Planarization of Nonmagnetic Films on Bit Patterned Substrates by Gas Cluster Ion Beams

Keisuke Nagato[1], Hiroaki Hoshino[1], Hiroki Naito[2], Tomokazu Hirota[2], Hiroshi Tani[3], Yasuo Sakane[4], Noriaki Toyoda[2], Isao Yamada[2], Masayuki Nakao[1], and Tetsuya Hamaguchi[1]

[1]Department of Mechanical Engineering, Graduate School of Engineering, The University of Tokyo, Tokyo 113-8656, Japan
[2]Incubation Center, Graduate School of Engineering, University of Hyogo, Himeji-shi, Hoyogo-ken 671-2280, Japan
[3]Mechanical Engineering Department, Kansai University, Osaka 564-8680, Japan
[4]Western Digital Media Operations, San Jose, CA 95131 USA

We studied Ar gas cluster ion beam (GCIB) planarization effect on patterned surfaces refilled with Cr, Ta and SiO_2. The patterns of 20 nm in depth were fabricated on Si substrate by using electron beam lithography and CHF_3-reactive-ion-etching. The bit pattern pitches and the height of peak-to-valley were 150/200/300/400 nm and 20 nm, respectively. Then, refilling materials were deposited 30 nm in thickness on the patterned substrates. The test samples were irradiated by Ar-GCIB and the resultant surface profiles were measured by atomic force microscopy. Acceleration energy for a cluster was 20 keV. The dose was set from 2×10^{15} to 5×10^{15} ion/cm^2. Although there was a difference in the dose, the patterns disappeared clearly by irradiating GCIB. The reduction rate of peak-to valley height decreased with decreases of the pattern pitch. We indicated that GCIB irradiation is effective for the planarization of patterned surface refilled with Cr, Ta, and SiO_2.

***Index Terms*—Gas cluster ion beam, patterned media, planarization.**

I. INTRODUCTION

A PATTERNED medium is one of the excellent candidates to overcome the limitation of an increase in density of magnetic disks. Recorded spins will interfere with next ones due to their thermal stability and to achieve high recording density such as over 1 Tbit/in^2, bits must be discretely separated [1]–[3]. However, because the indented surface of bit patterned media (BPM) make head-slider flying instability, the media need flat surfaces as well as conventional nonpatterned disks. Soeno *et al.* demonstrated refilling the grooves of magnetic thin film by depositing of SiO_2. Subsequent ion milling of the extra SiO_2 resulted in flat patterned media [4]. Nunez *et al.* indicated that diamond-like carbon (DLC) is a efficient refilling material in terms of mechanical behavior for head-slider stress by using finite-element-method simulation [5].

On the other hand, a gas cluster ion beam (GCIB) technology has been developed as a novel smoothing technique [6], [7]. Our group proposed GCIB planarization for refilling nonmagnetic materials, and we demonstrated planarization of patterned DLC [8]–[10]. GCIB can planarize only surface in depth several nm without ion-damaging inside of the magnetic film. However, we have not studied the planarization of other nonmagnetic materials than DLC. In terms of compatibility with the magnetic layer, nonmagnetic materials other than DLC can be better candidates to refill the grooves. In this study, we studied Ar GCIB planarization effect on surfaces using patterned test samples refilled with Cr, Ta ,and SiO_2. For the demonstration of planarization of them, we used patterned Si substrates as an alternative to magnetic material.

Manuscript received November 10, 2009; revised February 02, 2010; accepted February 12, 2010. Current version published May 19, 2010. Corresponding author: K. Nagato (e-mail: nagato@hnl.t.u-tokyo.ac.jp).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TMAG.2010.2044379

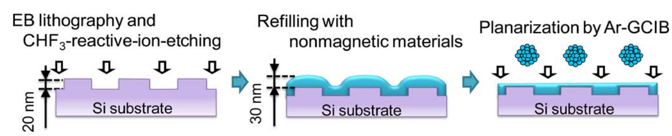

Fig. 1. Schematic of experimental method.

II. EXPERIMENT

A. GCIB Apparatus

In the GCIB system, neutral Ar cluster beams were formed by supersonic expansion of high pressure gas through a nozzle and skimmer. Subsequently, the neutral clusters were ionized by electron bombardments and accelerated to 20 keV. In this study, the clusters formed 3000 atoms at maximum in the distribution.

B. Experimental Method

Fig. 1 shows a schematic of an experimental method. The bit patterns were fabricated on Si substrates by electron beam lithography and CHF_3-reactive-ion-etching (RIE). The bit pattern pitches and the height of peak-to-valley (P-V) were 150/200/300/400 and 20 nm, respectively. Then, Cr, Ta, and SiO_2 as refilling materials were deposited 30 nm in thickness on the patterned substrates by magnetron sputtering.

These dot patterned surfaces were irradiated by the Ar GCIB. The dose was set from 2×10^{15} to 5×10^{15} ion/cm^2. After GCIB irradiations, the resultant surface profiles were measured by an atomic force microscopy (AFM, Dimension 3100, Veeco Instruments). The dimension of the area under observation was $1 \times 1\ \mu m^2$.

III. RESULTS AND DISCUSSIONS

We compared the surface roughness of samples before and after GCIB irradiation. Fig. 2 shows the AFM comparison of the

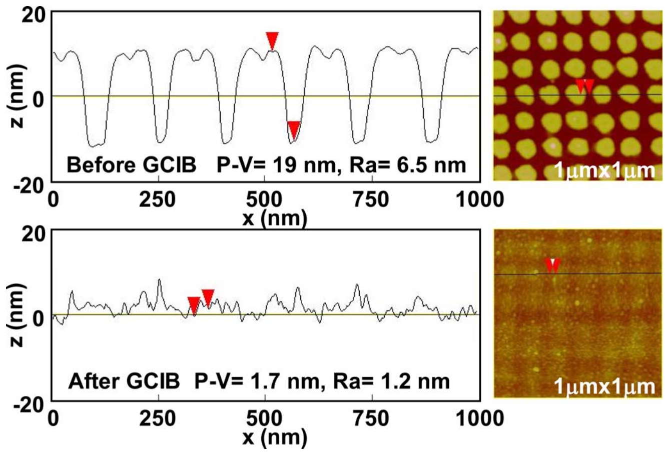

Fig. 2. Cr surface profiles and AFM images before/after GCIB (pitch: 150 nm, dose: 5×10^{15} ion/cm^2).

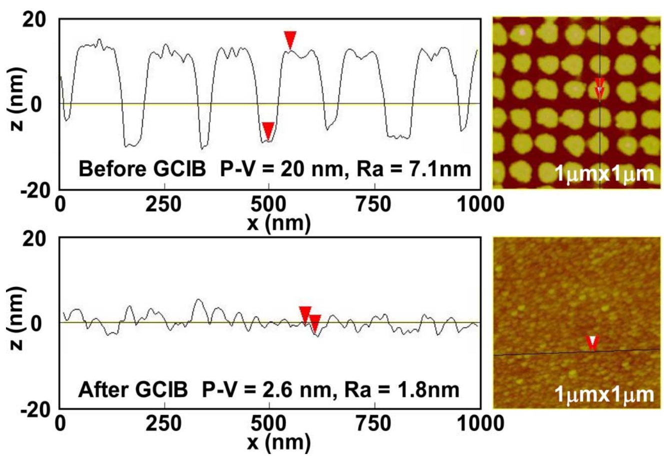

Fig. 3. Ta surface profiles and AFM images before/after GCIB (pitch: 150 nm, dose: 5×10^{15} ion/cm^2).

surface roughness of the sample with the dot pitch of 150 nm refilled with Cr before and after irradiation with an ion dose of 5×10^{15} ion/cm^2. The dot patterns with 19 nm depth were clearly obliterated by GCIB. Average roughness (Ra) after GCIB was decreased from 6.5 to 1.2 nm. In this study, we aim to study the pitch dependence of GCIB planarization effect. Therefore, we stopped irradiation when the samples with 150 nm pitch pattern were disappeared. Therefore, we have confirmed that the roughness improvement was saturated. Further irradiation will be carried out in the future.

In the same way, Figs. 3 and 4 show the comparison of the samples refilled with Ta, SiO_2 before and after irradiation with ion doses of 5×10^{15} and 2×10^{15} ion/cm^2. The dot patterns were disappeared and Ra was decreased.

Fig. 5 shows the dependence of Ra on the ion dose of GCIB. We once had studied samples refilled with DLC, thus the data of DLC was used as a reference of refilling material. Because Ar-GCIB has the physical sputtering effect, the sputtering yield by cluster ion is proportional to the reciprocal of the sublimation energy of target atoms [11]. The sublimation energy depends on the binding energy of the atom and the condition of film. Difference of the sublimation energy made difference of the planarization rate.

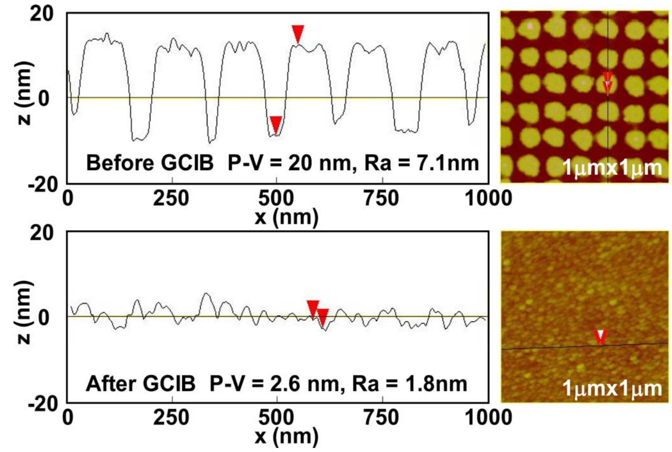

Fig. 4. SiO_2 surface profiles and AFM images before/after GCIB (pitch: 150 nm, dose: 2×10^{15} ion/cm^2).

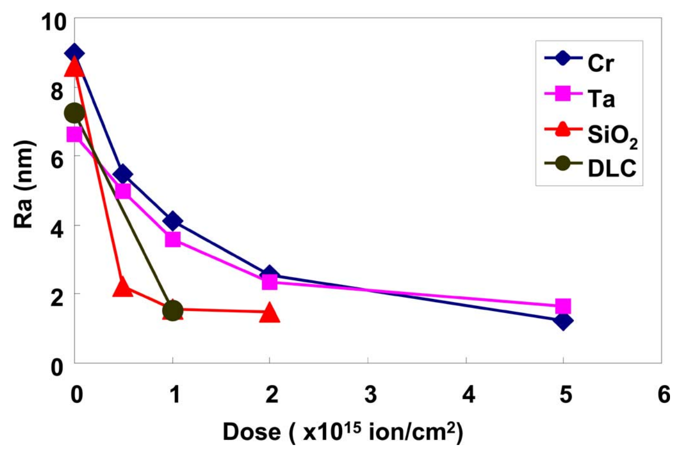

Fig. 5. The dependence of Ra on the ion dose of GCIB.

TABLE I
ETCHING DEPTH AS IRRADIATION WITH ION DOSES OF 1×10^{16} ION/CM^2

	Cr	Ta	SiO_2	DLC
Depth(nm)	4.9	4.6	7.0	12

Table I shows the data about etching depth as irradiation with ion doses of 1×10^{16} ion/cm^2 on plain films. Because the refilling materials were deposited 30 nm in thickness on the 20-nm-height dot patterns, the shortest distance between the bottom of Si surface and the top of dot was 10 nm. After irradiating with ion doses of 1×10^{16} ion/cm^2, the plain films of Cr, Ta, and SiO_2 were etched less than 10 nm. Therefore, we consider that the refilled materials still remain on the patterned samples as irradiation with each ion doses.

Fig. 6 shows the pitch dependence of Ra attenuation rate at the wavelengths of the dot pitches, which are defined as rates of the amplitudes after GCIB divided by those before. The reduction rate was higher at high density track pitch. Patterned media will be used in high density recording region with track pitch of under 150 nm. Therefore, GCIB planarization is assumed to be useful especially for the narrower dot region of patterned media.

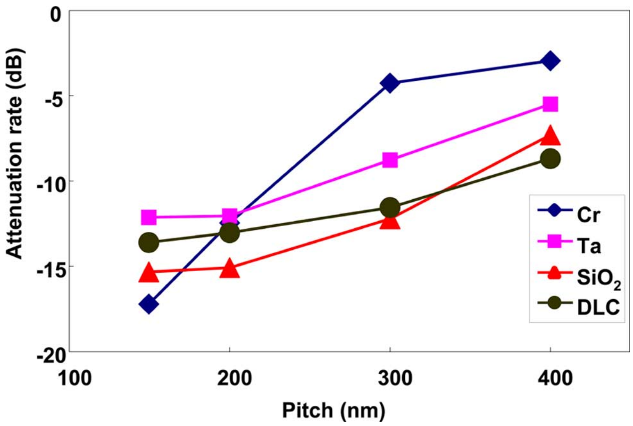

Fig. 6. Pitch dependence of Ra attenuation rate (dose: 5×10^{15} (Cr), 5×10^{15} (Ta), 2×10^{15} (SiO_2), and 1×10^{15} (DLC) ion/cm^2).

IV. Conclusion

We studied Ar GCIB planarization effect on patterned surfaces of Cr, Ta and SiO_2 as refilling nonmagnetic materials for bit-patterned media. Dot patterned surfaces of Cr, Ta, and SiO_2, which were fabricated by depositing on patterned Si substrates, were successfully planarized by Ar GCIB. The planarization rate depended on the sublimation energy of target atoms. As GCIB planarization is effective for small size of structure below 150 nm, it is a suitable planarization process for patterned media. We resulted that GCIB irradiation is effective for the planarization of patterned surface refilled with Cr, Ta, and SiO_2.

Acknowledgment

The bit patterns were fabricated using an electron beam writer (F5112+VD01) at the VLSI Design and Education Center (VDEC), the University of Tokyo, which was donated by Advantest Corporation. This work was supported in part by a Grant-in-Aid for Scientific Research (No. 19106003, 21860015) and by the Global Center of Excellence (G-COE) Program "Global Center of Excellence for Mechanical Systems Innovation (GMSI)" from the Ministry of Education, Culture, Sports, Science and Technology, Japan.

References

[1] M. Albrecht, C. T. Rettner, A. Moser, M. E. Best, and B. D. Terris, "Recording performance of high-density patterned perpendicular magnetic media," *Appl. Phys. Lett.*, vol. 81, pp. 2875–2877, 2002.

[2] H. J. Richter, A. Y. Dobin, O. Heinonen, K. Z. Gao, R. J. M. Veerdonk, R. T. Lynch, J. Xue, D. Weller, P. Asselin, M. F. Erden, and R. M. Brockie, "Recording on bit-patterned media at densities of 1 Tb/in^2 and beyond," *IEEE Trans. Magn.*, vol. 42, pp. 2255–2260, 2006.

[3] H. J. Richter, A. Y. Dobin, R. T. Lynch, D. Weller, R. M. Brockie, O. Heinonen, K. Z. Gao, J. Xue, R. J. M. van de Veerdonk, P. Asselin, and M. F. Erden, "Recording potential of bit-patterned media," *Appl. Phys. Lett.*, vol. 88, p. 222512, 2006.

[4] Y. Soeno, M. Moriya, K. Ito, K. Hattori, A. Kaizu, T. Aoyama, M. Matsuzaki, and H. Sakai, "Feasibility of discrete track perpendicular media for high track density recording," *IEEE Trans. Magn.*, vol. 39, pp. 1967–1971, 2003.

[5] E. E. Nunez, C.-D. Yeo, R. R. Kutta, and A. A. Polycarpou, "Effect of planarization on the contact behavior of patterned media," *IEEE Trans. Magn.*, vol. 44, no. 11, pp. 3667–3670, 2008.

[6] I. Yamada, J. Matsuo, N. Toyoda, and A. Kirkpatrick, "Materials processing by gas cluster ion beams," *Mater. Sci. Eng. R*, vol. 34, pp. 231–295, 2001.

[7] S. Kakuta, S. Sasaki, T. Hirano, K. Ueda, T. Seki, S. Ninomiya, M. Hada, and J. Matsuo, "Low damage smoothing of magnetic material films using a gas cluster ion beam," *Nucl. Instrum. Methods B*, vol. 257, pp. 677–682, 2007.

[8] K. Nagato, H. Tani, Y. Sakane, N. Toyoda, I. Yamada, M. Nakao, and T. Hamaguchi, "Study of gas cluster ion beam planarization for discrete track magnetic disks," *IEEE Trans. Magn.*, vol. 44, pp. 3476–3479, 2008.

[9] N. Toyoda, K. Nagato, H. Tani, Y. Sakane, M. Nakao, T. Hamaguchi, and I. Yamada, "Planarization of amorphous carbon films on patterned substrates using gas cluster ion beams," *J. Appl. Phys.*, vol. 105, p. 07C127-1-3, 2009.

[10] N. Toyoda, T. Hirota, K. Nagato, H. Tani, Y. Sakane, M. Nakao, T. Hamaguchi, and I. Yamada, "Planarization of bit-patterned surface using gas cluster ion beams," *IEEE Trans. Magn.*, vol. 45, pp. 3503–3506, 2009.

[11] J. Matsuo, N. Toyoda, M. Akizuki, and I. Yamada, "Sputtering of elemental metals by Ar cluster ions," *Nucl. Instrum. Meth. B*, vol. 121, pp. 459–463, 1997.