# Microprobe Array With Electrical Interconnection for Thermal Imaging and Data Storage

Dong-Weon Lee, Takahito Ono, Takashi Abe, and Masayoshi Esashi

***Abstract*—In this work, new novel methods for fabricating a thermal probe array with 32 × 32 probes on one chip are proposed. It consists of silicon micromachined probe, AlN actuator, pyramidal $SiO_2$ tip on which the nano-scale metal–metal junction is formed using a self-alignment technique. The nano-junction can be used as a thermocouple to measure a local temperature on a sample surface or as a nano-heater to make a local deformation on a media. In self-alignment process, a metal layer (Pt/Ni) is deposited on the inside of $SiO_2$ hollow tip fabricated by low temperature (950 °C) oxidation of silicon etch pit. This low temperature oxidation results in a smaller oxide thickness at the tip apex than other flat area. Therefore, after selective etching the $SiO_2$ in buffered HF, a small hole surrounding the Pt/Ti tip apex can be created. Another metal (Ni) is deposited outside the Pt/Ti tip to make the nano-junction. For electrical interconnection between the thermal probe and an IC chip, a hole array with 30 $\mu$m of a hole diameter is made by dry etching through the 150-$\mu$m-thick Pyrex glass, and then Ni is electroplated into the through etched-hole. Finally the Pyrex glass plate was anodically bonded to the probe array. Using the fabricated thermal probe, temperature distribution is measured on a prepared sample surface and the local heating capability of the thermal probe is confirmed. Preliminary experiments for data writing and reading are performed on a phase change medium. [666]***

***Index Terms*—Data storage, electrical interconnection, microprobe, nano-heater, thermal imaging.**

## I. Introduction

SThM (Scanning Thermal Microscope) [1], as one type of SPM (scanning probe microscope), is very advantageous for analyzing thermal properties in nanometer scale. To measure the thermal properties in the local area, a thermal sensor is integrated on a tip of microprobe. Many kinds of technical approaches, such as electron beam (EB) lithography or field evaporation (FE) have been proposed to make the thermal sensor at the apex of the tip [2], [3]. However, these methods are unsuitable for mass production due to the IC noncompatible fabrication process. For example, the position of thermal sensor in EB lithography is determined by the accuracy of alignment process and the performance of machine. On the other hand, the individual metallization of probe by FE process also limits the efficiency of the mass production of the thermal probe array. Undoubtedly both approaches are time consuming process.

Another potential application of the thermal probe is for the high-density storage [4]. In recent NEMS (nanoectromechanical system) researches, the probe-based data storage has become one of the most important technologies for next generation data storage with recording density up to 1 Tb/in$^2$. There are various data reading and writing principles for the probe-based data storage. For example, electric-field-assisted deposition for nanometer-size gold structures [5], charge injection on a insulator surface [6], poling of piezoelectric materials [7], conductance change of LB film [8] and phase change of film [9], near field optical microscopy [10], and thermomechanical deformation [11], etc. are widely studied by many research groups. In the early 1990s, IBM group proposed the thermomechanical storage via heating the tip on a thin polymer film [11]. Recently, parallel operation of 32 × 32 AFM cantilever array with integrated tip was demonstrated by Vettiger *et al.* at IBM Zurich [12]. The critical issues in developing the probe-based data storage system are cost, data transfer rate, signal-to-noise ratio, signal processing of the probe array, heat value, reliability, and durability in a long term.

In this paper, we present a novel-batch fabrication method of the thermal probe array with a sub-100 nm heater for nanoscale measurement and deformation. A metal–metal junction is formed at the apex of a probe tip without an alignment process. The nano-junction can be used as a thermal sensor or as a nano-heater with a small thermal mass, which could be heated up and cooled down more quickly. Parallel operation of the probe array (32 × 32) can achieve a high data transfer rate, which is comparable to that of the hard disk head. The possibility of high-density data storage was evaluated using the fabricated thermal probe and a commercially available medium (GeSbTe).

## II. Design and Fabrication of Thermal Probe Array

One important requirement of the thermal probe used in thermal imaging and data storage is the rate of heating up and cooling down, that is, fast thermal response is desired for high-speed reading and writing the information. This could be achieved by reducing the thermal mass of the heater due to its geometry dependence. Another consideration in the design of the two dimensions thermal probe array is an electrical interconnection between the thermal probe array and the IC. The probe array density is mainly determined by the size of IC and metal wire for signal processing. To realize the high-density probe array system, simple interconnection method with a low electrical resistance is required to reduce the area of metal lines.

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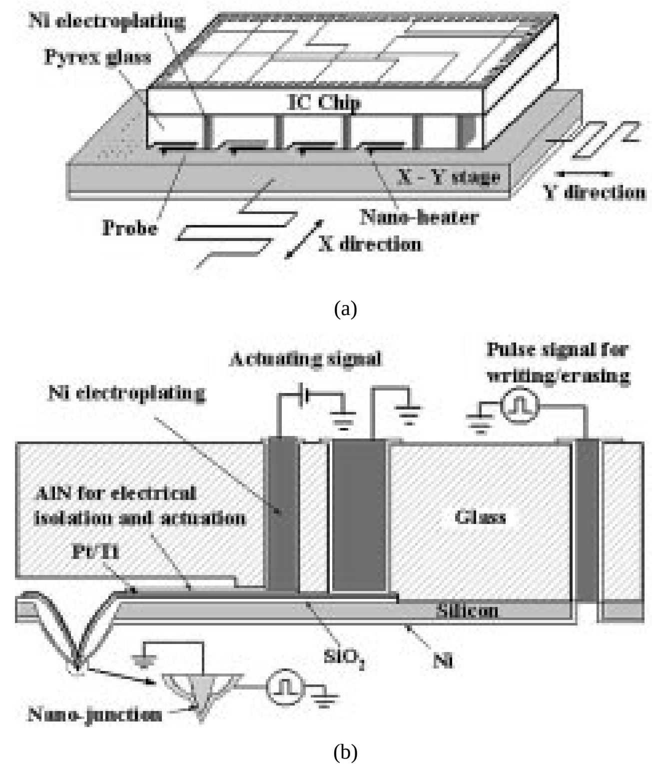



Fig. 1. Schematic diagrams of (a) the thermal probe array for application of thermal imaging and high-density recording, and (b) the cross section of thermal probe with electrical interconnection.

We propose a novel fabrication and a recording mechanism of probe array with nano-heaters for high-density data storage. And also, deep RIE of Pyrex glass and an electroplating of Ni are developed for integrating IC chip on the probe array [4], [13]. Fig. 1(a) shows a schematic diagram of the thermal probe array bonded with the IC chip for signal processing. A magnified image of a thermal probe is shown in Fig. 1(b). The whole system consists of Pyrex glass plate with Ni stick, the thermal probe with integrated actuator, and a sharp tip with metal–metal nano-junction. To solve the problem of interconnection in the two dimensions array, electrical signal coming from the thermal probe are directly connected to the IC chip through the Ni stick formed in the inside of the Pyrex glass. This new interconnection method reduces dramatically the size and resistance of metal wires. The calculated resistance of Ni stick with 150 $\mu$m in thickness and 50 $\mu$m in diameter is around 5.3 m$\Omega$. A nano-metal tip (Pt/Ti) protruded through an opening hole of $SiO_2$ tip is embedded in the outer layer (Ni) at the apex of the probe tip. Pt/Ti and Ni junction was selected because the junction produces good thermoelectric voltage as a function of temperature. The metal–metal nano-junction is exactly situated at the apex of the probe tip without an alignment process. The nano-junction can be used as a thermal sensor to measure thermal properties and a nano-heater to heat up a sample surface. The local heating ability of the thermal probe is applied to the probe-based data storage with a high recording density. The individual thermal probe can be actuated using an AlN piezoelectric film deposited on the thermal probe. The designed thermal probe has a fundamental resonance frequency of around 212 kHz and the spring constant is designed under 2 N/m for contact operation between the tip and a medium. The thermal probes in the array are arranged in 140 $\mu$m pitch horizontally and in 100 $\mu$m pitch vertically.

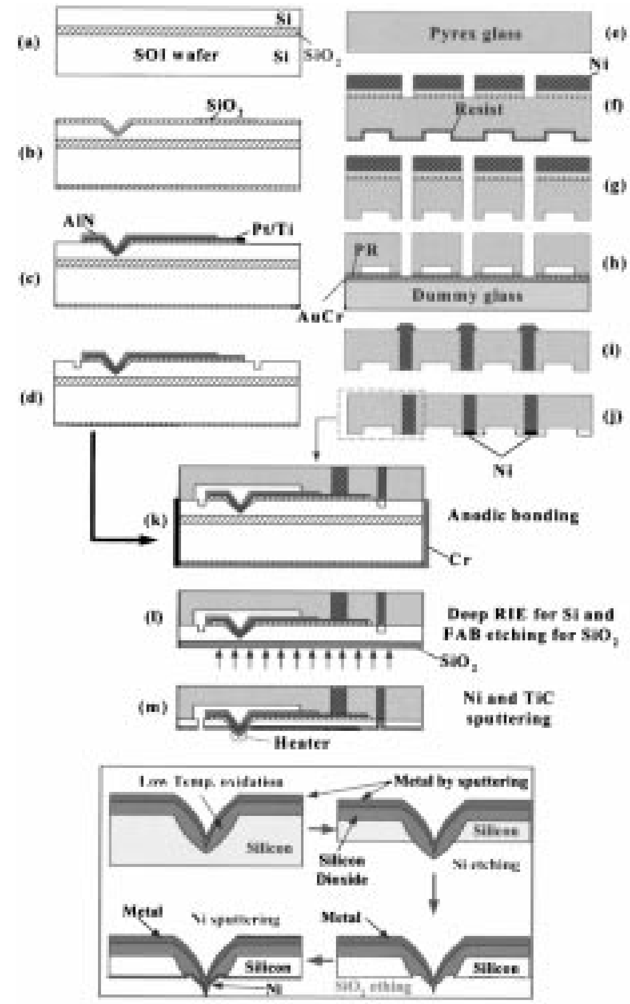



Fig. 2. Fabrication flow of the thermal probe array with electrical interconnection.

Fig. 2 shows the process flow of the thermal probe array. N-type (100) oriented SOI (top-Si: 25 $\mu$m/ intermediate $SiO_2$: 1 $\mu$m /Si substrate: 374 $\mu$m in a thickness) wafer with 5–15 $\Omega \cdot$cm was used as the starting material (a). A 300-nm-thick $SiO_2$ is thermally grown on the wafer by wet-oxidation at 1100 °C for 15 min. Pyramidal etch pit on the silicon was formed using a tip mold by photolithography, $SiO_2$ etching and consecutive Si wet etching. Next, nonuniform $SiO_2$ for tip-sharpening process was grown on the silicon etch pits in steam at 950 °C for 10 hours (b). It is known that the thickness of oxide at convex and concave corner grown at low temperature is thinner than that on the plane surface of silicon. Using this mechanism, a small opening at the apex of the $SiO_2$ tip was easily obtained by time-controlled etching the $SiO_2$ in buffered-HF solution at step l. Ti layer with a thickness of 5 nm for adhesion and (100) oriented Pt layer with a thickness of 100 nm were consecutively coated by sputtering at 150 °C with a backpressure of $1 \times 10^{-4}$ Pa. Photolithography and FAB (fast atom beam) dry etching were performed for making a metal pattern on the probe (c). The FAB dry etching has a good directionality because FAB is electrically neutral [14]. The good directionality allows a nano-fabrication with or without contact mask. The probe pattern was defined by photolithography, $SiO_2$ etching with FAB and silicon etching using ICP-RIE (inductively coupled plasma reactive ion etching) (d). The AlN thin film was deposited on the Pt electrode at 400 °C by reactive magnetron sputtering using a $N_2$ gas and Al target. The AlN thin film was chosen for electrical isolation of Pt layer except the nano-junction area.

The process flow of the Pyrex glass plate for electrical interconnection to the IC chip is shown in Fig. 2(e)–(i). First, we prepared the Pyrex glass plate with the thickness of 150 $\mu$m by polishing (e). Thin Au/Cr (100 nm/30 nm) is sputtered on the Pyrex glass for the seed layer of Ni electroplating (f). For making a gap between the probe and the glass, the Pyrex glass was etched in buffer-HF solution after photolithography of the bottom side (f). Thick Ni film was selectively electroplated on the substrate using a thick photoresist as a mold with a thickness of 15 $\mu$m–20 $\mu$m (f). The deep-etching of the Pyrex glass was carried out by ICP-RIE using $SF_6$ gas in step (g) under following conditions: the pressure of $SF_6$ gas is 0.2 Pa, the self-bias voltage is −390 V and the stage temperature is 293 K. The etch rate in Pyrex glass increased to 0.6 $\mu$m/min with decreasing the pressure to 0.2 Pa. The etching selectivity of the Pyres glass to the Ni mask is around 30. By using a photoresist as an adhesion layer, the Pyrex glass with the etched holes was bonded to a dummy substrate with Au/Cr seed layer (h). Ni was fully filled into the small holes of the Pyrex glass by pulse electroplating method. Finally, the Pyrex glass is released from the dummy substrate in acetone (i), and then it was chemically polished to obtain a flat surface for anodic bonding between the silicon and the Pyrex glass (j). Measured electrical resistance of the Ni interconnection using a 4-point probe method is about $35 \pm 13$ m$\Omega$.

After anodic bonding the silicon with the Pyrex glass (k), the bottom silicon was etched by the ICP-RIE from backside, and then an intermediate oxide layer of the SOI is dry-etched by fast atom beam (l). The cantilever pattern was released by etching the top silicon from backside (m). The $SiO_2$ tip was thinned in buffered-HF solution at 36 °C until metal protrusion comes in slight. As a result, metal nano-wire appears at the apex of the tip through small opening hole of the $SiO_2$ layer. The hole sizes from 20 nm to 300 nm are experimentally achieved with the etching time ranging from 3 min to 5 min [15], [16]. Finally, a Ni thin film was sputtered on the backside to make a metal–metal junction (nano-heater), as shown in Fig. 2(l). By using this technique, the metal–metal junction situated exactly at the apex of the tip can be formed without an alignment process. The size of the fabricated thermocouple and nano-heater depend on several factors: oxidation temperature, selective etching time of the $SiO_2$ tip and a thickness of Ni at the $SiO_2$ tip. To solve the problem of the tip wear in contact operation, a thin TiC (titanium carbide) layer with an excellent wear-resistance is coated on the Ni film of the thermal probe. Fig. 3 shows the cross-sectional SEM (scanning electron microscopy) view of the fabricated Pyrex glass with fine electrical interconnection. The diameter of the holes was below 30 $\mu$m in the bottom. We succeeded to fill the Ni in the through holes with the aspect ratio of 6. A SEM view of the fabricated probe array is shown in Fig. 4(a).

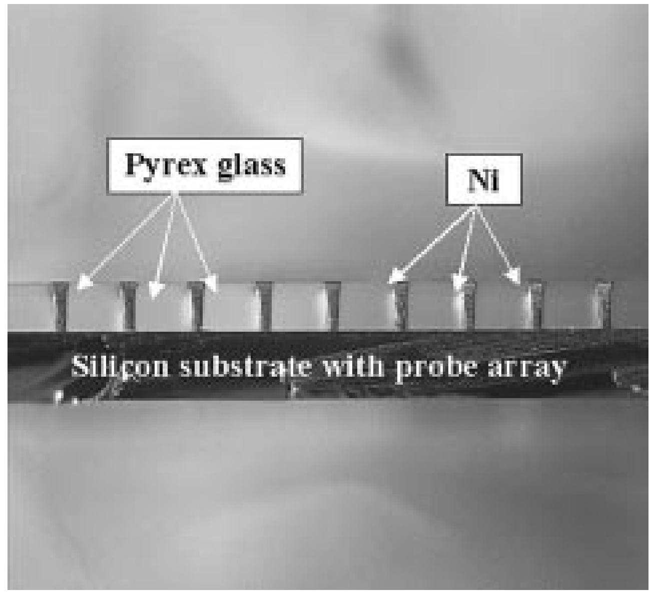


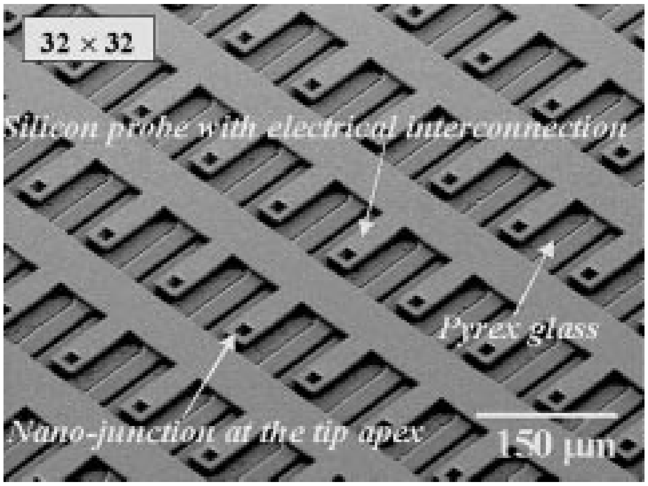

Fig. 3. A SEM view of electrical interconnection made by deep RIE of Pyrex glass and pulse electroplating of Ni.

And Fig. 4(b) shows a close-up view of the thermal tip with 30 nm in curvature radius. A cross section of the thermal tip with metal–metal junction is shown in Fig. 5, which is obtained by FIB (focused ion beam) cutting.

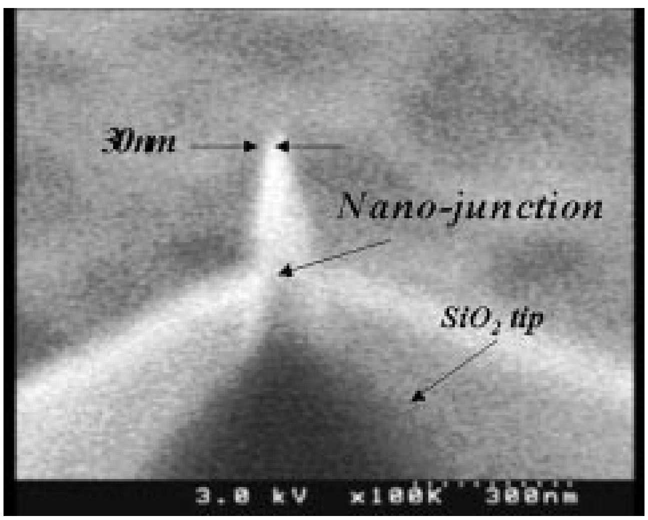
## III. Experimental Results

The typical measured resistances of the metal–metal junction are 50 to 176 Ω, depending on the junction size and the different contact resistances. Firstly, we evaluated the basic characteristics of the fabricated thermal probe. The thermal probe was set on a temperature-controlled stage to measure a thermoelectric voltage. A commercial thermocouple is located on the same stage for monitoring the temperature. The stage temperature is slowly increased from 0 to 120 °C, then the thermoelectric voltage of Pt/Ti–Ni junction and Au/Ti–Ni junction of the thermal probe was monitored as a function of temperature. The measured thermoelectric voltage at the end of the thermal probe was 16 $\mu$V/°C and 23.3 $\mu$V/°C for Pt/Ti–Ni and Au/Ti–Ni junctions, respectively (Fig. 6). These values are consistent with the estimated value from bulk characteristics.

Next, the thermal probe is used to obtain a thermal imaging by mapping the temperature distribution on a surface. In comparison, the corresponding topography is obtained by an atomic force microscopy (AFM). The thermal probe was placed onto a specially designed microprobe-holder. A preamplifier with $10^3$ gains is used to amplify the thermoelectric voltage. The output voltage of the amplifier is fed to a commercial AFM system for imaging the thermal distribution. To demonstrate the capability of the thermal imaging, metal wires (Au/Cr) of 20 $\mu$m in width and 15 nm in thickness made on Pyrex glass was observed. The resistance of the metal wire is 25 Ω, and 100 nm thick resist is coated on the sample for electrical isolation between the tip and the metal wire. A current for Joule heating flows into the metal wire on the sample surface, and then the thermal probe




(a)




(b)

Fig. 4. SEM views of (a) the thermal probe array (32 × 32) with nano-junction and (b) the magnified nano-junction.

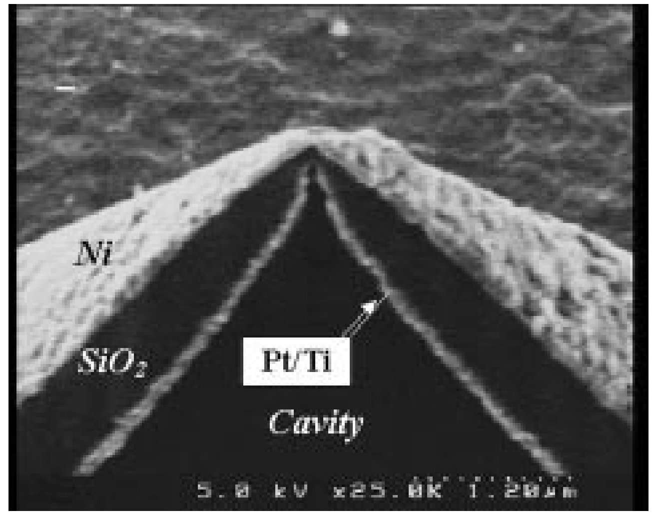



Fig. 5. A cross-sectional SEM view of the $SiO_2$ tip made by FIB cutting.

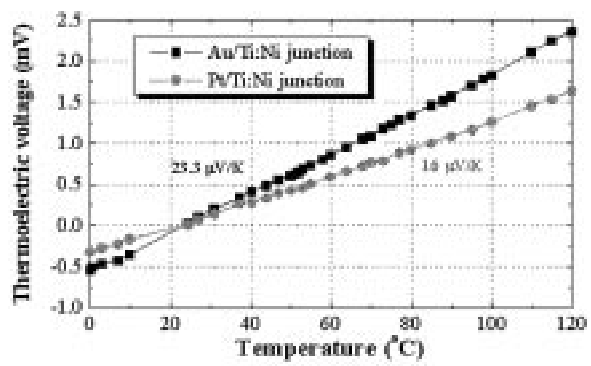
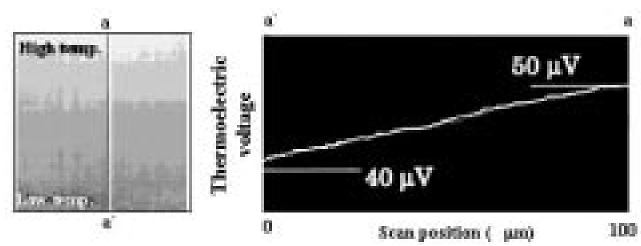
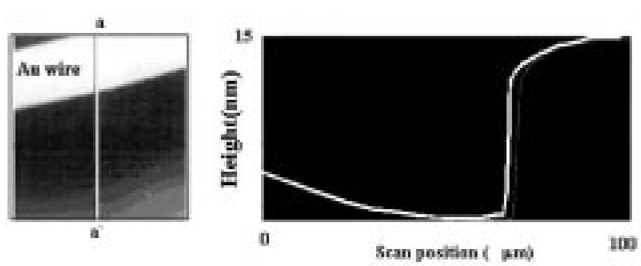



Fig. 6. Thermoelectric voltage of the metal-to-metal junction as a function of temperature.




(a)



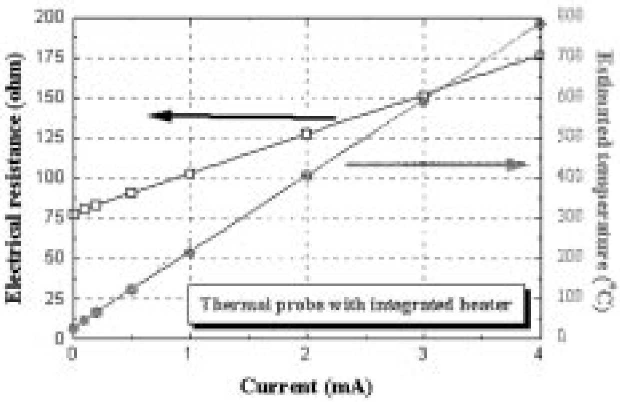

(b)

Fig. 7. (a) Thermal image on electrically heated sample surface and (b) corresponding topography.

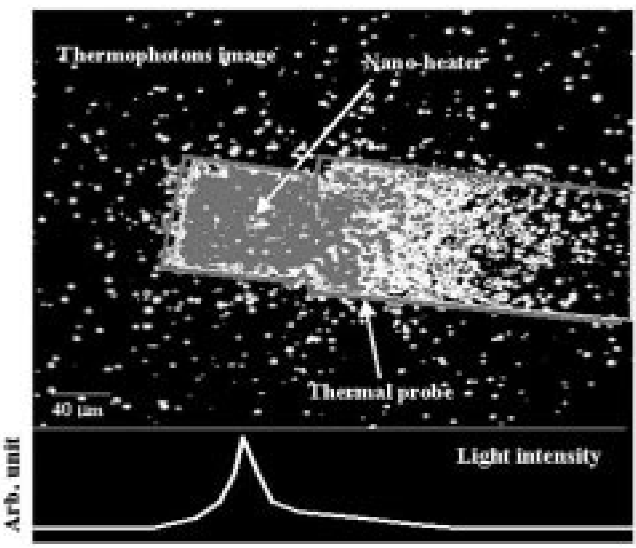
was scanned on the sample surface in contact mode. The topography and the corresponding thermal image were simultaneously obtained with the scan speed of 30 $\mu$m/sec, as shown in Fig. 7(a) and (b), respectively.

Temperature vs. electrical resistance characteristics of the thermal probe was measured using a temperature-controlled oven. Electrical resistance variation of metal lines occurred by the entire heating is calculated using electrical properties as a function of temperature. We subtracted the calculated values from the measured values, and these results are shown in Fig. 8(a). When flowing a current to the thermal probe, the changes of the resistance were also observed. From these results, the estimated temperature at the tip point was plotted on the same figure. The measured positive temperature coefficient of the resistance for the thermal probe is 0.13%/°C. Heating ability of the thermal probe at the tip end was also tested using a photon counting CCD camera. 5 $V_{\rm p-p}$ voltage with the pulse width of several tens msec were applied to the heater through a 1-k$\Omega$ resistor, and corresponding thermophotons emitted from the free end of the thermal probe can be imaged by the photon counting CCD camera, as shown in Fig. 8(b).

The thermal time constant was measured using a method employed by Mastrangelo *et al.* [17]. The negative pulse $V_{\rm heating}$ for electrical heating is applied to the thermal probe through a diode. At the end of the negative pulse, the polarity of the pulse

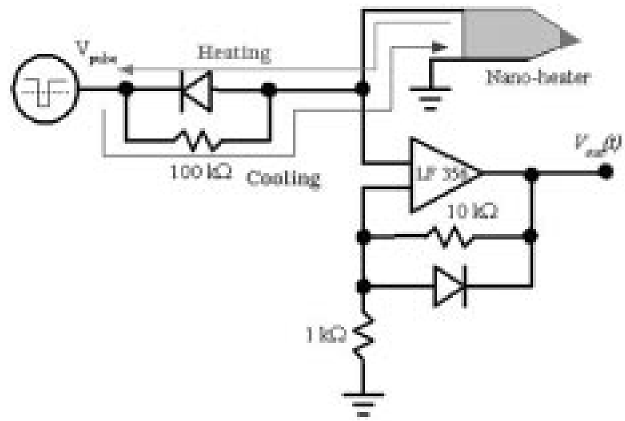



(a)

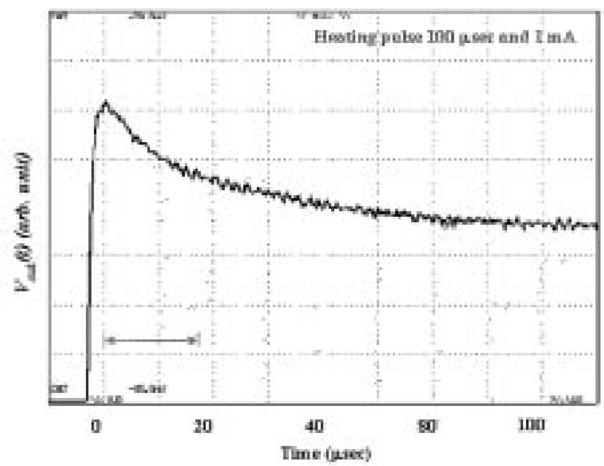



(b)

Fig. 8. (a) Current versus electrical resistance and estimated temperature as a function of current and (b) thermophotons image obtained by photon counting CCD camera.




(a)

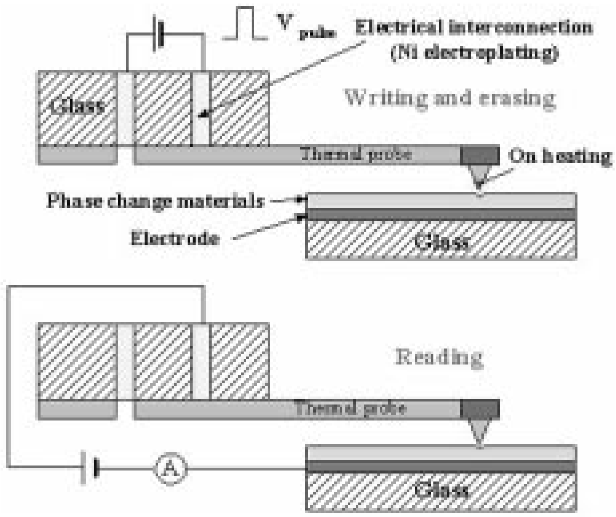



(b)

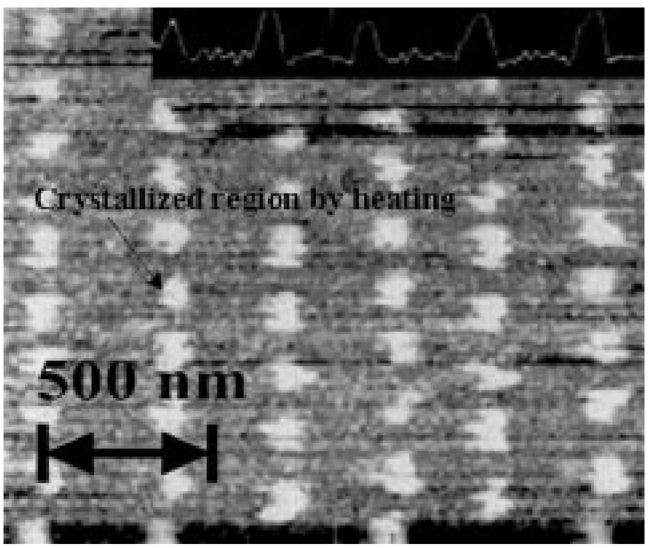
Fig. 9. (a) Electrical circuit for measuring a thermal time constant and (b) measured thermal response time of the thermal probe, where the heater with a size of 1 $\mu$m in diameter is used.

is changed, and the positive pulse $V_{cooling}$ for cooling is applied to the thermal probe through a large series resistor (100 k$\Omega$). In this cooling cycle, the thermal probe cools down in a short time. The voltage across the thermal probe is monitored using a noninverting operational amplifier (LF 356). The time dependent voltage $V_{\rm out}(t)$ is directly measured using a simple circuit as shown in Fig. 9(a). Fig. 9(b) shows the temperature (electrical resistance) as a function of time following a 100 $\mu$sec heat pulse. The electrical resistance is decreased during the positive pulse, which indicate the cooling of the thermal probe. By measuring the variation of an electrical resistance as a function of temperature, the temperature at the tip end can be calculated. Measured thermal time constant of the thermal probe with a heater (1 $\mu$m in a diameter) is roughly 18 $\mu$sec. This value will be decreased when the thermal tip was placed in contact with a medium surface.

The nano-heater can be used as a storage device instead of a focused laser on a phase change material such as GeSbTe, which were already in practical use as a storage medium in DVD-RAM or CD-RW system. Short pulse heating the nano-heater can make and erase small bits since heat conduction into large area can be avoided. As a result, the limitation of recording density is eliminated because of the bit size on a medium is decided by the heater size. As shown in Fig. 10(a), by locally heating a phase change film above the crystalline temperature, the phase of the film changes from amorphous to crystalline state. If the temperature is higher than the melting point of the film and the temperature decreasing rate is sufficiently large (below 100 ns [18]), the crystalline state will be changed to the amorphous. Preliminary experiments for data writing and reading were performed on a phase change film (GeSbTe). When applying a tip-voltage of 5–10 V between the tip and the recording medium in contact operation, the tip end is heated by a current flow into the tip. The heated tip locally changes the crystallography of the phase change film from amorphous to crystal. The local modification can be measured by the conductivity change [9]. Fig. 10(b) shows the conductivity image that was mapped by measuring a current flow in scanning. The bright areas show larger conductivity area formed by crystallization. In this measurement, the applied voltage was kept below 2–3 V unless further phase change modifies the film. The written bit size is below 100 nm in a diameter.




(a)




(b)

Fig. 10. (a) Schematic diagrams for writing and erasing on phase change material and (b) formed marks on a thin GeSbTe.

## IV. Conclusion

This work demonstrates that the thermal probe array can be applied for the nanoscale thermal image and high-density data storage. New approaches were developed to fabricate the thermal probe array and electrical interconnection using a micromachining technology. The nano-junction for local sensing and heating is ideally formed on the apex of the $SiO_2$ tip to obtain a fast thermal response time. The sizes of nano-junctions are well controlled by a selective etching the $SiO_2$ tip. A promising electrical interconnection method between the thermal probe and the IC chip is firstly introduced. Primary experiments were performed for application of the thermal imaging and data storage. Small marks below 100 nm in a diameter are formed on the GeSbTe by using the electrically heated tip. The nano-heater could be heated over 1000 °C by flowing a small current into the junction. This temperature is sufficient to write and erase bits on the phase change film. We are currently studying to reduce the thermal response time for application of rewritable storage system.

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