Planarization of amorphous carbon films on patterned substrates using gas cluster ion beams

Noriaki Toyoda,[1,a)] Keisuke Nagato,[2] Hiroshi Tani,[3] Yasuo Sakane,[4] Masayuki Nakao,[2] Tetsuya Hamaguchi,[2] and Isao Yamada[1]
[1]*Incubation Center, University of Hyogo, 2167 Shosha, Himeji, Hyogo 671-2280, Japan*
[2]*Department of Engineering Synthesis, School of Engineering, the University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan*
[3]*Department of Mechanical Engineering, Kansai University, 3-3-35 Yamate-cho, Suita, Osaka 564-8680, Japan*
[4]*Western Digital Media Operations, 1710 Automation Parkway, San Jose, CA 95131, USA*

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Surface planarization and modification of a patterned surface were demonstrated using gas cluster ion beam (GCIB). Grooves with 100–400 nm intervals were formed on amorphous carbon films using focused ion beams to study the special frequency dependence of the planarization. Also, line and space patterns were fabricated on Si substrates, and amorphous carbons were deposited as a model structure of discrete track media. Subsequently, surface planarization using Ar-GCIB was carried out. After GCIB irradiations, all of the grooves were completely removed, and a flat surface was realized. And it showed that GCIB irradiation planarized grooves without huge thickness loss. From the power spectrum density of an atomic force microscope, GCIB preferentially removed grooves with small intervals. It was found from energy dispersive x-ray spectroscopy that surface planarization without severe damage in the amorphous carbon and magnetic layers was carried out with GCIB. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3073665]

I. INTRODUCTION

The capacity of a hard disk drive has increased rapidly by shrinking the size of bit on recoding media. However, if the grain size of 1 bit becomes too small, the energy required to flip the magnetization is so low that it would be thermally unstable. Therefore, discrete track media (DTM) or bit patterned media (BPM) have attracted extensive attention for high areal density of a hard disk drive. However, there are many difficulties to overcome for these new media. One of the most difficult challenges is a surface planarization of patterned media for the flying stability of a slider. It was reported that surface planarization promotes the slider stability.[1]

We have developed the gas cluster ion beam (GCIB) process for surface smoothing of various materials.[2,3] Gas cluster ions are aggregates of thousands of gaseous atoms or molecules. When GCIB bombards a target surface, it induces the lateral motion of sputtered atoms; as a result, surface smoothing proceeds. Besides surface smoothing, GCIB realizes the low-energy ion beam process.[4] Energy per atom of a gas cluster ion can be easily reduced to several eV/atom, which attains a low-damage process for magnetic materials. In this study, pattered samples were prepared, and surface planarization of a nanoscale pattern with GCIB was studied.

II. EXPERIMENT

Neutral gas cluster beams were formed by supersonic expansion of high pressure gas through a Laval nozzle. Subsequently, neutral cluster beams were ionized by electron bombardments and accelerated up to 30 kV. Monomer ions in GCIB were removed by a permanent magnet. Samples were scanned in both horizontal and vertical directions. In this study, Ar gas was used for surface planarization. To study the spatial wavelength dependence of planarization with GCIB irradiation, line and space patterns were formed on amorphous carbon films using focused ion beam (FIB, FB-2000A, Hitachi). In addition, line and space patterns were formed on a Si substrate, and an amorphous carbon film was deposited on it, which was used as an alternative to DTM. The interval of the line and space pattern was 200 nm. Figure 1 shows the experimental procedure. In the case of

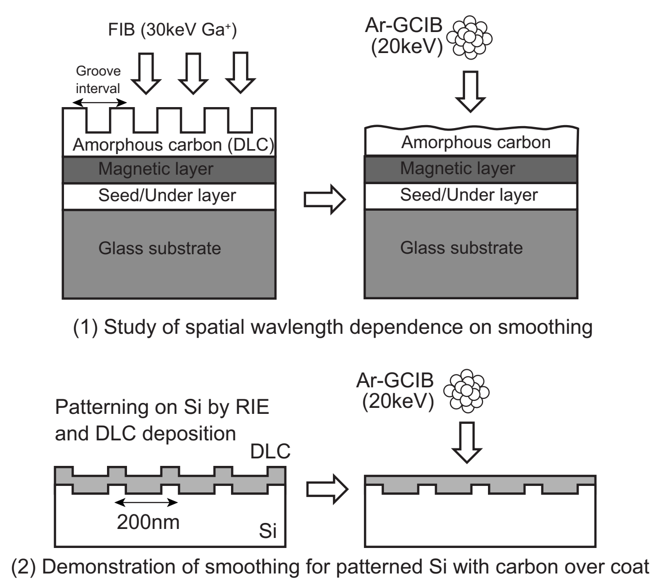

FIG. 1. Experimental procedures.

[a)]Electronic mail: ntoyoda@incub.u-hyogo.ac.jp.

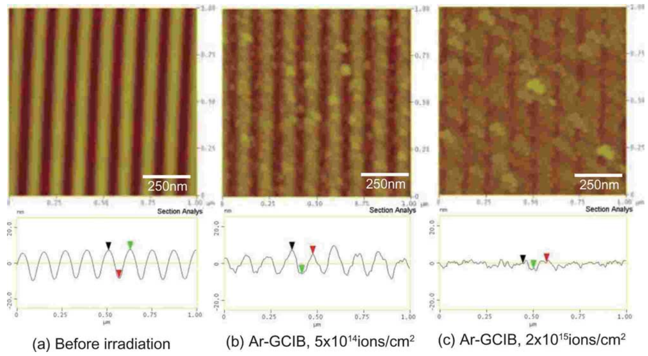

FIG. 2. (Color online) Surface morphology and cross-section profile of AFM before and after Ar-GCIB irradiation with acceleration energy of 20 keV. The ion doses were (b) 5×10^{14} ions/cm^2 and (c) 2×10^{15} ions/cm^2.

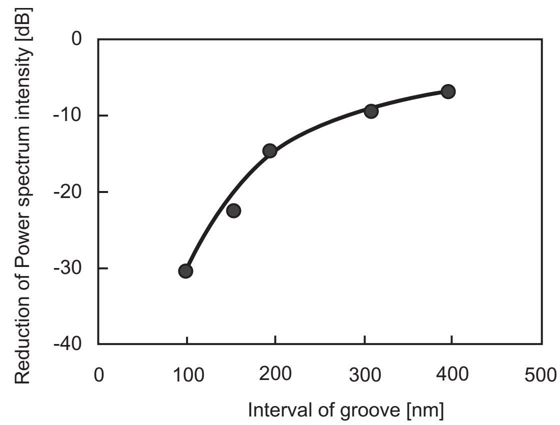

FIG. 4. Dependence of the reduction in carbon roughness power spectral intensity on groove interval.

spatial wavelength dependence study [Fig. 1(1)], the disks used as specimens have seed/underlayer, magnetic layer, and thin carbon overcoat deposited by chemical vapor deposition in 30 nm thickness. Grooves of various intervals were fabricated by FIB. The groove intervals were varied between 93 and 430 nm, and their depths were 15–20 nm. In the FIB sputtering, Ga ions were irradiated on amorphous carbon films [diamondlike carbon (DLC)] with an acceleration voltage of 30 kV and with spot sizes of 30–50 nm. The patterned area by FIB was 8×8 μm^2. For these patterned samples, Ar-GCIB irradiation with acceleration energy of 20 keV was carried out. The ion dose was changed from 5×10^{14} to 5×10^{15} ions/cm^2. The average cluster size was 2000 atoms/cluster.

In the case of the patterned Si samples with carbon overcoat, as shown in Fig. 1(2), Ar-GCIB irradiation was carried out with the acceleration voltage of 20 kV and the ion dose of 2×10^{15} ions/cm^2. After irradiation, surface morphologies were observed with an atomic force microscope (AFM), and the cross-sectional transmission electron microscope (TEM) observation was performed. In addition, energy dispersive x-ray spectroscopy (EDS) was used for an elemental analysis of the irradiated area.

III. RESULTS AND DISCUSSIONS

Figure 2 shows AFM surface images and cross-section profiles of (a) before irradiation, (b) after Ar-GCIB irradiation with 5×10^{14} ions/cm^2, and (c) after Ar-GCIB irradiation with 2×10^{15} ions/cm^2. The scan area of AFM was 1×1 μm^2. The interval and depth of grooves were 105 and 15 nm, respectively. Before irradiation, very clear grooves were observed. However, these grooves became unclear with increasing ion dose, and it showed an almost flat surface with an ion dose of 2×10^{15} ions/cm^2, as shown in Fig. 2(c). Planarization of these grooves was also observed with cross-sectional TEM images shown in Figs. 3(a)–3(c). Before irradiation (a), sinusoidal wave on an amorphous carbon layer can be observed due to the beam profile of FIB. The bright layer was amorphous carbon [shown as area {2} in Fig. 3(b)], and the dark layer beneath amorphous carbon was a magnetic layer [area {3} in Fig. 3(b)]. Because of the high-energy Ga irradiation of the FIB process, the irradiated area showed mixing of carbon and magnetic layers [area {1} in Fig. 3(b)]. After irradiation with an ion dose of 5×10^{14} ions/cm^2, the height of the hills decreased and the depth of the valley increased instead. With further increase in ion dose to 2×10^{15} ions/cm^2, a flat amorphous carbon surface was realized. Even though the surface was planarized, most of the amorphous carbon layer still remained. This result indicated that surface planarization without huge thickness loss is possible using GCIB irradiation.

To investigate the groove interval dependence of planarization with GCIB, samples with various groove intervals (100–400 nm) were prepared. After Ar-GCIB irradiations, AFM images of these samples were taken, and spatial wavelength dependence was studied from the power spectrum of AFM images. Since the intense peak appeared at the wavelength equal to the groove interval, the reduction in the peak intensity before and after Ar-GCIB irradiation was plotted. Figure 4 shows the relationship between the groove interval and the reduction in power spectrum intensity. Under this

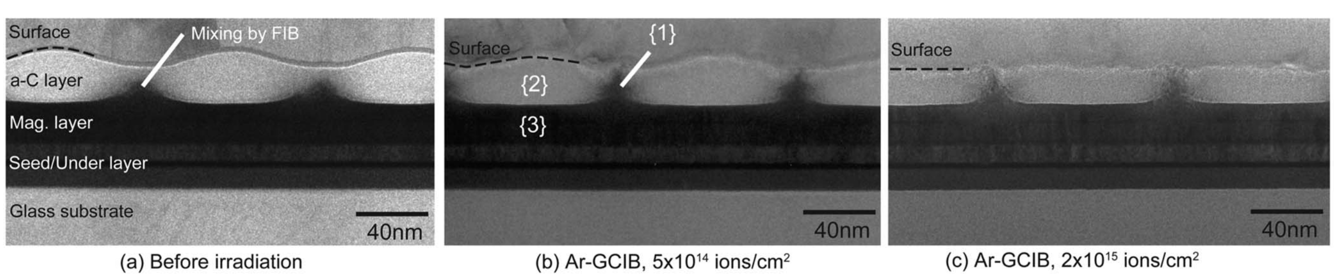

FIG. 3. Cross-sectional TEM view of grooves on amorphous carbon after irradiation of Ar-GCIB (acceleration energy: 20 keV; ion dose: 5×10^{14} and 2×10^{15} ions/cm^2).

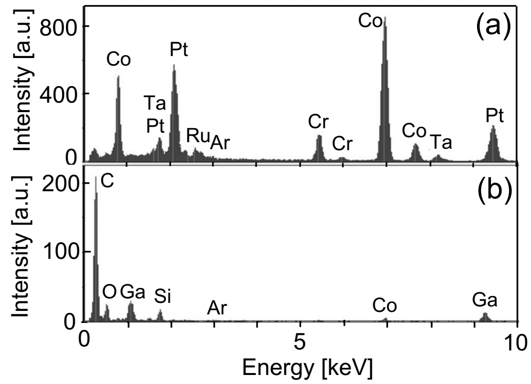

FIG. 5. EDS of (a) amorphous carbon and (b) magnetic layer after Ar-GCIB irradiation with an ion dose of 5×10^{14} ions/cm^2.

irradiation condition (Ar-GCIB, acceleration energy of 20 keV, and ion dose of 5×10^{15} ions/cm^2), surface planarization with GCIB was effective for the pattern having a groove interval below 200 nm. As the surface planarization with GCIB was dominated by the lateral motion of atoms induced by individual gas cluster ion impacts, structures with small spatial wavelengths were removed preferentially. This result showed that surface smoothing with GCIB is effective for patterns with small intervals.

The low-damage process is one of the important characteristics of GCIB. As the individual gas atoms or molecules have the energy divided by their cluster size, quite low-energy ion beam with several eV/atom is easily realized. Figure 5 shows EDS spectra for the area irradiated with Ar-GCIB. The acceleration energies of Ga ion (FIB) and Ar-GCIB were 30 and 20 keV, respectively. The ion dose of Ar-GCIB was 5×10^{14} ions/cm^2. In the case of the area irradiated with Ga ions, as shown in Fig. 3(b) ({1}), mixing of Ga and carbon occurred. Also, Ga ion implantation to the magnetic layer beneath carbon layer was observed. On the other hand, as shown in Fig. 5(a), there was no Ar implantation in area {2} in Fig. 3(a). The Ar peak should appear around energies of 2.9 and 3.2 keV. Also, the magnetic layer beneath it [Fig. 3(b), {3}] had no damage, which is shown in Fig. 5(b). This result indicates that low-damage processing and surface modification for only the top surface layer are possible using the GCIB process.

To demonstrate the smoothing effect with GCIB on DTM, patterned Si with carbon overcoat was prepared, as shown in Fig. 1 and 2. Figure 6 shows a cross-sectional TEM image of patterned Si with carbon overcoat after Ar-GCIB irradiation. AFM images of before irradiation and after Ar-GCIB irradiation were also presented. Before irradiation, there were lines with an interval of 200 nm. However, these lines were completely removed after Ar-GCIB irradiation. From the cross-sectional images, it is clarified that only the amorphous carbon layer was smoothed and the shape of the Si pattern was retained. Thus, embeddings of the carbon overcoat layer into the gap of Si lines were realized, and a plane carbon surface was obtained. Although the pattern interval of this sample was 200 nm, GCIB smoothing is favorable for a small size of pattern, as shown in Fig. 4. Therefore, the GCIB technique would be a good candidate for planarization of DTM or BPM.

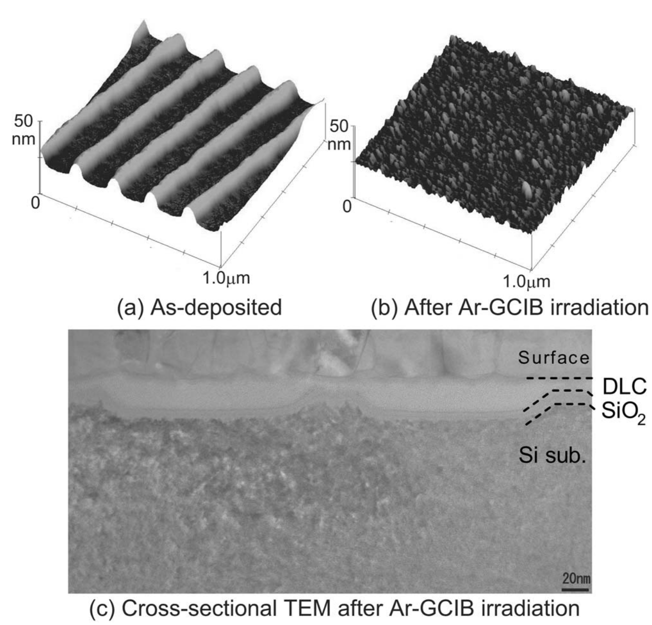

FIG. 6. Cross-sectional TEM image of the patterned Si with carbon overcoat after Ar-GCIB irradiation (acceleration voltage=20 kV; ion dose=2×10^{15} ions/cm^2). AFM images of before and after Ar-GCIB irradiation are also presented.

IV. SUMMARY

Planarization of a patterned surface on amorphous carbon with Ar-GCIB was studied, aiming at DTM or BPM. After Ar-GCIB irradiation, grooves formed by FIB were completely removed with an ion dose of 2×10^{15} ions/cm^2. The thickness required for planarization was quite small, and the damage in the magnetic layer was negligible. Also, the patterned Si with carbon overcoat was planarized with Ar-GCIB, and embeddings of the amorphous carbon film into the gap of Si lines were realized. As GCIB planarization is effective for a small size of structure below 200 nm, it is a suitable planarization process for patterned media.

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