Micro/nano electro mechanical systems for practical applications

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Abstract. Silicon MEMS as electrostatically levitated rotational gyroscope, 2D optical scanner and wafer level packaged devices as integrated capacitive pressure sensor and MEMS switch are described. MEMS which use non-silicon materials as diamond, PZT, conductive polymer, CNT (carbon nano tube), LTCC with electrical feedthrough, SiC (silicon carbide) and LiNbO3 for multi-probe data storage, multi-column electron beam lithography system, probe card for wafer-level burn-in test, mould for glass press moulding and SAW wireless passive sensor respectively are also described.

Keywords: MEMS, gyroscope, packaging, switch, data storage.

1. Introduction
An extended IC fabrication technology based on deep etching, anodic bonding and other advanced process technologies is used to produce value added MEMS (Micro Electro Mechanical Systems) and NEMS (Nano Electro Mechanical Systems) which have multi-functions. Examples of application oriented MEMS developed by open collaboration with industry will be described below.

2. Silicon MEMS

2.1. Electrostatically levitated rotational gyroscope
Silicon rotational gyroscopes have been developed for the purpose of motion control and navigation [1]. The principle and the photograph are shown in figure 1. A 1.5 mm diameter silicon ring which is electrostatically levitated by digital control using capacitive position sensing and electrostatic actuation is rotated at 74,000 rpm. The rotation is based on the principle of a variable capacitance motor. A 5μm radial gap between the ring rotor and stator electrodes is formed using deep RIE (Reactive Ion Etching) of a silicon wafer. The silicon is anodically bonded on both sides to specimens which have electrodes. The chip is packaged in a vacuum cavity to prevent a viscous dumping. This inertia measurement system (Tokimec Inc. MESAG (Micro Electrostatically Suspended Accelerometer Gyro)) can measure two axes rotation and three axes acceleration simultaneously with high precision (sensitivity 0.01 deg/s and 0.2mG, respectively).
Figure 1. Electrostatically levitated rotational gyroscope: a) structure, b) photographs of chip and inertia measurement system.

2.2. Capacitive silicon microphone
Capacitive silicon microphones were developed in the NHK research center [2] and has been produced by Panasonic Co. Ltd. The structure and an example of its application in TV programmes are shown in figure 2. The microphone is composed of a silicon membrane and a back plate and the motion of the membrane by sound is capacitively detected. This silicon microphone can be used even in humid environments.

Figure 2. Capacitive silicon microphone and its application.

2.3. Two dimensional optical scanner
Electromagnetic 2D (two-dimensional) optical scanner as shown in figure 3a was developed [3]. Mirror is deflected electromagnetically using planar coils on a silicon gimbal structure and external permanent magnets. The scanner (Nippon Signal Co. Ltd., ECO Scan) has been applied to a 3D imaging system by measuring the distance to the object using time-of-flight of laser light as shown in figure 3b.

Figure 3. 2D optical scanner and its application to a time-of-flight 3D imaging system: a) 2D optical scanner, b) Time-of-flight 3D imaging system.
2.4. Integrated capacitive pressure sensor

The fabrication process of the integrated capacitive pressure sensor [4] is shown in figure 4. The integrated capacitive pressure sensor has been produced in JTECT Inc. and used for low pressure measurement. The silicon is used not only for a capacitive diaphragm pressure sensor and a CMOS capacitance detection circuit, but also as a package. Packaged chip-size MEMS are fabricated by anodic bonding of a silicon wafer and a glass wafer and dicing the bonded wafer to chips. This process called wafer level packaging is effective for the MEMS because it makes batch assembly possible and hence assembly machines can be eliminated [5]. The method has advantages of reduced test cost, small chip-size packaging and high reliability. Electrical feedthrough from the glass hole plays an important role in the wafer level packaging.

![Figure 4. Structure and fabrication process of integrated capacitive pressure sensor by wafer level packaging.](image)

2.5. Capacitive vacuum sensor

Vacuum cavity can be made by putting a non-volatile getter which absorbs oxygen gas generated during the anodic bonding [6]. Capacitive vacuum sensors which have thin diaphragms and reference vacuum cavity with the getter in it (figure 5) are wafer level packaged and have been produced by Canon Anelva Corp. [7].

![Figure 5. Capacitive vacuum sensor.](image)
2.6. MEMS switch
MEMS switch which uses a thermal bimetal actuator for making electrical contact was developed [8] (figure 6). The electrical connections are made to the backside using the electrical feedthrough in a glass. The wafer level packaging results in not only low cost fabrication but also excellent reliability because the contact surface is kept contamination-free owing to the hermetic sealing. Operation more than $10^7$ cycles and high frequency response up to 20 GHz were achieved. This switch has been produced and used for latest high speed LSI tester by Advantest Inc. [9].

![Figure 6. MEMS switch.](image)

3. MEMS with non-silicon materials

3.1. Multiprobe data storage (PZT, diamond and polyaniline)
Parallel data recording and reading can be made using a multiprobe data storage system as shown in figure 7 (left) [10]. Since electrical interconnection from the probe array to the control IC chip is needed, high density electrical feedthrough in a glass (figure 7 (right)) was developed for the purpose [11].

![Figure 7. Concept of multiprobe data storage (left) and electrical feedthrough in Pyrex glass (right).](image)

![Figure 8. Monolithic PZT stage, photograph of monolithic PZT stage (left) and feedback control system (right).](image)
The stage in figure 7 has to move in X-Y direction to cover the area determined by the probe pitch. A monolithic XYZ stage was fabricated on a PZT (lead zirconium titanate) ceramic plate (figure 8). Multi-layer piezoelectric actuators were fabricated on both sides of the PZT by dicing and metal filling. The stage motion could be controlled precisely with a feedback using capacitive position sensor as shown in figure 8 (right) [12].

Electrical recording to a ferroelectric recording media (LiTaO₃) using a diamond multiprobe system was developed. The fabrication process of the diamond probes, hot filament diamond CVD and diamond probes with an example of ferroelectric recording are shown in figure 9 [13].

Electrical recording using the microprobe array on a conductive polymer (doped polyaniline) film has been also studied for the multiprobe data storage as shown in figure 10 [14]. A conductive polymer deposited on a conductive substrate was used as a patterned media with 30nm pitch which corresponds to 0.7 Tbit/inch². A +3V substrate voltage changes the recording media from conductive to nonconductive, on the other hand a -3V changes it vice versa reversibly. The conductance of the recording media was decreased more than ten times. The conductance modification is made in the atmosphere and the mechanism of the rewritable recording is supposed that the polymer film becomes conductive and nonconductive by electrochemical reduction and oxidation, respectively, as shown in figure 11 [15].

The fabrication process of the patterned media is shown in figure 12 [14]. The microphase-separation of polystyrene (PS)-block-polymethylmethacrylate (PMMA) was used to make a perpendicular-oriented nano-structure. Nano-holes made by removing the PMMA were filled by polyaniline.
3.2. Massive parallel electron beam lithography (carbon nano tube)
Electron field emitter array with electrostatic focusing lens has been developed for the purpose of high throughput multi-column electron beam lithography system [16]. A CNT (Carbon Nano Tube) was applied to the electron field emitter. The CNT was grown selectively at an apex of catalytic nickel by negatively biasing the substrate in a hot filament CVD system [17]. The CNT was also grown at the apex by remaining the catalytic nickel only at the apex by annealing after nickel deposition as shown in figure 13 [18]. Low threshold voltage for electron field emission and small emitter size for fine focusing were achieved owing to the essential feature of the CNT. Hydrogen coverage on the CNT enhanced the emission and reduced the noise of the emission current [19].

3.3. Probe card for wafer-level burn-in test (low thermal expansion coefficient LTCC)
Electrical feedthroughs can be made in LTCC (Low Temperature Co-fired Ceramics) [19]. As shown in figure 14 (left), the through holes are made by puncturing the soft green sheet and the holes are filled with a silver or a gold paste. The sheet is sintered to make a ceramic and the lateral dimension can be controlled by sintering under pressure. This LTCC wafer can be anodically bonded to a silicon wafer. A multilayered ceramic wafer is fabricated by laminating the green sheets before
sintering and the cross sectional photograph of the laminated LTCC with electrical feedthrough is shown in figure 14 (center). The thermal expansion of the LTCC is matched with silicon, as shown in figure 9 (right).

The LTCC with the electrical feedthrough was applied to a MEMS probe card [20]. The fabrication process and a photograph are shown in figure 15. Nickel probes are made by electroplating nickel into a silicon mold and then soldered to the LTCC wafer with AuSn. Finally the silicon mold is etched out. The probe card has similar thermal expansion with silicon, which makes wafer-level burn-in test (reliability test at elevated temperature on a wafer) possible.

Figure 13. Carbon nano tube electron field emitter.

Figure 14. LTCC with electrical feedthrough. Fabrication process (left), cross-sectional photograph (center) and thermal expansion of silicon and LTCC (right).
3.4. SiC microstructure for glass press moulding (SiC)

SiC (silicon carbide) microstructure can be used as a mold to form glass parts by pressing. This takes advantages of the hardness of the SiC at high temperature. The fabrication process is shown in figure 16a [21]. The SiC was deposited on a micromachined silicon wafer by CVD. The SiC surface is ground and bonded to a SiC ceramic plate by reaction bonding using an interfacial nickel film. Finally the silicon wafer is etched out. The micromachined silicon wafer which has a surface profile for non-spherical lens was made by transferring the resist profile using RIE. The resist profile was made by programmable mask less exposure system using DMD (Digital Micro mirror Device) [22]. The photographs of the SiC mould for a lens and the Pyrex glass press formed are shown in figures 16b and c, respectively.

![Figure 15. Fabrication process and photograph of probe card for wafer-level burn-in test.](image)

![Figure 16. SiC microstructure for glass press molding.](image)
3.5. SAW passive wireless sensor (LiNbO₃)

2.45GHz SAW (Surface Acoustic Wave) based passive transponders for wireless sensing has been
developed. The principle, the photograph and the structure of the pressure sensor are shown in figure
17. Receiving the 2.45GHz electromagnetic wave, a surface acoustic wave generated by the IDE (Inter
Digital Transducer) on a LiNbO₃ substrate propagates. It is reflected and a 2.45GHz electromagnetic
wave is transmitted back and the sensing can be performed by measuring the delay time. The delay
time is modulated by the deformation of the diaphragm by the pressure. Temperature can be also
measured from the temperature dependency of the delay time and therefore multiple reflectors are
formed for the temperature compensation in the pressure measurement. The SAW pressure sensor was
developed to apply to TPMS (Tire Pressure Measurement System) [23].

![Figure 17. SAW passive wireless sensor for pressure measurement.](image1)

Fabrication process of diaphragm by selective etching of LiNbO₃ is shown in figure 18. Thermal
inversion of polarization and polarization dependent selective etching are used for this process [24].

![Figure 18. Fabrication process of diaphragm by selective etching of LiNbO₃.](image2)

4. Conclusions

MEMS play important roles as key devices in various systems. Packaging and electrical
interconnection are needed for high reliability and arrayed MEMS respectively. Not only silicon but
also other materials such as diamond, conductive polymer, carbon nanotube and silicon carbide could
be used effectively for MEMS.

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