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Transition from in-plane to perpendicular magnetization in GdFeCo/AlN/TbFeCo magnetostatic coupling films

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Magneto-optic (MO) disks will be a powerful candidate as a removable memory in the upcoming "multimedia" world [1]. However, the recording density of the disks is limited by the size of a focused laser beam spot. The minimum bit pitch of an optical recording system is usually limited by the optical transfer function of the system and is give by: $d = 0.5\,\lambda/\mathrm{NA}$, where λ is the wavelength of a laser and NA is the numerical aperture of an objective lens. The center aperture detection magnetically induced superresolution (CAD-MSR) disks by using magnetostatic coupling films or exchange coupled double layers could circumvent the diffraction limit without any change of the optical components [2–7]. The CAD has two specific features comparing with the front aperture detection (FAD) method [8] or the rear aperture detection (RAD) method [9, 10], one is that no external magnetic fields are needed during readout. The other is that only two magnetic layers are required to realize the MSR disk, so that the CAD is the most prospective MSR method among the detection technologies.

In this letter, the magnetostatic coupling films (GdFeCo/AlN/TbFeCo) used for CAD disk were prepared by sputtering. Magnetization transition from in-plane to perpendicular magnetization caused by temperature changes have been investigated by M-H loops measured by vibrating sample magnetometer and Kerr rotation hysteresis loop.

Samples were prepared by magnetron sputtering on glass substrates. The GdFeCo and TbFeCo layers were deposited by RF sputtering with a composite target consisting of Tb chips and $Fe_{85}Co_{15}$ alloy and with a composite target of Gd chips and $Fe_{75}Co_{25}$ alloy respectively. The base vacuum was 1×10^{-4} Pa. The thicknesses of GdFeCo and TbFeCo, as measured by an Alpha-step 500 stylus profilometer, were fixed at 50 and 40 nm, respectively. The magnetic double-layer was sandwiched by aluminum-nitride layers.

The MO layer composition was determined by fluorescence X-ray analysis (XRF). The magnetic properties for single and double layers were investigated mainly by MO Kerr rotation and VSM at different temperatures. The temperature dependence of the saturation magnetization M_s measured by VSM was used to derive compensation temperature (T_{comp}) and Curie temperature (T_c). Table I gives the magnetic properties of the reading and writing layers. The Curie temperature of the GdFeCo and TbFeCo layers are 300 and 250 °C, respectively. The compensation temperature of the GdFeCo layer is about 150 °C and that of the TbFeCo layer is below room temperature.

Fig. 1a and b shows the M-H loops of the GdFeCo/AlN/TbFeCo magnetostatic coupling films at 25 and 125 °C, respectively. In order to interpret the unusual hysteresis loops, we applied the Kobayashi model and the extended Kobayashi model to our system, and therefore analyzed the magnetization transition caused by temperature changes.

Kobayashi *et al.* [11] have theoretically calculated the magnetization curves for exchange-coupled ferromagnetic double-layered films, assuming that each isolated layer of the films has a uniaxial anisotropy with the easy axis perpendicular to the film plane and exhibits

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TABLE I Magnetic properties for TbFeCo and GdFeCo monolayers

Layer	Material	Composition	T_c (°C)	T_{comp} (°C)	H_c ($10^5 Am^{-1}$)	Dominant
Readout layer	GdFeCo	$Gd_{27}(Fe_{75}Co_{25})_{67}$	300	150	— In-plane	RE-rich
Recording layer	TbFeCo	$Tb_{22}(Fe_{85}Co_{15})_{78}$	250	<R.T.	4	TM-rich

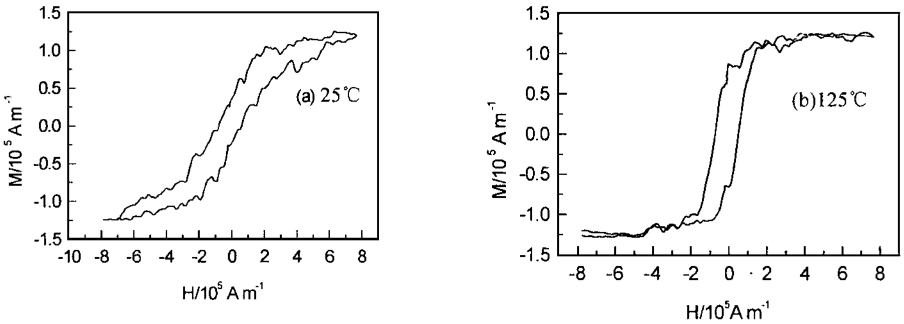
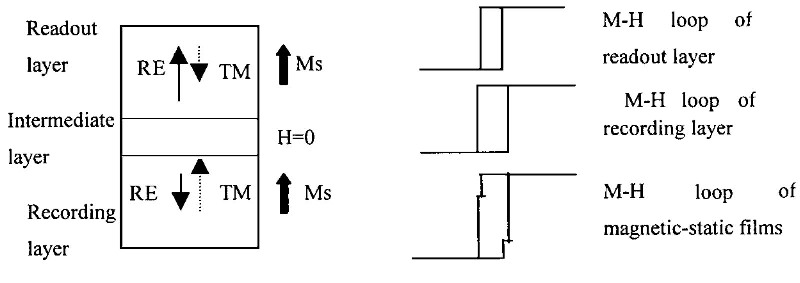


Figure 1 M-H loops of the GdFeCo/AlN/TbFeCo doubled-layered films measured by a vibrating sample magnetometer: (a) at 25 °C and (b) at 125 °C.

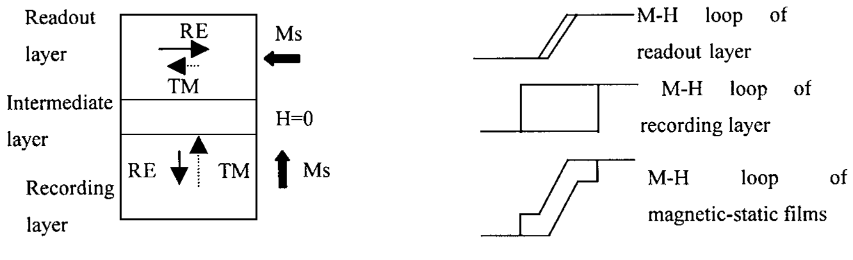
a rectangular hysteresis loop. Amorphous RE (heavy rare earth)—TM (transition metal) alloy films are classified into two types. In the first one, the TM moment is dominant in the first layer and the RE moment is dominant in the second layer, or the combination is reversed and this is refered as Type A (antiparallel). In the second type, the TM moment is dominant in both the first and the second layer or the RE moment is dominant in both layers and this is refered as Type P (parallel). The calculated magnetization curves of Type A magnetostatic coupling films are shown in Fig. 2a, if $H_{c1} < H_{c2}$, where H_{c1} and H_{c2} are the coercive force of readout and recording layers respectively.

Sbiaa *et al.* [12] investigated the magnetization processes in exchange-coupled double-layer films with in-plane and perpendicular anisotropy. The calculated magnetization curve of Type A magnetostatic coupling films are shown in Fig. 2b, if $H_{s1} < H_{c2}$, where H_{s1} and H_{c2} are the saturation field of the in-plane anisotropy readout layer and the coercive force of recording layer, respectively.

The RE moment is dominant in the readout layer (GdFeCo), and the TM moment is dominant in the recording layer (TbFeCo) at 25 °C, respectively. So the magnetostatic coupling films belong to "Type A" films at this temperature. The magnetostatic coupling films are also "Type A" films at 125 °C. The hysteresis loop



(a) Perpendicular / perpendicular, type: A



(b) In-plane / perpendicular, type: A

Figure 2 Calculated magnetization curves of magnetostatic coupling films: Type-A.

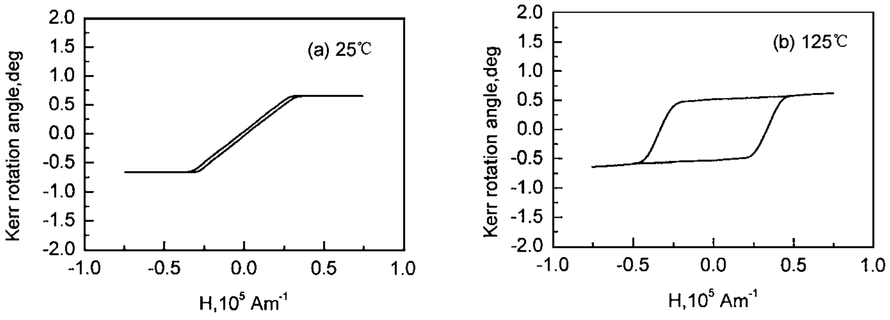


Figure 3 Kerr hysteresis loops of readout layers: (a) at 25 °C and (b) at 125 °C.

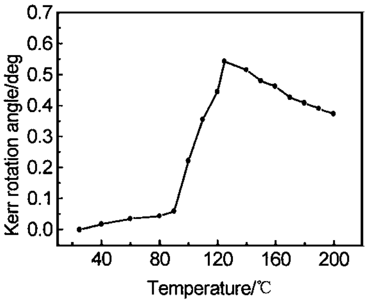


Figure 4 Temperature dependence of the Kerr rotation angle of readout layers.

obtained by VSM at 25 °C (Fig. 1a) is similar to the curve sketched in Fig. 2b. So the magnetic direction of readout layer is in-plane at 25 °C. Fig. 1b shows the same situation as Fig. 2a, so the readout layer magnetization becomes perpendicular at 125 °C. In conclusion the transition from in-plane to perpendicular magnetization occurs with increasing temperature.

Fig. 3a and b show the polar Kerr hysteresis loops measured from the GdFeCo readout layer side at 25 and 125 °C, respectively. We note that the Kerr rotation angle at no external field (remanence) is almost zero, and the magnetization direction of the readout layer is in-plane at 25 °C. Fig. 3b shows that the magnetization direction is perpendicular at 125 °C, $\theta_{\mathrm{kr}}/\theta_{\mathrm{k}} \approx 1$, $\theta_{\mathrm{kr}} = 0.54°$, where θ_{kr} and θ_{k} are the remanent Kerr angle and saturation Kerr angle, respectively.

The temperature dependence of the Kerr rotation angle of readout layer is given in Fig. 4. The Kerr rotation angle increases with increasing temperature, the magnetic direction of the readout layer turns to perpendicular from in-plane, so the magnetostatic coupling films could be used for CAD disk. The remanent Kerr angle is small between room temperature and 75 °C, but drastically increases with temperature in the range 75 to 125 °C to a maximal value at 125 °C, and then slowly decreases with increasing temperature. The magnetization direction of the readout layer changed from in-plane to perpendicular in the narrow temperature range. The rapid change is important to obtain an excellent MSR performance.

In magnetic thin films the orientation of the magnetization is determined by the effective perpendicular anisotropy constant K given by

$$K = K_{\mathrm{u}} - 2\pi M_{\mathrm{s}}^2,$$

where $2\pi M_{\mathrm{s}}^2$ is the demagnetizing energy, K_{u} is the uniaxial perpendicular anisotropy constant, and M_{s} is the saturation magnetization. When K is negative, the magnetic film exhibits in-plane magnetization. On the other hand, when K is positive, the magnetic film exhibits perpendicular.

Fig. 5a and b shows the temperature dependence of the saturation magnetization M_{s} of recording and readout layers, respectively. The saturation magnetization of recording layer TbFeCo increased as the temperature increased, reaching a maximum at 125 °C. The leakage magnetic flux from the recording layer is proportional to the total magnetic moment. Therefore, the magnetostatic coupling force between the readout layer and the recording layer becomes stronger with increasing temperature, and thus favors the information in the recording layer transferring to the readout layer. The saturation magnetization of the recording layer GdFeCo almost linearly decreases with increasing temperature below the compensation temperature. The effective perpendicular anisotropy constant K of the readout layer

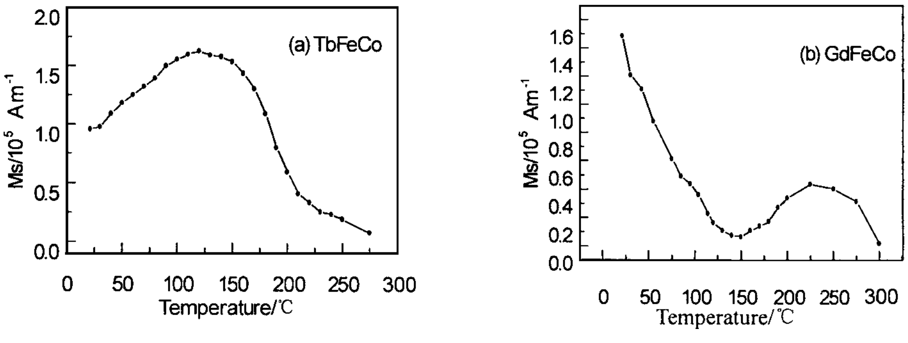


Figure 5 Temperature dependence of the saturation magnetization M_{s} of recording and readout layers respectively.

GdFeCo is negative due to the large the saturation magnetizations (M_s) and the demagnetizing energy ($2\pi M_s^2$) at 25 °C, the magnetic direction is in-plane. The demagnetizing energy of the GdFeCo layer decreases more quickly than the saturation magnetization. We know that the uniaxial perpendicular anisotropy constants K_u also reduces with increasing temperature, but the uniaxial perpendicular anisotropy constants decreased more quickly than the demagnetizing energy. When the temperature increased around the compensation temperature, K becomes positive, and the magnetic film exhibits perpendicular magnetization. Therefore the magnetization direction of the readout layer turns to perpendicular from in-plane with increasing temperature. The transition from in-plane to perpendicular magnetization of GdFeCo layers occurs mainly as a result of the changes in the saturation magnetization.

In conclusion, the magnetostatic coupling films (GdFeCo/AlN/TbFeCo) having the basic properties of the CAD-MSR disks were prepared by sputtering. The magnetization direction of readout layer changes from in-plane to perpendicular with increasing temperature. The transition occurs mainly as a result of the changes in the saturation magnetization. When the temperature is increased around the compensation temperature, the saturation magnetization and the demagnetizing energy of the GdFeCo layer decrease, and the transition of the GdFeCo layer from in-plane to perpendicular magnetization occurs.

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