FePtAg-C Nanogranular Film as Thermally Assisted Magnetic Recording (TAR) Media

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We studied highly $L1_0$-ordered FePtAg-C nanogranular film as a potential high-density storage medium for thermally assisted magnetic recording (TAR). A 6.4-nm-thick FePtAg-C film was fabricated on an oxidized silicon substrate with a 10-nm MgO underlayer at 550°C, with the perpendicular coercivity of 35 kOe, and average grain size of 6.2 ± 1.4 nm. The time-dependence measurement of remnant coercivity results in the energy barrier $E_b = 5.1$ eV $\sim 200\, k_B T$, meaning excellent thermal stability for long-term data storage. The static tester experiments by TAR head demonstrated an areal density of 550 Gb/in^2.

***Index Terms*—FePt granular thin film, thermal stability, thermally assisted magnetic recording (TAR).**

I. Introduction

THE $L1_0$-ordered FePt granular thin film is considered as the most promising candidate for perpendicular magnetic recording (PMR) media with the recording density of 1 Tbit/in^2 and above, because the high magnetocrystalline anisotropy ($K_u \sim 7 \times 10^7$ erg/cc) of the $L1_0$ FePt phase enables reducing the grain size as small as 4 nm without thermal instability of magnetization [1]–[3]. The difficulty of switching the magnetization of high coercivity single domain $L1_0$-FePt particles can be overcome by the thermally assisted magnetic recording (TAR) method [4]–[6]. For the practical application of FePt films as TAR media, the c axis of magnetically isolated $L1_0$-FePt particles of less than 5 nm with a narrow size distribution (less than 1.0 nm) must be perfectly aligned in the normal direction to the film plane. In addition, appropriate thermal conductance for the substrate will be necessary, which enables excellent heat transfer for the TAR process. In our early effort, we reported well-separated perpendicular anisotropic granular films with a narrow size distribution by cosputtering FePt and C on the MgO interlayer [7]. Polycrystalline MgO layer grew with strong (001) texture on thermally oxidized silicon substrates, which worked as an effective seedlayer for the epitaxial growth of (001) FePt particles. Nevertheless, the coercivity of the FePt-C films was only 10 kOe. To increase the coercivity by enhancing the $L1_0$ ordering, we introduced Ag into the FePt-C granular thin films, and succeeded in the fabrication of high coercivity (37 kOe) FePtAg-C granular films with perpendicular anisotropy [8]. However, the squareness of the early film was not unity so that it did not give sufficient switching field distribution (SFD) behavior. In this paper, we present FePtAg-C granular film with improved recording performance using a TAR static write tester.

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II. Experimental

We fabricated a $Fe_{0.49}Pt_{0.41}Ag_{0.1} - 50$vol.%C film of about 6.4-nm thickness on a thermally oxidized silicon substrate with a 10-nm-thick MgO interlayer using an ultrahigh vacuum magnetron and RF cosputtering machine. The thickness of the film; the atomic ratio of Fe, Pt, and Ag; and the C volume fraction were estimated based on the precalibrated sputtering rates of Fe, Pt, Ag, and C. Note that the Fe:Pt ratio in this film was 54:46, not 50:50, for achieving the best $L1_0$ order in the film. This is consistent with other researchers' work on $L1_0$-ordered FePt thin films [9]–[11]. During deposition, the base pressure of the chamber was $\sim 1 \times 10^{-6}$ Pa. First, the MgO layer was deposited on the oxidized silicon substrate at 100 °C by RF sputtering under 1.3 Pa Ar gas pressure with a deposition rate of 0.033 nm/s. Subsequently, a FePtAg-C layer was deposited by co-sputtering Fe, Pt, Ag, and C on the Oxi.Si./MgO substrate at 550 °C under 0.6 Pa Ar, with the deposition rate of 0.02 nm/s. The crystalline structure and the $L1_0$ ordering of the film were examined by the standard X-ray diffraction (XRD) technique. The magnetic properties were measured through a superconducting quantum interferometer device (SQUID), Quantum Design MPMS with the applied magnetic field up to ±55 kOe. The microstructure of the film was characterized by the bright-field and high-resolution transmission electron microscopy (TEM) using Technai F30 TEM. The distribution of Ag and C in the film was analyzed qualitatively through electron energy-loss spectroscopy (EELS) by the post column imaging filtering technique using a Gatan Trideam imaging filter.

In order to demonstrate the recording performance of this FePt thin film, we applied an antenna-integrated TAR head in a static tester. The details of the TAR head were reported elsewhere [12], [13]. Nanosecond laser pulses and the pulsed magnetic field from the write pole were applied for static tester recording experiments. Images were generated by scanning the onboard tunneling magnetoresistive (TMR) element (70 nm width), or the TMR element from a second head (narrower width).

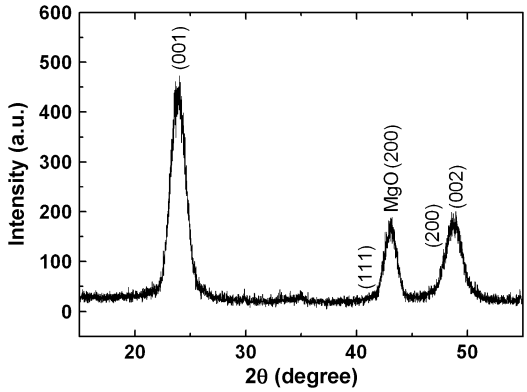

Fig. 1. XRD pattern of the FePtAg-C granular film.

III. Results and Discussion

Fig. 1 shows an XRD pattern of the FePtAg-C granular film. The $(001)_{\mathrm{FePt}}$ and $(002)_{\mathrm{FePt}}$ peaks of the $L1_0$-FePt structure are clearly observed with a missing $(111)_{\mathrm{FePt}}$ peak, indicating the FePt grains are strongly (001) textured. This texture was induced by the $(200)_{\mathrm{MgO}}$ texture of the 10 nm-MgO underlayer [8]. We estimated the degree of $L1_0$-order from the ratio of the integrated intensities of (001) superlattice and (002) fundamental reflections to be 0.88, much higher than the previously reported values for FePt-C [7]. Note that the diffraction corresponding to an Ag phase was not confirmed, suggesting the dissolution of Ag in FePt particles. Fig. 2 shows the TEM bright field image, selected area electron diffraction (SAED) pattern, and grain-size distribution of the film. The SAED pattern also shows distinct (001) superlattice reflection and the (002) fundamental reflection of the $L1_0$-FePt. They are basically induced by the $(200)_{\mathrm{MgO}}$ texture from the interlayer. The missing $(111)_{\mathrm{MgO}}$ and $(111)_{\mathrm{FePt}}$ diffractions suggest that the MgO underlayer and $L1_0$-FePt crystals are strongly (001) textured. In the bright-field TEM image, FePt particles are observed with darker contrast though the contrast varies depending on the diffraction conditions arising from a slight change in orientations. The bright imaging channels are amorphous carbon. From the histogram analysis, the average grain size of the film was determined to be 6.2 ± 1.4 nm. The average value of center-to-center distance was measured to be 9.6 nm based on the TEM bright-field image, so that the average carbon spacing is estimated to be 3.4 nm or less.

Figs. 3 and 4 show the typical energy-filtered TEM images of the film in plane and cross-section views, respectively. For each figure, (a) shows the zero-loss bright field TEM images, and (b)$\sim$(f) display the Fe, Pt, Ag, C, and O maps, respectively. The O map represents the MgO and the thermally oxidized amorphous SiO_2 layer on the top of the crystalline silicon substrate. We found that the intensities for Ag, Fe, and Pt atoms are all higher in the FePt particles, suggesting that the Ag is dissolved in the FePt particles as reported previously by Platt *et al.* and You *et al.* [14], [15]. However, this contradicts the idea that Ag atoms are rejected from FePt, by which the kinetics for ordering are enhanced [14]. The intensity of the C map is stronger in the surrounding area, suggesting the C form intergranular phase that isolates $(\mathrm{FePt})_{0.9}\mathrm{Ag}_{0.1}$ particles. Finally, the intensity of the O map is stronger in the surrounding area and the layers beneath the FePtAg-C film layer, which is consistent with the MgO interlayer and the SiO_2 layer between the silicon substrate and the MgO interlayer. In Fig. 4, we found that the TEM specimen was bent during Ag, Fe, and O mapping. This is due to the high electron dosage during the filtering process.

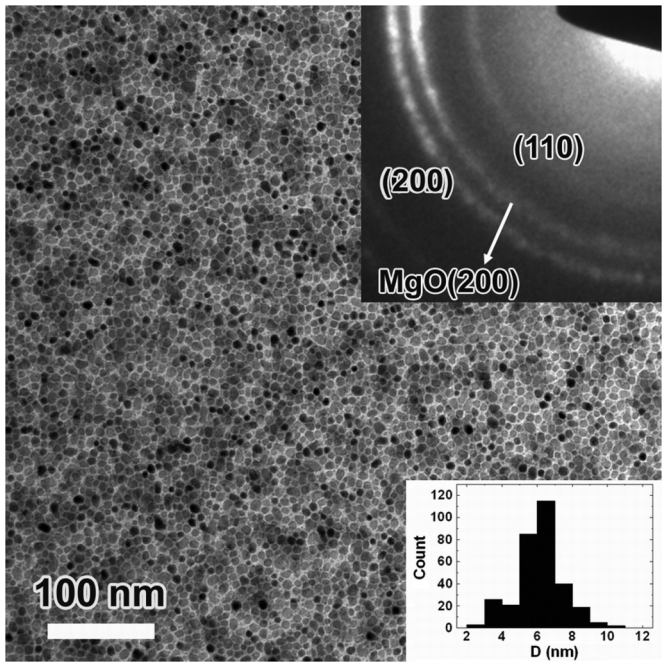

Fig. 2. TEM bright-field image, selected area electron diffraction (SAED) pattern, and grain-size distribution diagram of the FePtAg-C granular film.

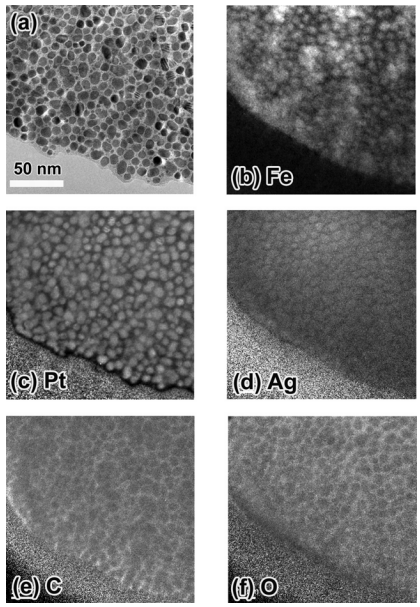

Fig. 3. Energy filtered plane-view TEM images of the film. (a) Zero-loss bright field image. (b) Fe map. (c) Pt map. (d) Ag map. (e) C map. (f) O map.

Fig. 5 shows (a) the plane-view and (b) cross-sectional high-resolution TEM images of FePt nanoparticles. From the plane view image, the $L1_0$-ordered FePt particles can be clearly seen on an MgO matrix. The grain boundaries of MgO crystals in the underlayer can be clearly viewed as indicted by the yellow

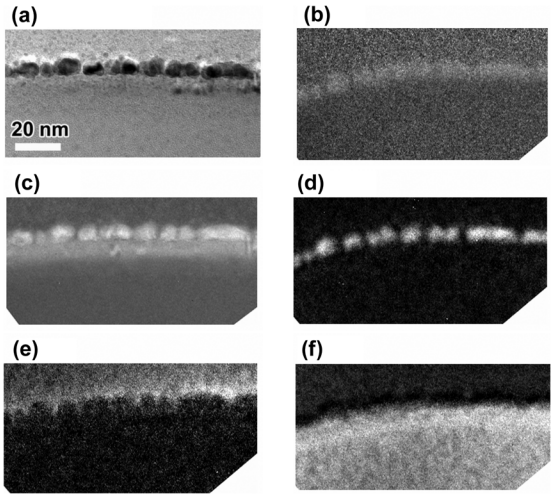

Fig. 4. Energy filtered cross-section TEM images of the film. (a) Zero-loss bright field image. (b) Fe map. (c) Pt map. (d) Ag map. (e) C map. (f) O map.

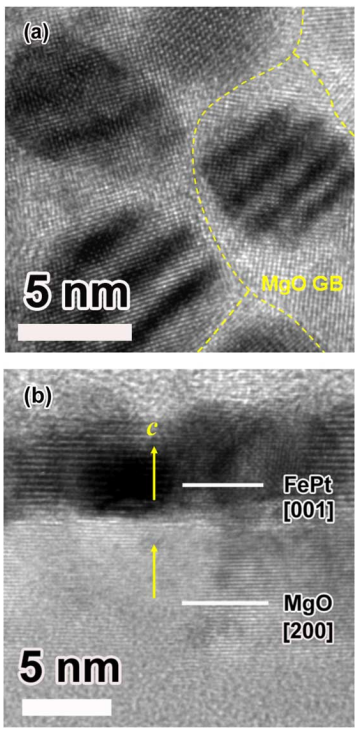

Fig. 5. (a) Plane-view and (b) cross-section high-resolution TEM images of FePt nano-grains, displaying a distinct $L1_0$ order.

broken lines. More than two FePt particles can be seen in a single MgO grain, suggesting that there is no direct correlation between the MgO crystal grain size and the size of FePt particles. The cross-sectional TEM image also shows that there is no direct correlations between the underlayer MgO grains and top-layer FePtAg particles. However, there is an epitaxial relationship between the FePt particles and MgO grains (i.e., $(001)[001]_{\mathrm{FePt}}//(001)[011]_{\mathrm{MgO}}$). This suggests that although the MgO polycrystalline underlayer has an effect of aligning FePt particles to the [001] direction normal to the film plane, it has no effect in controlling the crystal grain size of the FePtAg-C recording layer.

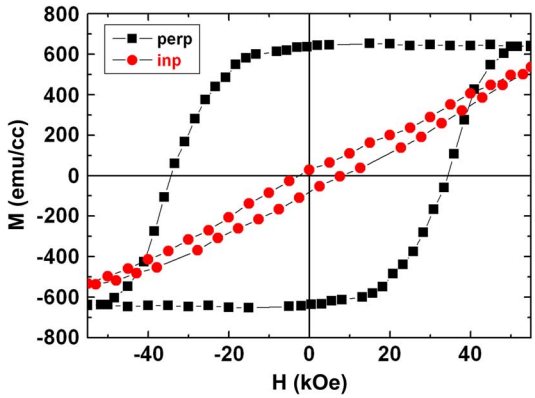

Fig. 6. Both perpendicular and in-plane M-H loops of the FePtAg-C granular film.

As expected from the strong (001) texture of this film, the M-H loops in Fig. 6 show that this film has a strong perpendicular anisotropy with perpendicular $H_{\mathrm{Cperp}} = 35$ kOe and $H_k = 65$ kOe. The anisotropy K_u of this film was calculated from the in-plane and out-of-plane M-H loops to be 3.0×10^7 erg/cc, which is approximately 50% of the value reported for the fully $L1_0$-ordered FePt. In calculating K_u, we apply the $M_S^* = 930$ emu/cc, the magnetization of FePtAg grains excluding carbon spacer, which is higher than the value shown in the MH loop [8]. Considering the degree of order estimated from XRD in Fig. 1, this anisotropy constant is reasonable. In addition, this film shows an inplane H_{Cinp} of 8 kOe. In order to improve the recording performance of the PMR media, $H_{\mathrm{Cperp}} \gg H_{\mathrm{Cinp}}$ is required [8]. It can be improved by optimizing the epitaxial growth of FePt grains on the MgO(200) interlayer.

Furthermore, we studied the thermal stability of this granular film by measuring the time dependence of the remnant coercivity $H_C(t)$ with different waiting times [16]. By fitting data with the Sharrock equation [17]

$$H_c(t) = H_{c0}\left\{1 - \left[\frac{k_B T}{E_b}\ln\left(\frac{f_0 t}{0.693}\right)\right]^{1/2}\right\}$$

we obtained $E_b = 5.1$ eV, and $H_{c0} = 37.5$ kOe. At $T = 300$ K, $k_B T = 0.025$ eV, so the energy barrier E_{b} is about 200 $k_B T$. When $E_b > 40 k_B T$, the magnetization of the grain in recording bits will be thermally stable for more than ten years [3]. The timing length increases exponentially with increasing E_b values. Therefore, this granular film has excellent thermal stability qualified for high-density magnetic recording media.

Fig. 7 shows the recording pattern tracks written at various bit lengths from 15 to 50 nm at a track width of 92 nm. The signal-to-noise ratio (SNR) was determined by the center-track scan lines of the image. We compare the SNR of the FePt-TAR tones to the SNR obtained on well-characterized conventional head and PMR media using the static tester. Using the measured 1T SNR of the conventional recording system as a benchmark, we found that the SNR on this FePt medium matches the 1T SNR of the conventional recording system for a bit pitch of 14.5 nm and a track width of 81 nm. By taking the narrowband amplitude full-width half maximum (FWHM) of the tracks as an estimation of the achievable track pitch and 14.5 nm as

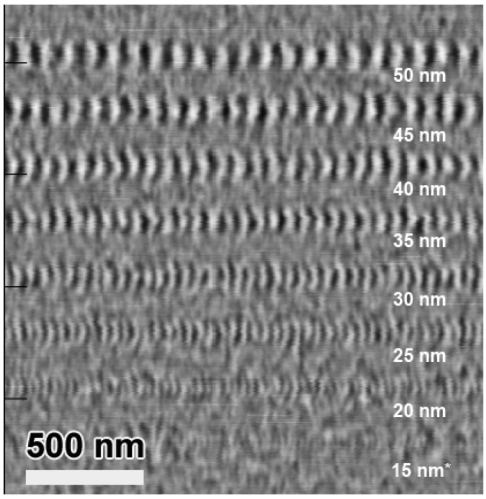

Fig. 7. Recording pattern tracks written at various bit lengths from 15 to 50 nm. The track width is 92 nm.

the smallest achievable bit length, we calculate the maximum achievable areal density as 550 Gb/in^2. Actual areal density at a sufficiently low error rate for commercialization may be somewhat lower or higher than this estimation. This recording density is substantially improved compared with our earlier report using a lower squareness film [16], suggesting that further improvement of the granular structure as well as the magnetic properties will lead to a higher recording density using a TAR static tester. In this paper, we used thermally oxidized silicon substrate, which is coated with a 120-nm amorophous-SiO_2 layer. Improved thermal conductance will influence the recording performance, and the work with different substrates as well as with heat sinks will be of great interest to understand the TAR recording performance.

IV. Conclusion

We successfully fabricated 6.4-nm FePtAg-C granular thin film on an oxidized silicon substrate through a strongly (001) textured MgO interlayer at a substrate temperature of 550 °C. This film has high perpendicular coercivity of 35 kOe and an average grain size of 6.2 ± 1.4 nm. The measurement of remnant coercivity with time decay shows that the film is thermally stable for data storage. The recording demonstration on this film by a TAR static tester shows excellent heat sinking, with a maximum areal density of 550 Gb/in^2. All of those results are encouraging to support the feasibility of applying FePtAg-C granular films to the next generation high-density recording media.

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