High Density Perpendicular Magnetic Recording Media of Granular-type FePt/MgO/Fe-Ta-C double-layers

Zhengang Zhang, Jinhua Yin, Amarendra K. Singh, A. Perumal, and Takao Suzuki
Information Storage Materials Laboratory, Toyota Technological Institute, 2-12-1, Hisakata, Tempaku-ku, Nagoya, 468-8511, Japan
Hiroshi Osawa
Showa Denko HD KK, 5-1 Yawatakaigai-dori Ichihara-shi, Chiba, 290-0067, Japan

Granular-type FePt films with perpendicular magnetic anisotropy are obtained on top of Fe-Ta-C magnetic soft underlayer by annealing FePt/MgO multilayers. For high-density perpendicular magnetic recording medium application, the issues regarding the FePt film crystallographic texture, microstructure, chemical ordering and magnetic properties are addressed in this paper. Based on this medium design, double-layered FePt disks are fabricated on 2.5-inch glass discs. The magnetic recording performances of these disks are evaluated by a spin-stand. The results reveal a close correlation between the disks SNR recording performance with the initial multilayer structure.

Key words: FePt films, grain size, perpendicular recording media, (001)-texture, chemical ordering

1. Introduction

With magnetic recording density approaching 1 Tbit/in², the currently used CoPtCr-based recording media will no longer be able to provide a thermally stable written bit1). To overcome this problem, one of the technical roadmaps is to utilize high magnetic anisotropy (Ku) materials such as L1₀ FePt alloy as recording medium3). FePt L1₀ phase exhibits a Ku value in the order of 10⁷ erg/cc, which is one order of magnitude higher than that of currently used media in commercialized hard disks. It is well accepted that double-layered perpendicular magnetic recording scheme will be employed for such a high recording density. Therefore, fabrication and testing of the double-layered FePt perpendicular recording disks are essential for future high-density magnetic recording.

With exchange-coupled continuous FePt films, double-layered FePt disks have been fabricated and tested, exhibiting both high resolution and high thermal stability of the recorded magnetization3). However, for granular-type FePt disks, it was only recently that the magnetic recording performance was demonstrated4). The obstacles to achieve double-layered granular-type FePt disks arise from the difficulty in controlling FePt crystalline texture on glass substrate and appropriate coercivity for spin-stand read/write testing5).

It was suggested that (001)-textured granular-type FePt films can be obtained on top of Fe-Ta-C magnetic soft underlayer (SUL) by annealing FePt/MgO multilayer films6). The magnetic properties and film microstructure can be modulated by varying the initial FePt/MgO multilayer structure and the annealing condition7)-8). Based on this FePt-MgO system, double-layered granular-type FePt perpendicular magnetic recording disks have been fabricated and tested on the magnetic recording performance by a spin-stand4).

In this paper, we will address the issues in more detail on how to control FePt film (001)-texture, microstructure, chemical ordering, and magnetic properties for the purpose of perpendicular magnetic recording medium application. The disk recording performance will be discussed based on the film microstructure and magnetic properties.

2. Disk fabrication and characterization

The schematic view of disk structure is shown in Fig.1. A 200-nm Fe-Ta-C film deposited by DC magnetron-sputtering with a deposition rate of about 100 nm/min was used as the magnetic soft underlayer. As deposited Fe-Ta-C film has an amorphous structure, which provides a smooth SUL surface for the subsequent film deposition. After annealing at about 500 °C, α-Fe nano grains precipitate out, exhibiting a good soft magnetic properties9). The reason for choosing Fe-Ta-C as SUL in our disks came from the relatively high process temperature of this material and relatively low recording noise from SUL10). However, we have found that our double-layered

Fig.1 Schematic view of disk structure.
SUL properties such as inducing an in-plane magnetic anisotropy along disk radial direction. The intermediate SiO₂ layer was used to induce MgO (200)-texture, which is critical for the subsequent epitaxial growth of fcc FePt film with an (200)-texture ⁶. For the deposition of SiO₂, MgO and FePt films, we used rf magnetron-sputtering. The sputtering condition for FePt film, having a composition close to Fe₅₀Pt₅₀, was optimized to suppress FePt sputtering condition for FePt film, having a composition close to Fe₅₀Pt₅₀, was optimized to suppress FePt sputtering. The sputtering condition for FePt film, having a composition close to Fe₅₀Pt₅₀, was optimized to suppress FePt sputtering with an (200)-texture ⁶. For the deposition of SiO₂, MgO and FePt films, we used rf magnetron-sputtering. The substrate temperature was ambient temperature for all film depositions. The base vacuum of our sputter chamber is 3×10⁻⁸ Torr. Subsequent annealing was applied to the disk after film deposition in another inter-connected high-vacuum chamber, where a Ta-plate heater is equipped. In this work, double-layered disks have the stack structure of [MgO/FePt]ₙ /MgO 4 nm/SiO₂ 4 nm/Fe-Ta-C 200 nm/Glass. Single-layered coupon samples were also made on glass substrates for structure analysis and some magnetic measurements. Annealed disks were then coated with carbon layer and lubricant layer for spin-stand testing.

X-ray diffraction was used to detect the film crystallographic texture and to determine the FePt chemical ordering. The bright-field plan-view images of annealed FePt/MgO multilayer films were observed by Transmission Electron microscopy (TEM). Polar magneto-optical Kerr effect was employed to measure out-of-plane hysteresis loops of double-layered disks. The angular-dependent coercivity measurement was performed using vibrating sample magnetometer. Alternating Gradient Field Magnetometer (AGFM) was utilized to measure remanent coercivity as a function of applied field waiting time, which allows us to estimate the perpendicular magnetic anisotropy and activation volume ⁷. For spin-stand testing, a commercialized merged recording head designed for 50 Gbit/m² longitudinal recording was used, which has a MWW = 0.26 μm and a MRW = 0.14 μm. The SN₉R ratio, defined here as the zero-to-peak signal at 66 kHzc divided by the integrated rms noise over 150 MHz bandwidth after writing at 790 kHzc, was evaluated on the tested disks. It should be noted that the combination of double-layered medium with ring-head writing might lead to a degraded resolution at high linear densities.

3. Results and discussion

3.1 FePt (001)-texture establishment

For perpendicular magnetic recording application, FePt films should be (001)-textured, i.e., the magnetic easy-axis (c-axis) should be along film normal direction. Since (111)-textured FePt grains have the minimum surface energy, it is common to find the (111) XRD peak in annealed FePt films. On MgO underlayer, a thickness dependence of FePt film texture and suppression of FePt (111)-texture in annealed FePt/MgO multilayer films have been discovered ⁸. To completely avoid the (111)-texture in FePt films, the rf sputter power and Ar pressure were also the critical factors. Fig. 2 shows the influence of power on FePt film texture. Only in 5 W-deposited FePt film, we have not observed any FePt (111) peak. It was also found that with increasing Ar pressure, the relative intensity of FePt (111) peak decreases. It is understood that the sputtered species from FePt target should have a low kinetic energy, which can be achieved by a low sputter power or a high Ar pressure, to favor the growth of (200)-textured fcc FePt film on MgO underlayer. In order to see the effect of annealing, we have compared both as-deposited and annealed samples prepared at 5 W power. In Fig. 2, with decreasing the rf sputter power, the FePt (001) superlattice peak becomes stronger and moves to small lattice constant 20 angle and concurrently the fcc FePt (200) diffraction peak disappears, indicative of the much higher FePt chemical ordering in perfectly (001)-textured FePt films. This correlation between FePt (001)-texture with FePt chemical ordering reveals that the stress effect from the lattice mismatch between FePt and MgO epitaxial layers plays an important role in affecting the FePt chemical ordering process.

In order to control FePt grain size, MgO volume ratio, and recording layer M_r, one need to vary the FePt/MgO multilayer structure including FePt and MgO layer thickness and multilayer repetition period. Therefore, the FePt texture should be investigated with regard to these varying. Fig. 3 and 4 show the FePt thickness and MgO thickness effect on FePt texture, respectively. It is observed that neither increasing the FePt thickness up to 3 nm nor decreasing the MgO thickness down to 1 nm induce FePt (111) peak. Unlike the FePt texture, the FePt chemical ordering exhibits a sensitive dependence on the FePt layer thickness. With decrease in FePt thickness down to 1 nm, almost no ordered FePt phase can be detected for this sample with the used annealing condition. The dependence

![Fig. 2 X-ray diffraction patterns of [MgO 2 nm/ FePt 2.5 nm] films in both as-deposited conditions and annealed at 600 °C for 5 min's. The FePt films were deposited with different rf powers at 3 mTorr Ar pressure.](image-url)
of FePt ordering on MgO thickness is not as sensitive as that on FePt thickness.

Fig.3 X-ray diffraction patterns of \([\text{MgO } 2 \text{ nm/ FePt } t \text{ nm}]_3\) multilayer films in both as-deposited and annealed at 600 °C for 1 min conditions.

Fig.4 X-ray diffraction patterns of \([\text{MgO } t \text{ nm/ FePt } 2 \text{ nm}]_3\) multilayer films annealed at 600 °C for 1 min.

3.2 FePt grain size control

Figure 5 shows TEM plan-view image of annealed FePt/MgO multilayer film. Granular-type microstructure is observed. The mean FePt gain size, calculated from the corresponding histogram, is about 7 nm. The most effective way to decrease FePt grain size is by decreasing the FePt layer thickness. Fig. 6 shows the FePt grain size dependence from about 11.5 to 4.5 nm. Consequently, the activation volume is decreased. The tendency of approaching a constant value for activation volume with decreasing the FePt thickness after 2 nm is believed due to the low ordering of FePt in these samples. It has been found that the MgO volume ratio and annealing condition can also affect the FePt grain size and activation volume.

Fig.5 TEM bight-field plan-view image of \([\text{MgO } 2/\text{FePt } 2 \text{ nm} ]_3\), annealed at 600 °C for 1 min and FePt grain size distribution.

3.3 FePt/MgO layered structure

For recording medium application, a column structure is more preferred than layered structure. Compared with column structure, the problems associated with layered structure are smaller activation volume for a same grain diameter and enlarged effective in-plane grain diameter, which will induce decreased thermal stability factor and high transition noise, respectively. Fortunately, by decreasing the MgO thickness, the layered structure in annealed FePt/MgO films can be removed. Fig. 7 compares the low-angle X-ray diffraction patterns of two multilayer

Fig.6 FePt grain size dependence on FePt layer thickness. The activation volume is also plotted. The multilayer structure is \([\text{MgO } 2 \text{ nm/ FePt } t \text{ nm}]_3\), annealed at 600 °C for 1 min.

Fig.7 Low-angle X-ray diffraction patterns of (a) \([\text{MgO } 2 \text{ nm/FePt } 2.5 \text{ nm} ]_3\), as-grown and annealed at 550 °C, 10 min’s (b) \([\text{MgO } 0.8 \text{ nm/FePt } 1.5 \text{ nm} ]_4\), as-grown and annealed at 550 °C, 10 min’s. The insets schematically depict the cross sections of as-grown and annealed FePt/MgO multilayer films.
structures. In the case of (a), after annealing, the low-angle diffraction peaks clearly demonstrate the layered structure in this sample. The peak position matches very well with the total thickness of FePt plus MgO (4.5 nm). However, in the case of (b), where a very thin MgO layer thickness is used in this multilayer structure, the X-ray diffraction pattern of annealed film does not show any diffraction peak, even layered structure is found in as-grown state. The obtained results can be understood schematically from the insets of Fig.7.

3.4 AC-demagnetized domain structure

Magnetic cluster (magnetic domain) size is one of the critical factors affecting transition jitter in perpendicular magnetic recording media. A fine uniform ac-demagnetized domain structure is indispensable to obtain a low transition noise. Continuous exchange-coupled FePt films with a perpendicular magnetic anisotropy usually exhibit a strip domain structure. In Fig. 8, the domain structures of different FePt/MgO multilayer structures are compared. The observed domain structures in FePt-MgO disks are much finer than that in continuous FePt films, which is certainly a result of MgO doping. In the structure of [FePt 2.5 nm/MgO 2 nm]_2, an island-like domain structure is observed. With a same FePt and MgO layer thickness, 3 times repetition sample shows a bigger domain structure than 2 times repetition sample, which is possibly due to the layered structure in these samples.

3.5 Angular dependence of coercivity

Angular dependence of recording layer coercivity has been normally used to investigate the magnetization reversal mode. Fig. 9 plots the film coercivity versus the angle from film normal direction for one of the FePt/MgO structures. In this structure, the MgO volume ratio is only about 35% based on the thickness ratio. 10 min’s annealing at 550 °C gives an easy-axis coercivity of about 1.6 kOe. With 12 min’s annealing, the out-of-plane coercivity can reach 3.9 kOe. For both samples, the coercivity exhibits a drastic decrease with the angle. Therefore, most likely, rotational magnetization reversal mode takes place in annealed FePt/MgO films, originating from the nature of granular-type microstructure. With this rotational magnetization reversal mode, annealed FePt/MgO films can easily exhibit a very large coercivity above 10 kOe. However, for the sake of spin-stand testing, the film coercivity is controlled usually below 6 kOe in our case. Since the film coercivity is governed by the FePt chemical ordering, by varying the annealing condition, we carefully optimized the FePt chemical ordering, so that the recording layer coercivity can be controlled in a desired coercivity range.

3.5 Determination of magnetic activation volume in double-layered disks

In double-layered disks, the presence of magnetic SUL inhibits the utilization of VSM or AGFM to measure hysteresis loop. However, for out-of-plane remanent magnetization measurement, they may be applicable, since SUL should exhibit a zero remanence along film normal in principle. Fig. 10 shows the remanent magnetization curve of one double-layered disk. This disk has unity squareness and a negative nucleation field (1kOe), as revealed by the hysteresis loop measured by Kerr effect. In the as-measured remanence curve, an initial magnetization drop is found, which is neither consistent with the hysteresis loop nor with the remanence curve of single-layered disk. It is clarified that this initial magnetization drop comes from the Fe-Ta-C SUL, as shown in Fig. 10 inset. Subtracting the SUL background signal gives rise to the corrected remanent magnetization curve, from which the remanent coercivity is obtained. The observed remanent magnetization from the SUL is one of the noise sources in double-layered disks and...
should be completely suppressed by optimizing the magnetic properties of Fe-Ta-C SUL.

The magnetic activation volume is obtained by fitting the remanent coercivity data, measured as a function of applied field waiting time, using Sharrock’s formula\(^8\) defined as

\[ H_c(t) = H_c(1 - \frac{K_u T}{(K_u V)} \ln(t_f))^{1/2} \]  

(1)

The fitting results are shown in Fig. 11.

\[ H \text{(Oe)} \quad \text{Magnetic field (kOe)} \]

\[ H_c \text{(Oe)} \quad \text{Remanent moment (10^4 emu)} \]

\[ M_r \text{(10^4 emu)} \quad H \text{(kOe)} \]

\[ K_u = (1.94 \pm 0.03) \times 10^6 \text{erg/cm} \]

\[ V = (1.74 \pm 0.07) \times 10^{-5} \text{cm}^3 \]

Fig. 11 (a) Remanent magnetization curves measured with different negative applied field waiting time for the sample shown in Fig. 10. (b) Fitting result by Sharrock’s formula.

3.5 Recording SN\(_{nR}\) performance of double-layered FePt-MgO disks

The SN\(_{nR}\) ratios of all tested double-layered disks are summarized in Fig. 12, where FePt layer thickness is used as the abscissa. For some multilayer structures, different annealing conditions were employed to achieve different coercivities for these disks. The FePt/MgO multilayer structure strongly affects the final SN\(_{nR}\) recording performance. To achieve a high SN\(_{nR}\) ratio, the FePt thickness should be below 2 nm. As discussed above, the FePt grain size and activation volume can be pronouncedly decreased with decreasing the FePt layer thickness. Therefore, a lower transition noise is expected with decreasing FePt layer thickness. Fig. 13 shows the close correlation between SN\(_{nR}\) ratio and activation volume.

\[ \frac{\text{SN}_{nR} \text{ ratio}}{\text{Activation volume (10^{-18} cm^3)}} \]

Fig. 12 Summary of the SN\(_{nR}\) ratio of FePt-MgO double-layered disks with different multilayer structures. For a same multilayer structure, the scattered data points are corresponding to different annealing conditions.

4. Conclusion

(001)-textured granular-type FePt films can be fabricated by annealing FePt/MgO multilayers, exhibiting a fine domain structure and a rotational magnetization reversal mode. The FePt grain size and activation volume can be controlled by modifying the FePt/MgO multilayer
structures. The measured SN\textsubscript{mR} recording performance of the double-layered FePt disks demonstrates a close correlation with the magnetic activation volume.

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