Silicon Nitride Cantilever Arrays Integrated with Si Heater and Piezoelectric Sensors for SPM Data Storage Applications

Hyo-Jin Nam, SeongSoo Jang, Young-Sik Kim, Caroline Sunyong Lee, Won-Hyeog Jin, Il-Joo Cho, and Jong-Uk Bu

***Abstract*—Silicon nitride cantilevers integrated with silicon heaters and piezoelectric sensors were developed for the scanning probe microscope (SPM) based data storage application. These nitride cantilevers are expected to have better mechanical stability and uniformity of initial bending than the previously developed silicon cantilevers. Data bits of 40 nm in diameter were recorded on PMMA film and the sensitivity of the piezoelectric sensor was 0.615 fC/nm, meaning that indentations less than 20 nm in depth can be detected. For high speed operation, 128×128 cantilever array was developed.**

***Index Terms*—SPM, data storage, piezoelectric sensor, nitride cantilever**

I. Introduction

As nanometer size bit writing and high speed readout have become important parameters in storage technology, Scanning probe microscopy (SPM)-based data storages are considered to be one of the desirable future data-storage devices. Since SPMs can image surfaces at the atomic scale by using sharp tips of radius less than 10nm and these nano-size tips can be fabricated with micrometer scale patterning technique, several SPM based data storage system can overcome the storage density limit of HDDs, optical storages and semiconductor memories [1].

Vettiger et al. suggested thermo-mechanical data storage system where a resistively heated AFM tip writes data bits by making nano-size indentation on a polymer film and reads it back with thermo-resistive method [2]. The speed of this system is no more a problem as they devised an array type of system, improving it by more than thousands times. In the previous work, we introduced a thermo-piezoelectric data storage system where the data bits are recorded with a resistively heated AFM tip and are detected by the integrated piezoelectric PZT sensor [3]. This system consumes less power and does not require extra circuitry to compensate the off-set voltage of each sensor.

Firstly, this thermo-piezoelectric data storage system was developed with silicon cantilevers integrated with heaters and piezoelectric PZT sensors. An array of silicon cantilevers, however, has poor uniformity of the initial deflection, mostly caused by the thickness non-uniformity of the silicon cantilevers made of SOI wafers. The thickness of the silicon cantilever is determined by the initial thickness of the device silicon layer and the etched depth of the device silicon during the tip fabrication process, both of which have large variation in general. Silicon nitride cantilevers, however, can have very uniform thickness and good mechanical stability because the LPCVD silicon nitride film is very uniform. Moreover nitride cantilevers have superior mechanical properties to silicon cantilevers.

In this research, we have firstly integrated silicon tip heaters and PZT sensors on a silicon nitride cantilever array for SPM-based data storage.

II. Structure and Operation

In the previous study, we have introduced the thermo-piezoelectric read/write mechanism with a resistively

Manuscript received January 15, 2005; revised March 15, 2005
MS Group, Devices and Materials Lab., LG Electronics Institute of Technology, Woomyon-dong Seocho-gu, Seoul, Korea.
E-mail : hyojnam@lge.com

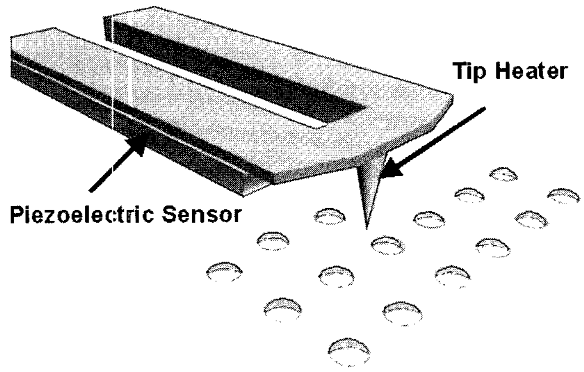


Fig. 1. Schematics of thermo-piezoelectric read/write system

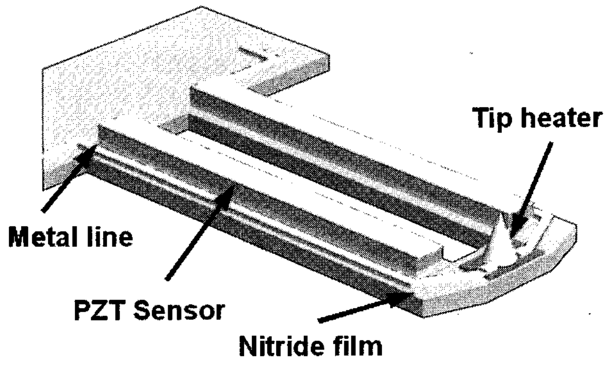


Fig. 2. Schematic drawing of thermo- piezoelectric silicon nitride cantilever

heated AFM tip and a piezoelectric PZT sensor as shown in Fig. 1. The resistively heated tip writes the data bits while scanning over a polymer media and the piezoelectric sensor reads data bits by the induced charges along with the deflection of the cantilever over the indentations on the polymer media.

In a piezoelectric cantilever, like PZT, the mechanism of sensing is as follows; as the PZT cantilever scans across the indentation of a polymer film, the cantilever deflects along with the indentation of the film, causing a stress variation on the PZT film. The variation of stress in the PZT film produces self-generated charges on the surface of the PZT capacitor with no applied voltage. The charge is not generated by the absolute stress, but by the variation in stress. Therefore, the piezoelectric sensing method has advantages of low power consumption, no off-set voltage and high reading speed compared to the thermal sensing method of IBM. And, the power consumption in writing can also be reduced by selecting polymer media having low glass transition temperature which is limited in the thermo-resistive reading system.

The uniformity in initial bending and the mechanical stability of the cantilever array are crucial to reliable read/write operation of SPM based storages using cantilever array, both of which are not easily attainable with silicon cantilevers made of SOI wafer. The thickness of the silicon layer in the thermo-piezoelectric cantilever, which greatly affects the initial deflection of the PZT cantilever, is not uniform due to the thickness non-uniformity of the device layer of the SOI wafers and the non-uniformity of the remaining silicon layer after tip etching process.

In this work, the silicon nitride cantilever with PZT sensors and silicon tip heaters was designed for uniform initial bending and good mechanical stability of the cantilever as shown in Fig. 2. The PZT sensor and the silicon tip heater are formed on the nitride cantilever. The silicon heater is electrically connected via the shallow metal lines. The nitride layer deposited by LPCVD method has very uniform thickness and superior mechanical properties to silicon layer. Using these nitride cantilevers, very uniform probe array can be made and more reliable read/write operation of SPM based data storage is possible.

III. FABRICATION

In this study, silicon tips were formed on silicon nitride films. The formation of the nitride cantilever with the silicon tip is complicated because silicon film cannot be grown epitaxially on nitride film. Grow et al. developed nitride cantilevers with silicon tips by growing nitride films on the silicon tips [4]. The fabrication process is very complex and the protection of silicon tip during the nitride etching process is difficult. We maded SOI wafers with nitride buried layer instead of the oxide.

Fabrication process for the nitride cantilever with silicon heater tip is summarized in Fig. 3. A silicon nitride buried SOI wafer was fabricated by joining and annealing of a oxidized wafer and a low stress nitride deposited wafer with thickness of 500 nm (a, b). The nitride film was deposited by low press chemical deposition (LPCVD). After the silicon tips and an electrical silicon contact regions were formed on the nitride film (c), the thermal oxide of 50 nm was grown on it to reduce the surface damage resulting

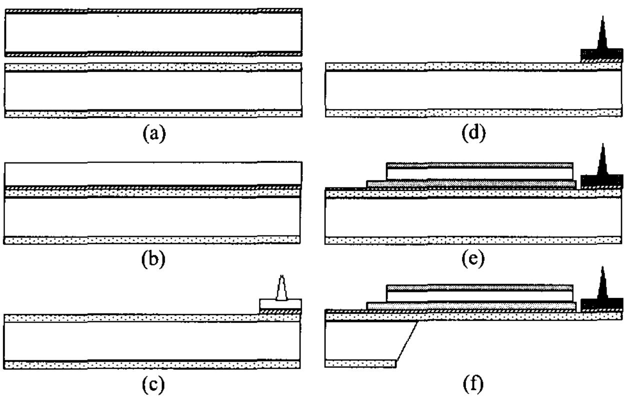


Fig. 3. Fabrication process of silicon nitride thermo-piezoelectric cantilever

from ion implantation. Boron was implanted at 40 keV with a dose of 5×10^{14} cm^{-2} at the silicon tip heater region and with a dose of 5×10^{15} cm^{-2} at the silicon electric contact region (d). Then, the wafer was subjected to furnace annealing in a N_2 ambient at 900°C for 30 minutes.

After depositing LPCVD oxide of 200 nm to protect inter-diffusion between PZT and Si layer, the PZT capacitor was formed as described in the previous work [5]. The bottom electrode was formed by sputtering thin titanium (Ti) adhesion layer, followed by 120-nm thick platinum (Pt) layer. The PZT layer was formed by sol-gel process. The PZT films were annealed at 650°C for 1 minute using the rapid thermal process. The resulting PZT film is 300 nm thick and its composition is near the morphotropic phase boundary. On the PZT, a RuO2 film was deposited as the top electrode. The PZT capacitor structure was patterned using an inductively coupled plasma reactive ion etching system (e). The Pt/Ti pad was formed by sputtering and lift-off process. Finally, backside silicon was selectively removed in an aqueous potassium hydroxide (KOH) solution (f).

After the wafer was diced into individual cantilevers, the tip of the cantilever was heated to record a series of data bits on a polymer media. For polymer media, 40 nm thick PMMA film was prepared by spin coating method.

IV. Results and Discussion

Figure 4 shows the scanning electron microscopy (SEM) images of the fabricated nitride cantilever

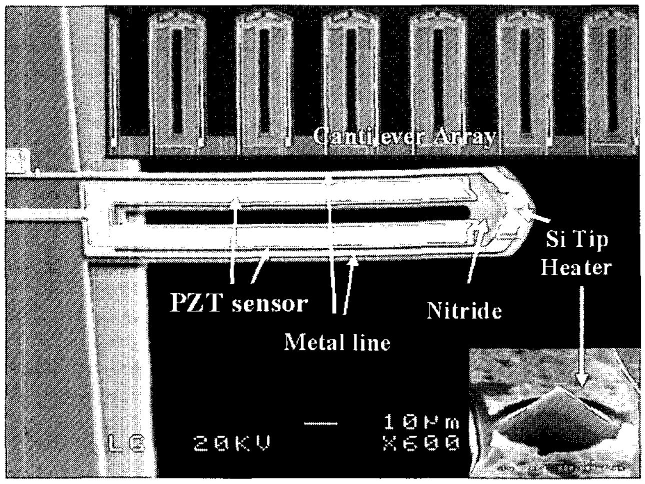


Fig. 4. SEM image of the nitride cantilever

integrated with silicon tip and PZT sensor. The silicon heater and PZT sensor on the nitride cantilever are clearly defined in the figure. The fabricated cantilever is bent upward slightly. The thickness uniformity of the nitride film is below 2% over the 4 inch wafer.

The cantilever array shows uniform bending status. The length of cantilever is 120 μm, and thickness of nitride film and PZT film is 500 nm and 300 nm, respectively.

Figure 5 is the schematic drawing of the piezoelectric sensing system where piezoelectric charges are collected from the PZT sensor as the tip is deflected over the bit indentation [6]. The generated charge is amplified by a charge amplifier (model No.: CS515-2, Clear Pulse Company). The amplified signals can be compared to the initial setting values using a comparator to differentiate the data to be either "0" or "1"

To measure the sensitivity of the PZT sensor, the induced charge signals were collected with various cantilever deflection, as shown in Fig. 6. The deflection was measured using a stacked piezo-block which consists of a series of stacked PZT capacitors and produces a known displacement at a given voltage. Piezoelectric

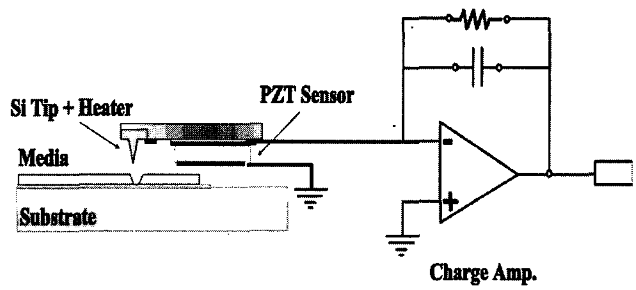


Fig. 5. Schematic of thermo-piezoelectric read/write system

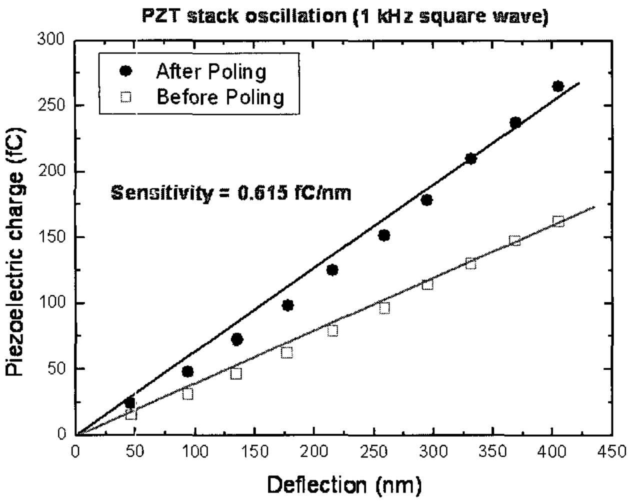
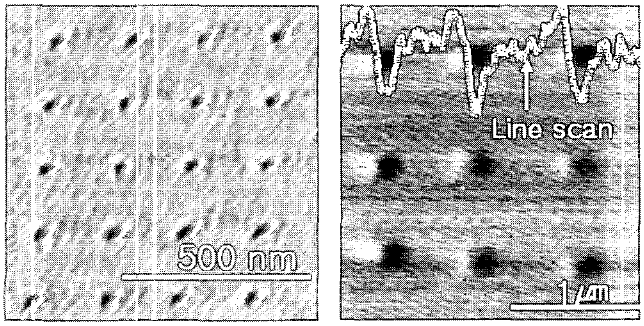


Fig. 6. Piezoelectric charge output as a function of cantilever deflection

charges were generated from the PZT sensor as the piezo-block moves up and down by the applied voltage while the tip of the cantilever just contacted the piezo-block. These charges were collected by a charge amplifier with gain of 2V/pC at a square wave of 1 kHz. The signal was linearly proportional to the cantilever deflection. The sensitivity was 0.4 fC/nm and 0.615 fC/nm without and with poling of the PZT film. The PZT film reaches the saturated state by poling treatment, which leads to the increase of the sensitivity.

Using the fabricated cantilever, a series of data bits were written on a PMMA media, as shown in Fig. 7(a). A voltage with pulse width of 20 micro second was applied at 10V. Indentation data bits of about 40 nm were recorded on the PMMA film. The writing voltage can be further decreased by minimizing the silicon heater size. Fig. 7(b) shows the piezoelectric charge outputs obtained on PMMA media with the data bits of about 150 nm. The readback



(a) Written data bit (b) Piezoelectric read-out

Fig. 7. Thermo-piezoelectric read and write on PMMA substrate

signals from PZT sensor were observed from the line scan data. As the tip travels down the indentation, negative charges are generated.

The signal from the indentation is clearly distinguished from the noise signal. But, the piezoelectric charge outputs were not clearly differentiated from the noise on the data bits below 40 nm.

To detect smaller bits, we are attempting to increase the aspect ratio of the indentations and increase signal to noise (S/N) ratio. The depth of the indentation was only 20nm while the diameter was 150 nm. To increase indentation depth, new materials for media and writing method are under study. The sensitivity can be more improved by the optimization of the PZT layer and the cantilever structure. The noise signals from the flat area are mostly due to system noise. We are trying to eliminate the exact sources of the electric noises to improve the S/N ratio.

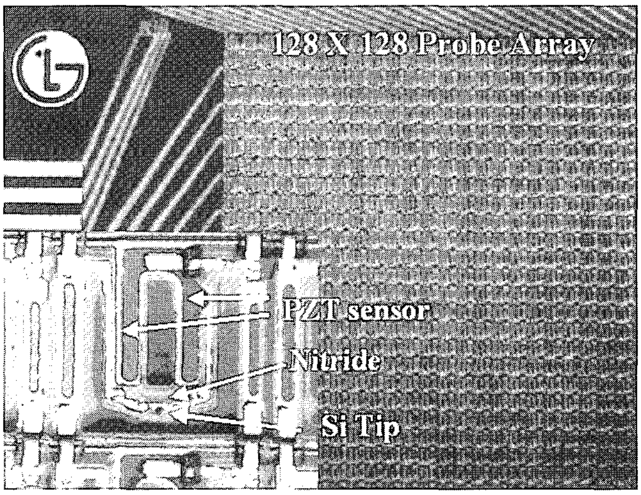


Fig. 8. Thermo-piezoelectric nitride cantilever array (128×128 probes)

For high speed operation of SPM based data storage, 2D array type cantilever with uniform initial bending are required. We made 128 × 128 2D thermo-piezoelectric probe array using surface micromachining technology. The fabricated probe is very uniform as shown in Fig. 8. The tip heaters and the PZT sensors are very well defined. Using this array of cantilevers, parallel read/write operation is under progress.

V. Conclusions

Nitride cantilever integrated with a silicon tip heater and a piezoelectric sensor has been firstly developed using SOI wafer with nitride buried layer for uniform initial bending and mechanical stability of the cantilever array. Data bits of 40 nm in diameter were recorded on PMMA film and readback signals were obtained on the data bits of 150 nm. The sensitivity of the piezoelectric sensor was 0.615 fC/nm, implying that indentations less than 20 nm in depth can be detected. To improve the data rate, the 128 × 128 probe array was fabricated, whose initial bending was very uniform.

Acknowledgments

This work is supported by the National R&D Project for Nano Science and Technology (Project M1-0212-29-0000) of MOST. We would like to thank S.W. Choi, W.B. Choi of BNP Science Ltd. for their assistance in the wafer level bonding process.

References

[1] S. Hosaka : SPM based recording toward ultrahigh density recording with trillion bits/inch[2]", *IEEE Transactions on Magnetics*, Vol. 37, pp. 855-859, 2001.

[2] P. Vettiger, G. Cross, M. Despont, U. drechsler, U. Durig, B. Gotsmann, W. Haberle, M.A. Lantz, H.E. Rothuizen, R. Stutz and G. K. Binnig, "The "millipede"- nanotechnology entering data storage", *IEEE Transactions on Nanotechnology*, Vol. 1, pp. 39-55, 2002.

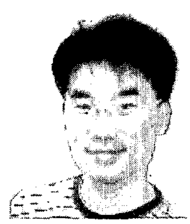
[3] C. S. Lee, H. J. Nam, Y. S. Kim, W. H. Jin, S. M. Cho, J. U. Bu "Microcantilevers integrated with heaters and piezoelectric detectors for nano data-storage application", *Applied Physics Letters*, Vol. 83, pp. 4839-4841, 2003.

[4] R.J. Grow, S.C. Minne, S.R. Manalis, C.F. Quate "Silicon nitride cantilevers with oxidation-sharpened silicon tips for atomic force microcopy", *Journal of Microelectromechanical Systems*, Vol. 11, pp. 317-321. 2002.

[5] H.J. Nam, S.M. Cho, Y.J. Yee, H.M. Lee, D.C. Kim, J-U. Bu and J.H. Hong : *Integrated Ferroelectrics*, **35** (2001) 185.

[6] C.S. Lee, T. Itoh and T. Suga "Micromachined piezoelectric force sensors based on PZT thin films", *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control*, Vol. 43, pp. 553-559, 1996.

Hyo-Jin Nam He received M.S., and Ph. D. degrees in material science from Korea Advanced Institute of Science and Technology (KAIST) in 1988 and 1998, respectively. He joined LG Electronics Institute of Technology in 1988. His research interests include the integrated microdevices made of piezoelectric thin films, and SPM-based high density data storage.

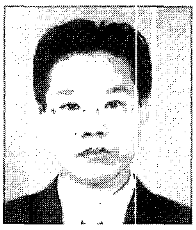


Seongsoo Jang He received the B.S., M.S. and Ph.D degrees in materials science and engineering from KAIST (Korea advanced institute of science and technology), Korea, in 1993, 1995 and 2001. respectively. Between 2001 and 2004, he spent 3 years in the memory research center of Hynix semiconductor Ltd. where he worked on the fabrication of DRAMs. In March 2004, he joined the device and materials laboratory of LG Electronics Institute of Technology. He is currently involved in the development of SPM based data storage system.

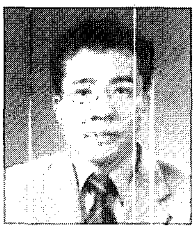
Young-Sik Kim He received M.S., and Ph. D. degrees in electrical engineering form Korea Univ. in 1993 and 2000, respectively. From 1993 to 1996 he was SDRAM circuit engineer in Hyundai Electronics, He joined LG Electronics Institute of Technology in 2000. His research interests include the integrated MEMS based device, semiconductor device physics and SPM-based data storage and its control circuit.

Caroline Sunyong Lee She received the B.S. and M.S. degrees in Materials science and Engineering from Massachusetts Institute of Technology, Cambridge, MA, in 1993 and 1995 respectively, and the Ph.D. degree in Materials Science and Engineering from the University of California, Berkeley, in 2001. From 1995 to 1997, she was a process engineer in Intel Corporation and Applied Materials, Inc. She joined LG Electronics Institute of Technology in 2002. Her research interests include SPM-based high density data storage and NEMS device.

Won-Hyeog Jin He received the B.S. and M.S. degrees in mechanical engineering from Yonsei University, Korea, in 1997 and 1999 respectively. He was a research engineer at PSIA Corp. from 1999 to 2002. In 2002, He joined the device and materials laboratory of LG Electronics Institute of Technology, where he is engaged in the development of SPM based data storage system.



Il-Joo Cho He(S'98-A'00-M'04) received the B.S, M.S., and ph.D. degrees in electrical engineering from the Korean Advanced Institute of Science and Technology (KAIST), Deajeon, Korea, in 1998, 2000, 2004, respectively. His doctorial research concerned the MEMS micromirrors and RF MEMS switches. Since 2004, he has been with LG Electronics Institue of Technology, Seoul, Korea, where he has worked on the area of MEMS. His research interests include nano data storage, RF MEMS switch and Bio MEMS.



Jong. U. Bu He is a research fellow and a group leader with Microsystem group in LG Electronics Institute of Technology. He received the Ph.D. degree in Metallurgical Engineering from Korea University in 1992. He has been with LG Electronics Institute of Technology, Seoul, Korea since 1984, where he has worked on the area of silicon micromachining and microsensors. From 1995 to 1996, he has been with the Center for Integrated Sensors and Circuits, Department of Electrical Engineering and Computer Science, University of Michigan, Ann Arbor, as a visiting scholar. His research interests include development of microfabrication and micromachining technologies for microsystem; micro sensors, optical communication components, RF MEMS, and MEMS embedded high density data storage systems. He has published and presented more than 90 MEMS related papers and 100 patents.