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Nano-Probe Sensing and Multi-Probe Data Storage

Takahito Ono, Masayoshi Esashi[a]
Faculty of Engineering, Tohoku University, [a]New Industry Creation Hatchery Center, Tohoku University

Abstract

Silicon micromachining technology enables to realize various miniaturized systems in which many micro-components, such as mechanical elements, optics, electronics can be integrated. One of the typical micro systems is scanning probe system with the capabilities of sensing and processing in a nanoscale, as it has been used for scanning probe microscope. According as the dimensions of the micro-components decrease, physical parameters dominated in the nano-scale also change. For example, higher mechanical resonance, quicker thermal responses etc. are expected as the dimensions decrease, which will make the sensitivities higher, and make the thermal processing speeds quicker. We present the fabrication and demonstration of microprobes with specific characteristics due to further miniaturization. An ultra-thin cantilever scaled down to 20~170 nm thickness with a high quality factor for ultra-sensitive sensing, an tiny aperture with the diameter of 20 nm for near-field scanning optical microscope, a nano-heater integrated 2D multi-probe array for high density data storage are described.

Proximity probe techniques represented by scanning probe microprobe (SPM), scanning tunneling microscope (STM), are making tremendous progress. The most essential part of these techniques is micro-probe with a sharp stylus made by micromachining, which is utilized as scientific tools with atomic resolution, and also as engineering tools. Many efforts have been made to increase the sensitivity of the probe sensor by miniaturization. We have developed the fabrication technique of the probe sensor toward a nano-scale, and applied to mass sensing and very weak force sensing.

On the other hands, it is well known that the density of magnetic memory is drastically grown up with about 100% annually and now is approaching the limitation due to the paramagnetic effect that leads to a thermal instability of the recording bits at room temperature. The density of optical memory is also limited due to the diffraction effect. However, optical storage with density of over 100 Gbit/inch^2 or with bit size of smaller than 100 nm seems too difficult to achieve.

Many works on SPM-based storage process show that these effective tools for nanometer-scale surface observation are applicable to data storage devices. The ultimate data density was demonstrated with atomic resolution. However, many problems, such as low throughput, reliability, etc., remain and more realistic data storage solutions must be developed. Several novel recording devices have been proposed by some groups [1]. We have developed near-field microprobe with a high optical transmittance for optical recording. This fabrication technique is extended to make nano-heater integrated probes for thermal recording.

Nano-probe sensing

Ultrahigh force sensitivity and fast response of the cantilever are crucial points for the achievement of atomic scale force resolution in scanning probe microscopy (SPM). The force resolution achievable for a freely vibrating cantilever is limited by the thermo mechanical noise in the mechanical system. Mass sensor to detect mass changes smaller than nano gram is another important application of the cantilevers. It also has been known that the sensitivity of mass change can be gained by scaling down. The resonating sensors are applicable to various sensing with weak interaction forces, and many efforts have been made to achieve ultimate sensing with capabilities to measure even one electron, spin and atom, based on above principles. Main problem to raise the sensitivity is that the quality factors (*Q*-factor) of the resonating sensors decrease with decreasing the dimension. External forces applied to the resonator are stored as vibration energy of the resonator, and the dissipation of vibration energy decreases the sensitivity. Therefore, the energy dissipation should be small; in turn *Q*-factor should be large.

Figure 1 shows the example of the fabricated single crystalline Si resonator with the thickness of 60 nm. Minimum thickness achievable was below 20 nm. Main energy dissipation source of small resonator, especially for very thin cantilever beam, is the surface energy loss.

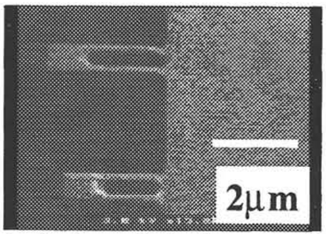

Fig.1. Typical view of single crystalline silicon resonators

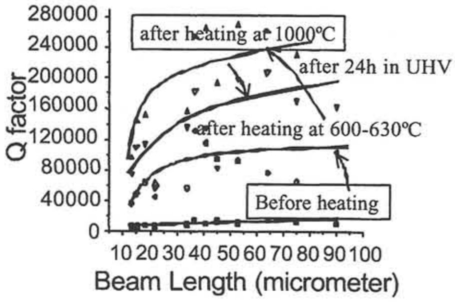

Fig.2. *Q*-factors are plotted with the function of the beam length of 170 nm thick Si cantilevers under various surface treatments in UHV.

Recent articles have suggested that the Q-factor decreases proportionally to the cantilever thickness because the surface-to-volume ratio increases, therefore the surface loss becomes dominant in a thinner cantilever [2]. As mentioned above very thin cantilevers show very low Q-factors. However, this problem can be overcome by the cleaning of the cantilever, which was performed by flash-annealing to remove natural oxide on the Si surface in ultra-high vacuum (UHV)[3]. Figure 2 shows the length dependence of Q factor for cantilevers with 170 nm thicknesses under different treatments in the UHV chamber. The freshly fabricated cantilevers have Q-factors around 10^4. The shorter the cantilevers ($<$30 µm), the lower the Q factors due to obvious support loss. For cantilevers 30–90 µm long, annealing at 600 °C for 30 min in UHV increases the Q factor by 1 order of magnitude (into the 10^5 range). Subsequent annealing at 1000 °C for 30 s causes a further increase of the Q values by a factor of 2–3. Keeping the sample in UHV for about 24 h after annealing at 1000 °C obviously reduces the Q factors of all the cantilevers, which suggests that the change in Q factor is caused by surface modification rather than annealing effect. These results indicate that the ultrathin cantilever is seriously subjected to the surface effect.

Using the ultrathin cantilever with the thickness of 170 nm, measurements of hydrogen storage capacity of small quantities of carbon nanotube bundle are demonstrated.

High Throughput Near-field Probe

One of the most attractive applications of the near-field optics is the next generation optical data storage. The optical memory with high density and high data transfer rate is highly demanded to utilize an aperture probe array of bright nano-scaled light sources (near-field) for writing and reading bits on a medium. Incident light is converted into near-field by a metal aperture.

It is known that the thickness of oxide grown at a low temperature at convex and concave corners is thinner than that at a flat surface of Si due to the compressive stress of oxide at the corner structures. This nonuniform Si oxidation effect at a pyramidal etched pit is applied to fabricate the aperture probe array [4]. Si wafer with pyramidal shaped Si structure was oxidized and the oxide was etched to make an aperture at the apex of the pyramidal-shaped structure. The tiny aperture with the minimum size of 20 nm could be formed with this methods. We fabricate several types of micromachined near-field probes with the small aperture tip on a cantilever structure, on a diaphragm, or at the end of optical fiber [5].

The throughput of a conventional optical fiber tip is quite low (e.g., 100 nm diameter aperture of optical fiber shows an approximately $10^{-5} \sim 10^{-7}$ throughput). The throughput of our probe is several orders of magnitude higher than that of the conventional optical fibers (100nm diameter aperture shows about 10^{-2} of optical transmittance)[5]. However, for the aperture smaller than 100 nm, the throughput is still drastically decreased.

Multi-Probe Array for Thermal Storage

As shown in Fig.3, 2D micro-thermal probe array for thermal recording based on an atomic force microscopy (AFM) are fabricated and charactrized [6]. A metal nanowire is formed at the apex of the probe tip, which acts as a heater by flowing a current. The nano-heater with a small thermal mass will promise a quick thermal response. The silicon probe array (32×32) is bonded to a Pyrex glass substrate in which metal wires (feed-through) are formed for electrical connections from the individual probe to IC. This structure will allow operating the probes in parallel, which possibly overcomes the low data transfer rate of the AFM-based storage. The small metal wire for a nano-heater is fabricated at the apex of a pyramidal SiO_2 tip, which is formed by low temperature oxidation of a silicon etch-pit, consecutive metal deposition (Pt/Cr or Au/Cr) to fill the metal into the etch-pit, and etching of the SiO_2 in buffered HF solution. Another metal (Ni) is deposited on the tip to form a metal-to-metal junction that enables to measure the temperature at the tip end. The silicon substrate formed the probe array is bonded to the glass substrate.

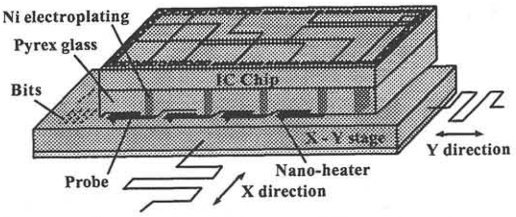

Fig. 3. Concept of the multi-probe storage device.

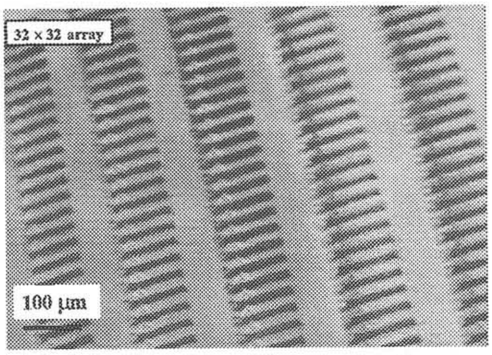

Fig. 4. SEM image of the fabricated probe array.

The heating capability of the nano-heater is confirmed by the resistance change of the nano-wire when flowing a small current into the nano-heater. Also, temperature of the heater was estimated to be 800°C when the flowing current was 4 mA. The measured thermal time constant of the nano-heater was about 18 µsec. From these results, total recording speed of about 300 Mbits/sec can be expected. By using a micro-probe, preliminary experiments in data writing and reading are performed on a phase change medium. If this probe array is combined with a micro-actuator, miniature storage device with a high areal bits density possibly be realized.

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