DIAMOND PROBE FOR ULTRA-HIGH-DENSITY FERROELECTRIC DATA STORAGE BASED ON SCANNING NONLINEAR DIELECTRIC MICROSCOPY

[1]Hirokazu Takahashi, [2] Takahito Ono, [3] Yasuo Cho, and [4]Masayoshi Esashi

[1]Corporate R&D Laboratories, Pioneer Corporation
6-1-1 Fujimi, Tsurugashima, Saitama 350-2288, Japan
E-mail: hirokazu_takahashi@post.pioneer.co.jp, htaka@mems.mech.tohoku.ac.jp
[2]Graduate School of Engineering, Tohoku University, Japan
[3]Research Institute of Electrical Communication, Tohoku University, Japan
[4]New Industry Creation Hatchery Center, Tohoku University Tohoku University, Japan

ABSTRACT

This paper reports on the development of a diamond multi-probe for ultra-high-density ferroelectric data storage based on scanning nonlinear dielectric microscopy (SNDM), which is a technique for determining polarized directions in ferroelectric domains by measuring a nonlinear dielectric constant with a inductance-capacitance resonator. SNDM has a capability of both reading and writing nano-sized polarized ferroelectric domain information at a high speed, since the SNDM technique is a purely electrical method. Boron-doped diamond synthesized by hot-filament chemical vapor deposition is chosen as a conductive and robust probe material. Probes are fabricated by using a silicon lost mold technique and selective growth method. We present the fabrication of the diamond multi-probe and data storage experiments using a ferroelectric $LiTaO_3$ thin film. It is demonstrated that boron-doped diamond probe can be used for data storage based on SNDM.

1. INTRODUCTION

The demands on mass storage are increasing with the progress in an information technology. The considerable increase in data recording density would lead to a high capacity of storage and realize a small storage device.

The data recording density of hard disk drives, which is representative of mass storage, has grown every year. However, the thermal fluctuation of magnetic domains on the hard disk limits the areal recording density. Data storage techniques using many kinds of probes have been also studied as a next generation ultra-high-density data storage [1] [2]. Scanning nonlinear dielectric microscopy (SNDM) is expected as a promising technique for an ultra-high-density data storage beyond 1 Tbit/inch^2 using a ferroelectric recording medium. SNDM is a purely electrical technique for determining polarized directions in the ferroelectric materials [3] [4] and observing ferroelectric polarization distribution with a resolution of sub-nanometer order.

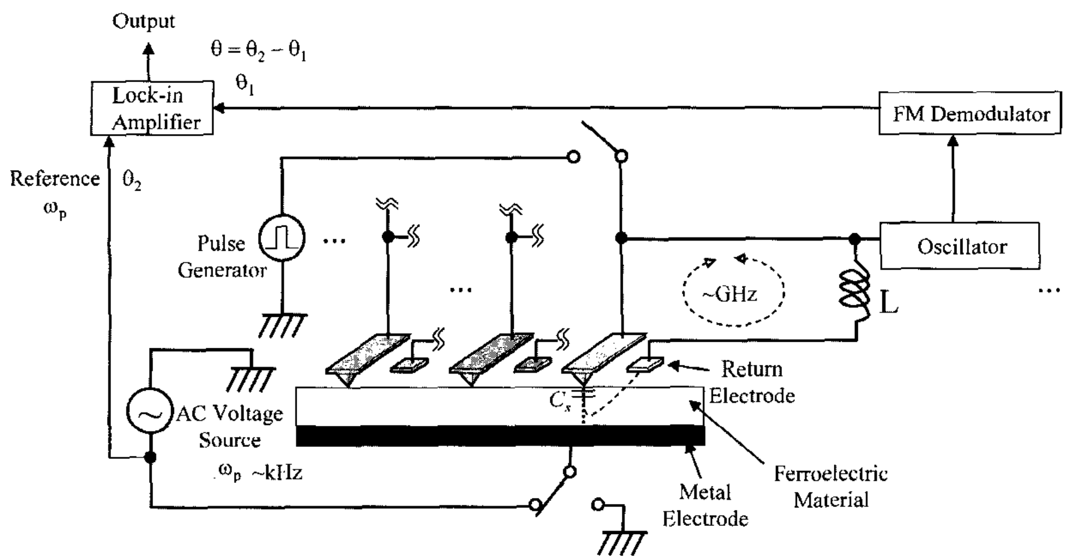

Figure 1: Schematic of a multi-probe data storage based on SNDM.

In the SNDM data storage, the ferroelectric polarized domain directions correspond to the data bits. Where recording is performed by inverting polarized small-domain direction with pulse electric filed and reading is performed by SNDM. The nano-sized ferroelectric domain engineering using the SNDM technique was demonstrated by using a scanning probe microscopy (SPM) equipment, a metal-coated Si probe, and a lithium tantalite ($LiTaO_3$) thin film crystal as a ferroelectric recording medium [2]. The features of the dot array recorded as a bit was about 20 nm, which is comparable to the memory density of 1.5 Tbit/inch^2. In this method, the capacitance C_s exists between the tip and the return electrode, and the inductance L parallel to the capacitance construct an electrical resonator of ~GHz as shown in Fig. 1. Therefore, well conductive probe is needed to ensure the electrical resonance of the LC circuit. In order to achieve a high data resolution and high data-transfer rate, the probe tip must be scanned in contact with the ferroelectric medium. Accordingly, robustness of the probe for the SNDM data storage is also required.

Diamond is well known for its hardness and lubricating property. In this study, the conductive diamond probe and its array were fabricated by a silicon lost mold technique and a selective growth of diamond. The boron-doped diamond, which was synthesized by hot-filament chemical vapor deposition (HF-CVD), was employed due to its high conductivity. A multi-probe would be more advantageous in durability and data transfer rate than that of a single probe.

We present the principle of ferroelectric data storage, fabrication of the diamond multi-probe, and data storage experiments based on SNDM using a ferroelectric, $LiTaO_3$, thin film.

2. PRINCIPLE OF FERROELECTRIC DATA STORAGE BASED ON SNDM

In this section, the principle of SNDM on a ferroelectric material is described. Reading with SNDM is performed by applying an electric field, which generates an electric displacement D in the ferroelectric material. Equation (1) shows a polynomial expansion of the electric displacement D as a function of electric field E.

$$D = P + \varepsilon_{33}E + \frac{1}{2}\varepsilon_{333}E^2 + \frac{1}{6}\varepsilon_{3333}E^3 + \frac{1}{24}\varepsilon_{33333}E^4 + \cdots, \tag{1}$$

where P is residual polarization, ε_{33} is the linear dielectric constant, and ε_{333}, ε_{3333}, and ε_{33333} are nonlinear dielectric constants. The signs of the odd order nonlinear dielectric constants, ε_{333}, ε_{33333}, $\cdots$, changes as the polarization direction inverses. In contrast, the signs of the even order nonlinear dielectric constants, ε_{33}, ε_{3333}, $\cdots$, do not change. The ferroelectric polarized directions in ferroelectric is recognized by measuring the sign of the lowest order nonlinear constant ε_{333}, since the signs of the lowest order nonlinear constant depend on the polarized direction [3] [4].

The probe is composed of a LC (inductance and capacitance) resonant circuit and an electrically conductive tip detecting the capacitance C_s of the ferroelectric just under the tip as shown in Fig. 1. When AC voltage $E\cos\omega_p t$ is applied to a metal electrode formed under the dielectric thin film, C_s slightly changes because of the nonlinear response. C_s is given as follows:

$$C_s = C_{s0} + \Delta C_s(t) \approx C_{s0} + C_{s0}\left(\frac{\varepsilon_{333}}{\varepsilon_{33}} E\cos\omega_p t + \frac{\varepsilon_{3333}}{4\varepsilon_{33}} E^2 \cos 2\omega_p t + \frac{\varepsilon_{33333}}{24\varepsilon_{33}} E^3 \cos 3\omega_p t + \cdots\right). \tag{2}$$

Where ΔC_s is the alternating variation and C_{s0} is the time independent statistic value of the capacitance. The resonant frequency of the LC circuit is modulated by variation of C_s according to equation (2). By demodulating this frequency-modulated signal and extracting a signal proportional to $\cos\omega_p t$ from the demodulated signal using a lock-in amplifier, the sign of ε_{333} can be determined.

3. DESIGN AND FABRICATION

We fabricated pyramidal shaped diamond tips and diamond structures by means of the silicon lost-mold technique and selective growth technique of diamond [5]. Figure 2 is the schematic view of a diamond probe. Boron-doped diamond was grown by HF-CVD. In order to reduce the electric resistance, aluminum was patterned on whole area of the cantilever as shown in Fig. 2.

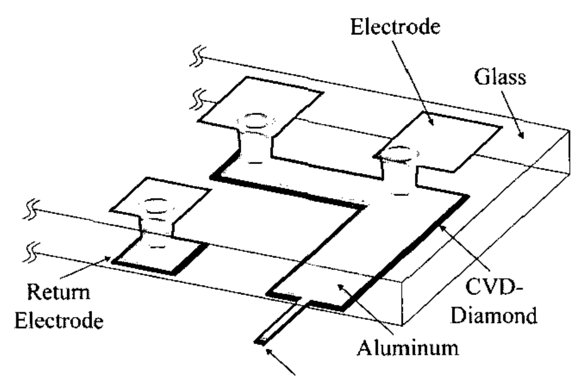

Figure 2: Schematic view of diamond probe.

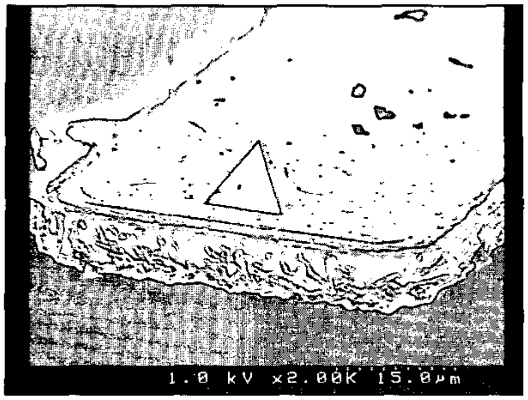

Figure 3: SEM image of the end of the diamond probe.

Figure 3 shows the typical SEM image of the end of the diamond probe. The tip surface is smooth because of the fabrication by the silicon lost-mold technique and selective growth technique of diamond. Both the tip and the cantilever were made of CVD diamond. The width, length, and thickness were 50 µm, 900 µm, 7 µm, respectively. The resonant frequency and spring constant were 20 kHz and 2.5 N/m, respectively. The width and height of pyramidal shaped tip are about 10 µm and 7 µm, respectively. The radius of the fabricated tips could be less than 100nm.

Figure 4 shows the fabricated diamond probe array. The pitch were 200 µm. The width, length, and thickness of a cantilever were 50 µm, 500 µm, 7 µm, respectively. Each probe has an individual electrode. These probes connect with SNDM systems in parallel with each other.

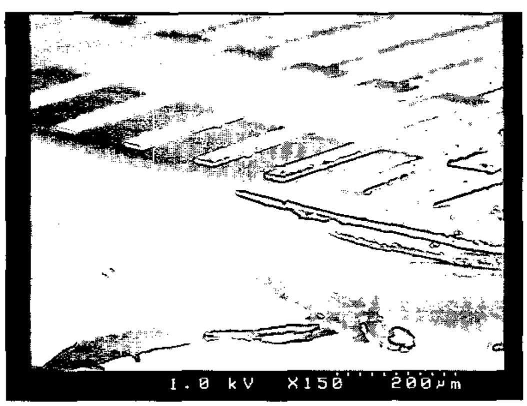

Figure 4: SEM image of the diamond probe array.

4. Experimental Result

We used a z-cut congruent $LiTaO_3$ (CLT) single crystal substrate with a thickness of 500 µm as a specimen. Its spontaneous polarization directions are perpendicular to the crystal face. SNDM measurements were performed using a SPM equipment at a constant force mode. Probe was connected with SNDM circuit by using a conductive glue.

Figure 5 shows the SNDM amplitude image of spontaneously polarized domain distribution measured using the single diamond probe on $LiTaO_3$. Dark and bright areas in Fig. 5 correspond to positively and negatively polarized domains, respectively [6]. AC voltage of 5 V was applied while the SNDM measurement was performed and its frequency was set to 10 kHz. The diamond probe tip was scanned at a contact force of 25 nN. The clear contrast in Fig. 5 verifies that the boron-doped diamond made by HF-CVD is applicable to SNDM.

Figure 6 shows the further result of writing and reading experiments on negatively polarized $LiTaO_3$ with a thickness of 60 nm. The array of a bit was formed by applying a pulsed DC voltage between a metal electrode underlying the $LiTaO_3$ film and a diamond tip. The applied voltage and its pulse width were 15 V and 1 ms, respectively.

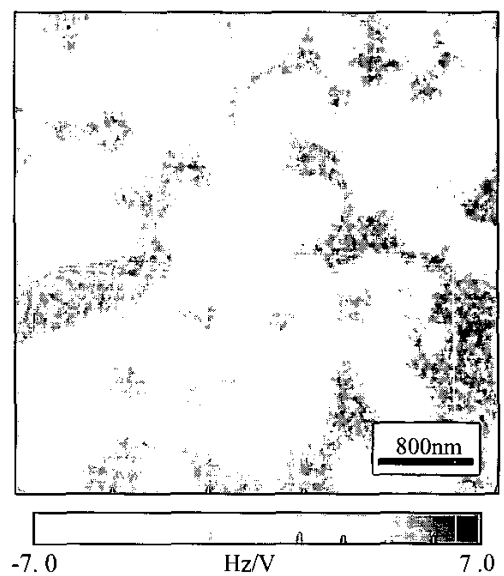

Figure 5: SNDM amplitude image of a spontaneously polarized domain distribution on $LiTaO_3$ using the CVD diamond probe.

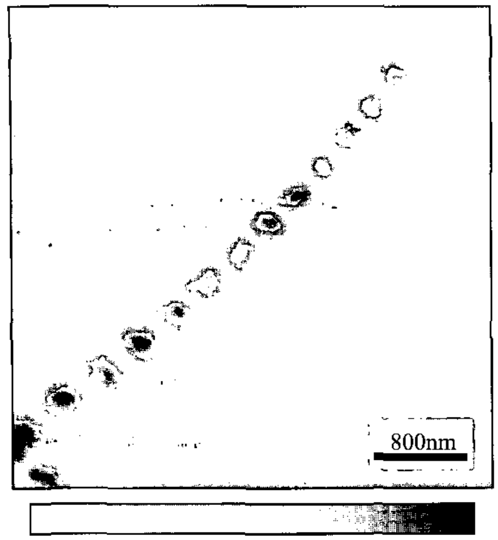

Figure 6: SNDM image of writing domain on $LiTaO_3$ using the CVD diamond probe.

In this SNDM measurement, AC voltage and its frequency were 2.5 V and 10 kHz, respectively. The dot diameter in Fig.5 is about 200 nm. The radius in the experiments using diamond probes would be smaller depending on writing condition and the radius of the tip. It should be noted that the tip of the probes used in these experiments was slightly etched by a focused ion beam to remove a contaminant. As a result, the tip radius was enlarged up to 400 nm, which resulted in the decrease the resolution in comparison with the reported values.

We also performed endurance tests. The diamond probe tip was scanned at a contact force of 200 nN and a scanning speed of 8 μm/s for an hour in contact with $LiTaO_3$ in nitrogen gas at 1000 Pa. It is known that diamond is etched due to oxidation [7]. There was little oxygen in the nitrogen atmosphere, but $LiTaO_3$ contains much oxygen and contacted with the tip of the probe. However, no apparent etching of the tip and medium was observed under this measurement condition. For the practical use, further durability experiments on environment, operating time, scan speed, and contact force etc. are necessary.

5. Conclusion

We fabricated the boron-doped diamond probe for ultra-high-density ferroelectric data storage by the silicon lost mold technique and the selective growth using HF-CVD. We performed SNDM experiments on CLT using the probe. Clear SNDM image was successfully obtained. Moreover, we demonstrated reading and writing of data bits on CLT thin films, which shows that the diamond probes are applicable to SNDM based data storage.

6. Acknowledgement

We are deeply grateful to Dr. J. H. Bae and Y. Hiranaga for their help, and A. Onoe and T. Maeda for their supports.

7. References

[1] P. Vettiger, G. Cross, M. Despont, U. Drechsler, U. Dürig, B. Gotsmann, W. Häberle, M. A. Lantz, H. E. Rothuizen, R. Stutz, and G. K. Binnig, „The "Millipede"—Nanotechnology Entering Data Storage", IEEE TRANSACTIONS ON NANOTECHNOLOGY, vol.1, no.1, pp. 39-55, 2002.

[2] Y. Cho, K. Fujimoto, Y. Hiranaga, Y. Wagatsuma, A. Onoe, K. Terabe, and K. Kitamura, „Tbit/inch^2 Ferroelectric Data Storage Based on Scanning Nonlinear Dielectric Microscopy", Appl. Phys. Lett. vol.81, pp. 4401-4403, 2002.

[3] Y. Cho, A. Kikihara, and T. Saeki, „Scanning nonlinear dielectric microscope", Rev. Sci. Instrum. vol.67, pp 2297-2303, 1996.

[4] Y. Cho, S. Atsumi, and K. Nakamura, „Scanning Nonlinear Dielectric Microscope Using a Lumped Constant Resonator Probe and Its Application to Investigation of Ferroelectric Polarization Distributions", Jpn. J. Appl. Phys. Vol.36, pp3152-3156, 1997.

[5] J. H. Bae, T. Ono, and M. Esashi, „Scanning probe with an integrated diamond heater element for nanolithography", Appl. Phys. Lett. vol.82, pp. 814-816, 2003.

[6] Y. Cho, S. Kazuta, and K. Matsuura, „Scanning Nonlinear Dielectric Microscopy with Contact Sensing Mechanism for Observation of Nano-Meter Sized Ferroelectric Domains", Jpn. J. Appl. Phys., vol.38, No.9B, pp.5689-5694, 1999.

[7] Q. L. Zhao, S. Dong, and T. Sun, „ Investigation of an Atomic Force Microscope Diamond Tip Wear in Micro/Nano-Machining", Key Engineering Materials vol.202-203, pp. 315-320, 2001.