint lithography using diamond mold Recording media in the shape of dots is called patterned media. This can minimize the interaction between bits. For the fabrication diamond mold for imprint

Fig. 16 Anti-corrosive integrated mass-flow controller

Fig. 17 Process and photograph of SiC microstructure for glass press molding

Fig. 18 The process of nano-imprint lithography

lithography has been developed to transfer the dot pattern onto the recording media⁽²⁶⁾. The fabrication process is shown in Fig. 18. Porous alumina which has periodic nanostructure is made by anodizing an aluminum plate. The porous alumina shown in Fig. 19 (a) and (b) is used as

Fig. 19 Porous alumina (a) (b), diamond mold fabricated by FAB using the porous alumina as a mask (c) and resist pattern made by the nano-imprint lithography using the diamond mold

Fig. 20 Contactor for wafer probing

a stencil mask to etch a diamond thin film using fast atom beam (FAB). Accelerated oxygen atom makes holes in the diamond film (Fig. 19 (c)). On the contrary to the ion, the atom has not electric charge and therefore the beam is not deflected by the surface charge. The diamond mold is pressed to the resist surface for molding as shown in Fig. 19 (d). By etch back method using the RIE the resist pattern can be transferred to the underling media material.

4. Testing and Measurement Equipments

4.1 LSI testing

4.1.1 Micro contactor for wafer probing

Micromachined contactor for wafer probing is shown in Fig. 20⁽²⁷⁾. The electrical feedthrough made by the deep RIE and nickel electroplating in the glass shown in Figs. 12–14 plays important roles in the contactor. The fabrication process and the photograph of the micro contactor are shown in Fig. 21. The silicon beams were fabricated by non-planer lithography using splay coating of resist and a large focus depth projection exposure system (UX-2000 Ushio Inc.). The silicon is etched out selectively leaving the p^+ layer after anodic bonding to the Pyrex glass.

4.1.2 Thermal RF relay Small size relays for high frequency operation are required. Figure 22 shows

Fig. 21 The fabrication process and the photograph of the micro contactor

a radio frequency (RF) relay which uses a thermal bimetal actuator for making contact to micro-springs⁽²⁸⁾. Owing to the multi micro-spring contact low on-resistance and high reliability (more than 10^7 cycles) were achieved. The micro-springs have electrical connections to the back-side of the glass using the electrical feedthrough shown in Fig. 12, which results in a good high frequency response up to 10 GHz and excellent reliability due to the hermetic sealing.

4.2 Nano instruments

4.2.1 Capacitive AFM and NSOM probe

MEMS plays important roles to make probes for scanning probe microscope (SPM). Figure 23 shows a probe for simultaneous measurement of atomic force microscope (AFM) and near field scanning optical microscope (NSOM)⁽²⁹⁾. The deflection of a thin silicon cantilever is capacitively detected because a distortion free thin silicon cantilever is made in parallel to the electrode on the glass with a narrow (1 μm) gap. A small diameter aperture is fabricated at the tip of the protrusion made at the end of the silicon cantilever. The aperture size

Fig. 22 Thermal RF relay

can be controlled down to 20 nm. Owing to the suitable aperture shape large light intensity of the near field is performed. The AFM and NSOM image can be obtained simultaneously using the probe as shown in Fig. 23 (c) and (d).

4.2.2 Evaluation of hydrogen storage capacity of carbon nano tube by resonating thin cantilever
Thin silicon beams can be used as highly sensitive resonating sensors. Reduced energy dissipation and hence high Q (quality factor) more than 200 000 was obtained in vacuum after removing surface natural oxide by heating in ultra high vacuum (UHV)⁽³⁰⁾.

The thin silicon cantilever was applied to measure the hydrogen storage capacity of a carbon nano tube⁽³¹⁾. The carbon nano tube have been attracted attentions for the application of reversible hydrogen storage for polymer electrolyte fuel cell. Figure 24 shows the carbon nano tube bundle attached to the end of a 170 nm thick silicon cantilever. The frequency changes of the cantilever after loading the carbon nano tube and after hydrogen adsorption are also shown in Fig. 24. Measured hydrogen storage capacity of 6wt% against the carbon nano tube weight was obtained from the experimental results.

5. Conclusions

Micro-nano structures and electromechanical systems

Fig. 23 Capacitive AFM and NSOM probe, (a) Probe, (b) Aperture (50 nm), (c) AFM image (5 μm×5 μm) and (d) NSOM image (5 μm×5 μm)

have been studied based on bulk micromachining. Key parts of robots, production equipments and measurement equipments are described. Sophisticated MEMS such as electrostatic levitation can be high performance sensors for navigation systems. High density electrical feedthrough in glass plays important roles for array MEMS as multi-column electron beam lithography systems. The high density electrical feedthrough in glass can separate IC chip from array MEMS devices and therefore IC fabricated in standardized method can be applied for controlling MEMS. Nanometric structures could be used for not only electron field emitter but also sensors which performs high sensitivity and spatial resolution.

Fig. 24 Carbon nano tube bundle attached on a silicon cantilever and the frequency changes of the cantilever after loading the carbon nano tube and after hydrogen adsorption. The hydrogen storage capacity measured is 6wt%

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