Precise Micro-Nanomachining of Silicon

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Advanced micro sensors for ultrasonic imaging, pressure, acceleration, angular rate and atomic force have been realized based on silicon bulk-micromachining. Novel techniques as deep Reactive Ion Etching (RIE), XeF₂ silicon etching have been developed for precise micromachining and applied for the sensors. The deep RIE of silicon has been applied for electrostatic microactuators. Parallel electrodes in a packaged glass-silicon structure enable electrostatic force balancing servo sensors, resonant sensors and electrostatically levitating micromotors. Nano-machining based on the Scanning Tunneling Microscopy (STM) technology have been also developed to fabricate extremely small structures.

Key words: Bulk-Micromachining, Precise-Micromachining, Microsensors, Nanomachining

1. INTRODUCTION

Bulk micromachining which is based on silicon etching and glass-silicon anodic bonding has been applied for packaged microsensors[1] and other microsystems. Precise bulk micromachining using dry etching of silicon and nanomachining using Scanning Tunneling Microscopy (STM) technology are described in this paper. These advanced bulk micro-nanomachining techniques provide design freedoms for microstructures and result in extremely sensitive and quick response sensors.

2. NEW BULK MICROMACHINING — DEEP RIE AND XeF₂ ETCHING —

Since anisotropic silicon etching has difficulty in structural freedom, deep RIE of silicon has been developed[2-4]. A cryogenic ICP RIE system[3] is shown in Fig.1. Sulfur hexafluoride (SF₆) is used as the etching gas. The directional etching gives rise to batch fabrication of high aspect ratio silicon structures. The deep RIE system in Fig.1 was also applied for the etching of quartz to fabricate a tuning fork gyroscope[5].

XeF₂ gas can be used for isotropic silicon etching and this etching is very selective[6,7]. The etching apparatus and a thin beam bulk-micromachining process developed for fabricating thin beam structures from silicon wafer is shown in Fig.2 and Fig.3 respectively. Side walls are thermally oxidized selectively using surface silicon nitride (Si₃N₄) as a mask. Lateral and vertical dimensions of the beam (about 20µm) are precisely defined and the beam is positioned at the middle of a wafer thickness as shown in Fig.4(top). Additionally, silicon dioxide vertical leaf spring structure as shown in Fig.4(bottom) can be fabricated. The thickness is approximately 400 nm and this can permit only the lateral motion.

Fig.1 Apparatus for ICP deep RIE [3]
3. SENSORS AND MICROACTUATORS

3.1 Ultrasonic Transducers

The XeF₂ silicon etching was applied for the fabrication of ultrasonic imager at the end of a catheter[8]. Piezoelectric PZT ceramic transducer array was made with a polyimide flexible circuit on a silicon wafer and the unnecessary silicon is removed using the selective XeF₂ etching. It is shown in Fig.5. Similar etching of the silicon substrate has been applied for the fabrication of catheter control circuits[9] and distributed optical bending sensors[10].

Novel process for ceramic microstructures has been developed[11]. A micromachined silicon wafer is used as a mold for sintering PZT as shown in Fig.6. The silicon mold is formed by the deep RIE and cast with a PZT slurry. High density PZT is obtained by the hot isotropic pressing and finally the silicon mold is etched out using XeF₂ gas. The high aspect ratio PZT rod array shown in Fig.6 (top) is expected for 1-3 composite ultrasonic transducer. This silicon mold process is also applicable for the batch fabrication of stacked piezoelectric ceramic actuator. This can generate large force and the driving voltage is reduced to 10 volt owing to the narrow 10 μm width [12].
3.2 Fiber Optic Pressure Sensors

Small diameter (125μm φ) fiber optic pressure sensor shown in Fig.7 has been developed for catheter use.[13] Thin diaphragm is formed at the end of an optical fiber and the deformation by the pressure is detected interferometrically. The fabrication process is shown in Fig.8. Silicon rod on which a diaphragm is formed is made by the deep RIE and it is bonded to the fiber end. Finally silicon is etched out with XeF₂ gas. The sensor output versus pressure is shown in Fig.9.

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Fig.5 Ultrasonic transducer array for imaging [8]

Fig.6 PZT rod array and its fabrication process using Si microstructure as a mold [11][12]

Fig.7 Fiber-optic pressure sensor [13]
3.3 Inertia Sensors

Weak spring and narrow electrode gap are required for wide dynamic range of electrostatic force balancing accelerometer. The structure shown in Fig.4(top) is developed for the weak spring. On the other hand, narrow gap is achieved by the distortion free anodic bonding of a silicon with a thick glass in optimum condition[14].

Advanced capacitive accelerometer which has weak spring made of p++ silicon, narrow gap and small chip size is shown in Fig.10[15]. As shown in the fabrication process (Fig.11) deep RIE and wet etching are used for making the spring.

Small size resonant angular rate sensors i.e. gyroscopes have been developed. The resonator causes a vibration in perpendicular direction by the Coriolis force. Precise dimensional control is required to adjust resonant frequencies in both directions. Silicon tuning fork resonant sensor which is driven electrostatically and detected capacitively was fabricated using the deep RIE[16]. The sensor shown in Fig.12[17] was fabricated using the thin beam bulk micromachining process (Fig.3). This sensor has the same principle as that developed by Maenaka[18] and is driven electrostatically and detected capacitively. An angular resonance type was also developed using this process[19]. Silicon gyroscope using electromagnetic excitation and sensing is shown in Fig.13[20].

Deep RIE was applied for the fabrication.
3.4 Electrostatic Microactuators

The deep RIE has been applied for electrostatic microactuators. An electrostatically levitating micromotor shown in Fig. 14 has been developed for rotational inertia measurement systems [21][22]. The rotor is fabricated using the deep RIE of silicon as shown in Fig. 14 (bottom). The levitation is performed by the force balancing in all direction using capacitive displacement sensing and electrostatic actuation which was developed originally for three-axis accelerometer [23]. The sensor can be used for not only gyroscope but also three-axis accelerometer. The levitation and rotation were successfully demonstrated [22].

High aspect ratio microstructures have been used in the electrostatic micro-pump array [24]. The structure with a fine pitch was fabricated using the deep RIE of silicon.

An electrostatic linear actuator with large force can be obtained by using an electrode array with large electrode area and narrow gap [25]. Fig. 15 shows an electrostatic microactuator developed for disk head tracking [26]. High aspect ratio array structure with 5\(\mu\)m gap and 100\(\mu\)m depth could be made using the deep RIE as shown in Fig. 15 (bottom).
3.5 Capacitive AFM/NSOM Probes

Thin silicon beam or diaphragm could be made by etching an uniformly doped silicon wafer using an optical in-situ thickness monitoring during silicon wet etching[27]. Thin silicon beam fabricated using p++ etch stop has built-in stress and shows a distortion[28], while that fabricated by etching a uniformly doped silicon wafer has no distortion. A thin silicon beam which have an opposed electrode with a narrow gap was developed[29] and applied for a capacitive Atomic Force Microscope (AFM) [30] and Scanning Near Field Optical Microscope (SNOM)[31] probe as shown in Fig.16. The capacitive AFM probe does not require extra component as laser and extremely small probes which have high resonant frequency can be fabricated for high rate imaging. Higher resonant frequency than 2.5MHz has been demonstrated with a 60nm thick and 2μm long cantilever[32]. The SNOM probe has pyramidal tip on a silicon cantilever and approximately 100nm size aperture is fabricated on the tip as shown in Fig.16. The parallel electrode can be used for the electrostatic actuation to control the narrow gap between the tip and a substrate. The probe could be used for optical imaging of surface in subwavelength resolution and is also suitable for near field optical data storage[32].

4. NANOMACHINING BASED ON STM

4.1 Field Evaporation Using UHV-STM

In order to make a fine stylus tip on the AFM probe, silicon nano-wire was grown by field evaporation using Ultra High Vacuum - Scanning Tunneling Microscopy (UHV-STM) as shown in Fig.17[33]. The silicon substrate with gold surface was heated at 700°C. The diameter of the nano-wire was less than 50 nm and the growth rate was approximately 200 nm/min.
4.2 Self-supported nanostructure

A self-supported silicon nano-structure was fabricated on a silicon diaphragm using STM induced anodization (STM lithography) and anisotropic silicon etching[34]. The photograph and fabrication process are shown in Fig.18. The width and thickness are approximately 150nm. Thin silicon diaphragm was fabricated from a SIMOX (Separation by ion IMplantation of OXygen) wafer. The hydrogen terminated silicon surface formed in hydrofluoric acid is anodically oxidized in air using a STM tip by positively biasing the substrate. After drawing a pattern silicon is etched using the oxide as a mask in tetramethyl ammonium hydroxide (TMAH). Finally supercritical drying using liquid CO₂ was applied to prevent stiction and collapse.

4.3 Near-field Lithography

Nanometer level pattern transfer has been achieved using the thin silicon diaphragm developed in the process mentioned above. Hard contact between the mask and the diaphragm was made as shown in Fig.19 and illuminated with Ultra Violet (UV) light. Fine pattern beyond the limitation of the wavelength was transferred using evanescent field[35]. Wire grid polarizer was fabricated with the STM lithography as shown in Fig.20 (top) [36]. The polarizer can be used for UV light and the polarized light can localize the evanescent field which results in a fine pattern transfer. Polarizer-integrated mask shown in Fig.20 (bottom) was developed. A preliminary experiment of nano-pattern transfer is being made[36].

Fig.18  Self-supporting nanostructure (top) and its fabrication process (bottom) [34]

Fig.19  Transfer of nanopattern using near-field lithography [35]
5. CONCLUSIONS

Novel silicon bulk-micromachining as deep RIE, XeF₂ silicon etching have been developed for precise micromachining and applied for the sensors and electrostatic microactuators. Nano-machining based on the STM technology have been also developed to fabricate extremely small structures.

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