Jpn. J. Appl. Phys. Vol. 40 (2001) pp. 4518–4523
Part 1, No. 7, July 2001

Magnetic Properties and Recording Characteristics of High Magnetization Exchange-Coupled Double-Layer TbFeCo for Magnetic Flux Reading Optical Recording

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(Received December 22, 2000; accepted for publication March 14, 2001)

The magnetic properties and recording characteristics of exchange-coupled double-layer (ECDL) disks consisting of a transition metal-rich TbFeCo readout layer with high magnetization and a recording layer were studied for magnetic flux reading optical recording. The effective coercivity of ECDL with rare-earth (recording)/transition metal-rich (readout) films could be greatly enhanced from 1.7 to 7.6 kOe through exchange coupling between two active layers. Moreover, ECDL disks possess a lower recording bias field (100 Oe) and a lower onset field (-150 Oe) for thermomagnetic writing. The enhanced effective coercivity was explained by the Kobayashi model, and the lower bias field and onset field of ECDL disks were analyzed by the modified nucleation field model. The ECDL disks with magnetization over 300 emu/cm^3, high stability and low recording bias field are potentially applicable for magnetic flux readout toward high density recording at a high writing rate.

KEYWORDS: exchange-coupled double-layer, magnetic flux reading optical recording, recording bias field, onset field, thermomagnetic writing, Kobayashi model, modified nucleation field model

1. Introduction

Magneto-optical (MO) recording media have the potential to form domains with dimensions of less than 40 nm.[1)] However, the recording density is restricted by the diffraction limited size of a readout laser beam spot. In order to increase the recording density, shorter wavelength laser beams are needed for detecting small-size marks. Several methods, such as optical super-resolution[2)] and magnetically-induced super-resolution (MSR),[3)] have been proposed to increase the recording density beyond the limitation of optical diffraction. In contrast, the readout signal is still low owing to the small mark size. On the other hand, the giant magneto-resistive (GMR) readout sensor in the hard disk drive has much higher sensitivity in terms of reading small marks. However, as the size of the recording bits of longitudinal media decreases to several tens nm, the super-paramagnetic effect becomes an issue. Combining the advantages of both thermomagnetic writing and magnetic flux detection and using perpendicular amorphous MO media, the hybrid recording reveals great potential for high-density storage.[4,5)]

High magnetization (M) for magnetic flux sensing and large coercivity (H_c) for stable domains are desirable characteristics for magnetic flux detection. Based on the mean field model[6)] and experimental results, single-layer rare-earth transition metal (RE-TM) film has difficulties in simultaneously satisfying the above requirements. Exchange-coupled double-layer (ECDL) films have been investigated as conventional MO recording media.[7)] However, the magnetization and H_c reported are not adequate to yield higher flux density and to ensure domain stability simultaneously. In addition, since a larger demagnetizing field (H_d) arises due to a large magnetization, the recording bias field (H_b) and the absolute of the onset field ($|H_{on}|$) need to be increased, typically to larger than 200 and 350 Oe, respectively, where H_b is the field required to ensure single-domain marks, and H_{on} is the field at which writing first occurs. In addition, the writing rate is inversely proportional to H_b. In this paper, we reported on a study involving designing, fabricating, and examining the ECDL disks consisting of a high-magnetization TM-rich readout layer and a recording layer for hybrid recording. Furthermore, the enhanced H_c and reduced H_b among ECDL disks were analyzed by the Kobayashi model[8)] and the nucleation field model.[9)]

2. Model

2.1 Magnetization process of ECDL

A magnetization process model established by Kobayashi *et al.* has been widely employed for analyzing the magnetization reversal mechanism of ECDL films.[8)] When a sufficiently large upward field (here, $+\infty$) is applied to an "A-type" ECDL film, the magnetizations of both layers are made parallel to the field in the state I shown in Fig. 1. Small arrows in states I to IV indicate the submoments, where white

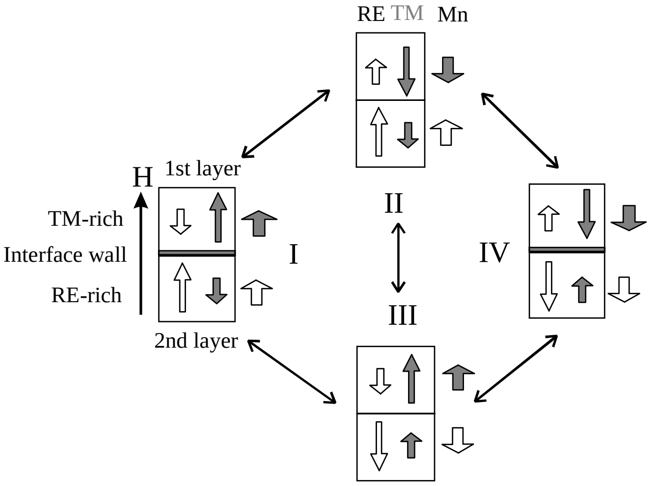

Fig. 1. Magnetization states and reversal paths of "A-type" ECDL films with an external field. Small arrows denote the submoments, where white and black arrows are RE and TM submoments, respectively; larger arrows represent the net magnetization direction of each layer.

and black arrows are RE and TM submoments, respectively; the larger arrows represent the direction of the net magnetization of each layer. If the field is then decreased from $+\infty$ to $-\infty$, the magnetization state may change from states I to IV along one of the paths indicated by arrows. The switching field H_{mn} from state m to n can be obtained by the change of the total free energy of an ECDL film, as shown in following equations[8)]

$$H_{12} = \frac{\sigma_{\mathrm{w}}}{2M_1h_1} - H_{\mathrm{c1}} \tag{1}$$

$$H_{21} = \frac{\sigma_{\mathrm{w}}}{2M_1h_1} + H_{\mathrm{c1}} \tag{2}$$

$$H_{13} = \frac{\sigma_{\mathrm{w}}}{2M_2h_2} - H_{\mathrm{c2}} \tag{3}$$

$$H_{31} = \frac{\sigma_{\mathrm{w}}}{2M_2h_2} + H_{\mathrm{c2}} \tag{4}$$

$$H_{24} = \frac{\sigma_{\mathrm{w}}}{2M_2h_2} - H_{\mathrm{c2}} \tag{5}$$

$$H_{34} = \frac{\sigma_{\mathrm{w}}}{2M_1h_1} - H_{\mathrm{c1}}, \tag{6}$$

where 1 and 2 are the TM-rich and RE-rich layers, respectively, and H_{c}, M, h, and σ_{w} denote the coercive field, magnetization, layer thickness, and interface wall energy density, respectively. $\sigma_{\mathrm{w}}/2Mh$ is an exchange bias field (H_{eb}).

According to the Kobayashi model, the actual path along which magnetization reversal takes place is not only dependent upon the magnetic properties of each layer, but also upon the interlayered exchange-coupling strength. Meanwhile, the switching field depends not only on the intrinsic coercivity of a single layer, but also on the exchange bias field, as shown in eqs. (1)–(6). Therefore, using A-type ECDL films, H_{c} of high magnetization media can be greatly enhanced by exchange coupling at the interface between two active layers.

2.2 *Nucleation field model*

H_{on} and H_{b} can be analyzed by the nucleation field model.[9)] In single-layer recording TbFeCo media, both H_{b} and H_{on} are determined mainly by the maximum demagnetizing field during thermomagnetic recording.[9)] Since an interface wall is formed at the interface between two active layers, both H_{b} and H_{on} of ECDL films are also affected by the exchange bias field H_{eb}, ($\sigma_{\omega}/2Mh$). Consequently, the H_{eb} term must be added into the nucleation field model.[9)] The modified equation is shown as eq. (7), where H_{t}, H_{d}, H_{a}, and H_{n} denote the total internal field, demagnetizing field, an applied field, and nucleation field, respectively. H_{n} is the field required for nucleation reversal and it is close to $H_{\mathrm{c}} + 4\pi M$.[9)] The value ($H_{\mathrm{n}} + H_{\mathrm{eb}}$) is defined as the nucleation field $H_n(A)$ for "A-type ECDL films." When $H_{\mathrm{t}} > H_{\mathrm{n}} + H_{\mathrm{eb}}$, the magnetization reversal takes place.

$$\begin{aligned} H_{\mathrm{t}} &= |H_{\mathrm{d}} + H_{\mathrm{a}}| > H_{\mathrm{n}} + \frac{\sigma_{\mathrm{w}}}{2Mh} \\ &= H_{\mathrm{n}} + H_{\mathrm{eb}} \approx H_{\mathrm{c}} + 4\pi M + H_{\mathrm{eb}} \equiv H_{\mathrm{n}}(A) \end{aligned} \tag{7}$$

In the simulation, the magnetizations of the single-layer and A-type ECDL films are assumed to be 300 and 142 (recording layer)/300 (readout layer) emu/cm^3, respectively. H_{d} of A-type ECDL can be derived from the single-layer formula [eq. (A2) of ref. 10]. Additionally, a measured magnetization temperature profile is used to model the magnetization profiles [$M(r)$] during the writing process. The simulated results of the radial dependence of H_{d}, H_{n} and $H_{\mathrm{n}}(A)$ are shown in Fig. 2, where "S" and "A" denote single-layer film and A-type ECDL films, respectively. The Curie temperature is located at a Curie radius (r_{c}) of approximately 0.3 μm. Simulation results indicate that H_{d} of A-type ECDL films is smaller than that of single-layer film due to the magnetizations being antiparallel in both layers. The slope of $H_{\mathrm{n}}(A)$ is larger than that of $H_{\mathrm{n}}(S)$ because H_{eb} is added into $H_{\mathrm{n}}(A)$. In the region where the radius is smaller than that at the intersection of the H_{d} and H_{n} region, H_{d} is larger than H_{n}, so the magnetization reversal takes place spontaneously. The intersections of H_{d} and H_{n} for single-layer film and A-type ECDL films are about 600 and 180 Oe, respectively. To completely suppress the magnetization reversal, an applied field (in this case $H_{\mathrm{a}} = H_{\mathrm{on}}$) is required so that H_{t} is smaller than H_{n}. Thus, H_{on} of the A-type ECDL disks, required to prevent subdomain formation, is smaller than that of the single-layer disk. In general, H_{b} is directly proportional to $|H_{\mathrm{on}}|$,[11)] and a lower H_{b} is required for A-type ECDL disks. Consequently, lower H_{b} and H_{on} are required for A-type ECDL disks, based on the modified nucleation field model analyses.

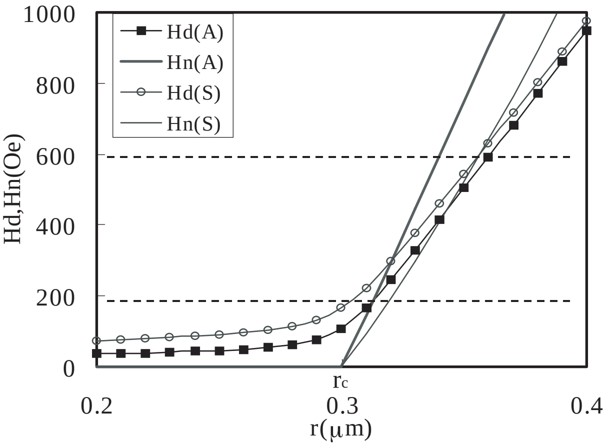

Fig. 2. Radial dependence of demagnetizing field (H_{d}) and nucleation field (H_{n}), where "S" and "A" denote single-layer and A-type ECDL films, respectively.

3. Experiments

A dual-magnetic layer, comprising a recording layer and a readout layer, was designed for magnetic flux detection. The readout layer was a TM-rich TbFeCo layer with composition different from the compensation composition (X_{comp}), in order to have large magnetization ($M > 300$ emu/cm^3). The compositions of the recording layer Tb$_x$(FeCo)$_{100-x}$ were varied, where $21 < x < 34$. An Al layer was added to the ECDL disks to optimize the writing process, and the thicknesses of both the protective and Al layers must be as thin as possible for magnetic flux detection. All of the disks and samples of ECDL films were deposited on 3.5″ polycarbonate substrates, 1″ glass coupons and Si wafers as shown schematically in Figs. 3(a) and 3(b), respectively, to study their magnetic and recording characteristics. The MO layer was DC magnetron cosputtered from Tb and FeCo-composite targets; the silicon nitride layers were deposited by RF magnetron re-

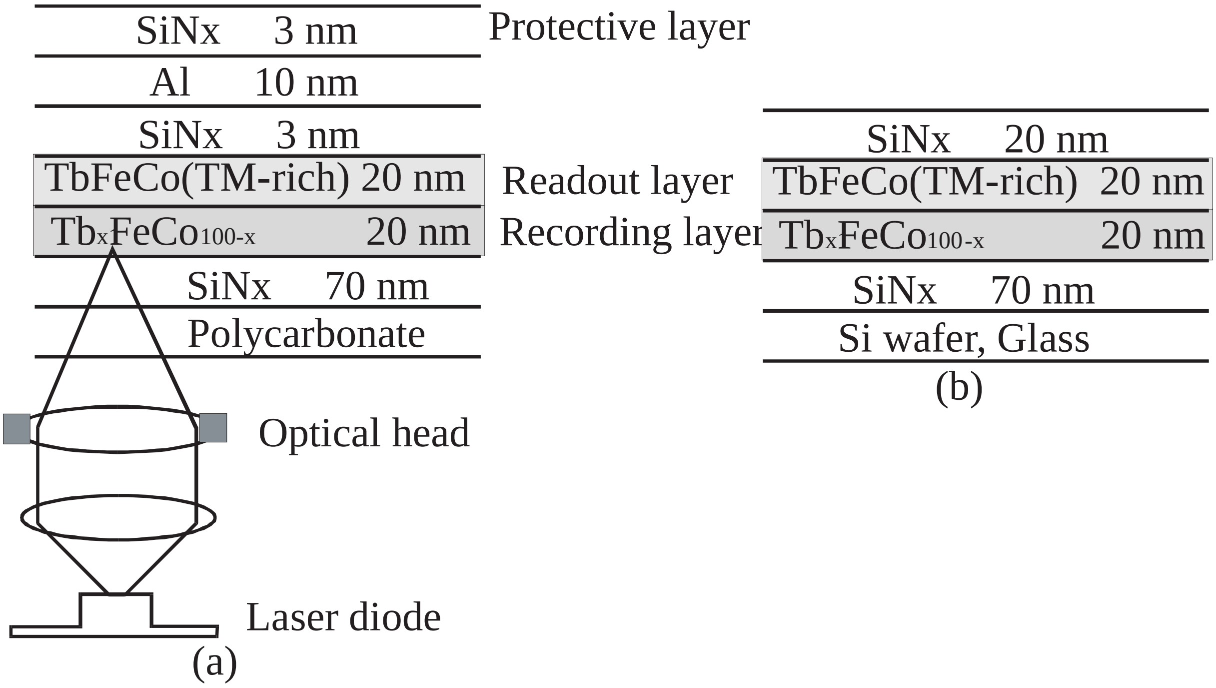

Fig. 3. ECDL films in configurations of (a) disks and (b) samples.

active sputtering from a Si target in mixture of Ar and N_2 gases. The magnetization of the samples was measured with a vibrating sample magnetometer (VSM). The temperature dependences of H_c used to obtain compensation temperature (T_{comp}), Curie temperature, and compensation composition were measured with a Kerr loop tracer. H_b and H_{on} were measured with a disk tester using light intensity modulation (LIM) at a laser wavelength of 785 nm and an objective lens with NA = 0.55.

4. Results and Discussion

4.1 Exchange-coupled double-layer disks

Using ECDL films, H_c of high magnetization media can be greatly enhanced because of the strong exchange coupling at the interface between the two active layers. Figure 4 displays the hysteresis loop of ECDL films of which the readout layer is a TM-rich layer with M of 300 emu/cm^3 and H_c of 1.7 kOe, and the recording layer is RE-rich film with M of 142 emu/cm^3 and H_c of 4.3 kOe. The ECDL films are in the configuration of glass/SiN (70 nm)/RE-rich recording layer (20 nm)/TM-rich readout layer (20 nm)/SiN (20 nm), as shown in Fig. 3(b). The effective coercivity (H_{ec}) was increased from 1.7 (single layer) to 7.6 kOe though the exchange coupling of the ECDL films. The magnetization states and the switching field required are shown in Fig. 4. There are four possible magnetization states, (I), (II), (III), and (IV). When the applied field increases gradually from 0 to 15 kOe, the initial state (III) becomes (I), where the moment of the recording layer reverses. If the field decreases from 15 to −15 kOe, the state changes from (I) to (III), and then to (IV). As the field is applied from −15 to 15 kOe, the state (IV) reverses to (II), and then to (I). The H_c enhancement of A-type ECDL films is due to the formation of an interface wall at the positive and negative saturation fields [states (I) and (IV)]. As shown in Fig. 4, the H_{ec} or the switching field for transition "E" of the readout layer H_{cE} is given as[8)]

$$H_{cE} = \frac{\sigma_w}{2M_{TM}h_{TM}} + H_{cTM} = H_{eb1} + H_{cTM} \tag{8}$$

where "TM" denotes the TM-rich readout layer, and $H_{eb1} = \sigma_w/2M_{TM}h_{TM}$ is an exchange bias field. Also, the effective coercivity of the recording layer, H_{cA}, as shown in transition "A," and the switching field (H_{cB}) for transition "B" are given as

$$H_{cA} = \frac{\sigma_w}{2M_{RE}h_{RE}} - H_{cRE} \tag{9}$$

and

$$H_{cB} = \frac{\sigma_w}{2M_{RE}h_{RE}} - H_{cRE} \tag{10}$$

where "RE" denotes the RE-rich recording layer. According to eqs. (9) and (10), and the 2Mh from VSM measurement, σ_w is derived to be approximately 4.3 erg/cm^2.

4.2 Recording layer composition dependence of enhanced coercivity

The composition of the recording layer significantly affects the magnetic properties of ECDL films. To explore the dependence of H_{ec} on the composition of recording layers, a series of media with different recording layer compositions were fabricated and examined. The compositions of the recording layer are $Tb_x(FeCo)_{100-x}$, where $21 < x < 34$. H_{ec} of the readout and recording layer is a function of the recording layer composition, as shown in Figs. 5 and 6, respectively. When the recording layer is TM-rich film, H_c of the readout layer is enhanced from 1.7 (single layer) to over 4 kOe as a result of exchange coupling. The H_{ec} of parallel type (P-type) ECDL films where the TM submoments are dominant in both layers can be expressed as[8)]

$$H_{ec} = \frac{M_1H_{c1}h_1 + M_2H_{c2}h_2}{M_1h_1 + M_2h_2} \tag{11}$$

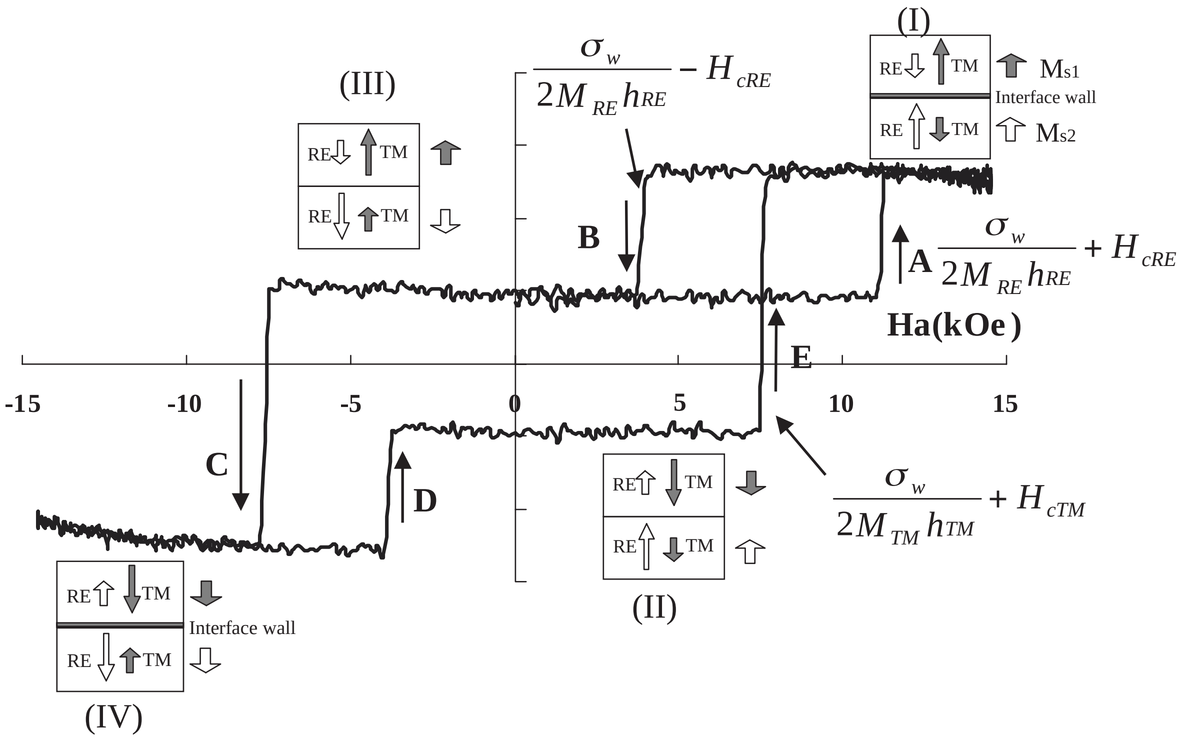

Fig. 4. Hysteresis loop of ECDL films composed of the TM-rich readout layer with M of 300 emu/cm^3 and H_c of 1.7 kOe, and the RE-rich recording layer with M of 142 emu/cm^3 and H_c of 4.3 kOe. Small arrows denote the submoments, where white and black arrows are RE and TM submoments, respectively; larger arrows represent the net magnetization direction of each layer.

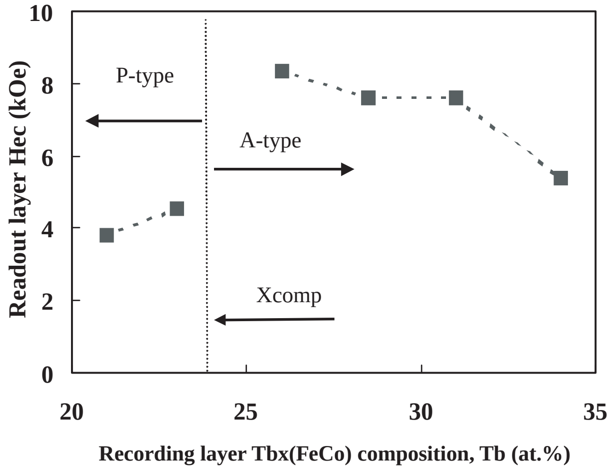

Fig. 5. Recording layer composition dependence of effective coercivity (H_{ec}) of readout layers, where P-type and A-type are ECDL films with TM- and RE-rich recording layers, respectively.

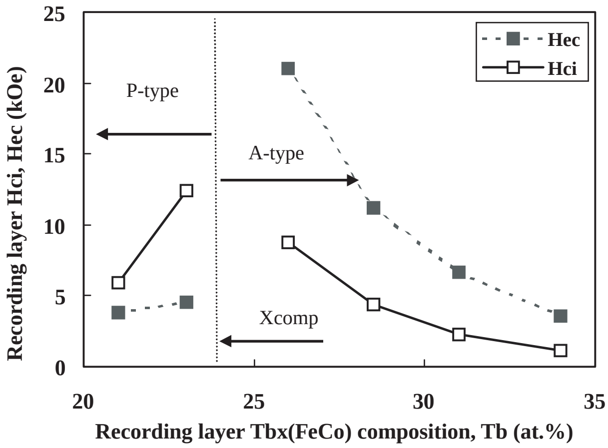

Fig. 6. Recording layer composition dependence of effective coercivity (H_{ec}) and intrinsic coercivity (H_{ci}) of recording layers, where P-type and A-type are ECDL films with TM- and RE-rich recording layers, respectively.

The intrinsic coercivity of the readout layer is smaller than that of the recording layer, so H_{ec} is larger than H_c of the readout layer; however, H_{ec} of the recording layer is smaller than the intrinsic H_c of the recording layer. In contrast, for RE-rich recording layers, H_c of the readout layer is enhanced from 1.7 to over 7 kOe when $26 < x < 31.5$, although H_{ec} decreases slightly for a high Tb content recording layer. When the recording layer is TM-rich film, as shown in Fig. 6, H_{ec} of the recording layer is reduced, as a result of H_{ec} of the P-type ECDL films. On the other hand, when the recording layer is a RE-rich film, H_{ec} increases as the composition of the recording layer approaches the X_{comp}. According to the above results, H_{ec} of the readout and recording layers can be enhanced by the exchange coupling of A-type ECDL films, implying that the small recording marks become more stable than these of a single active layer with high magnetization and low H_c.

4.3 *Dependence of recording bias field and onset field on the composition of ECDL disks*

Both recording bias and onset fields depend on the composition of ECDL disks. H_b and H_{on} were measured from the relationship between recording field and the carrier-to-noise ratio (CNR) when their CNRs are maximum and minimum,

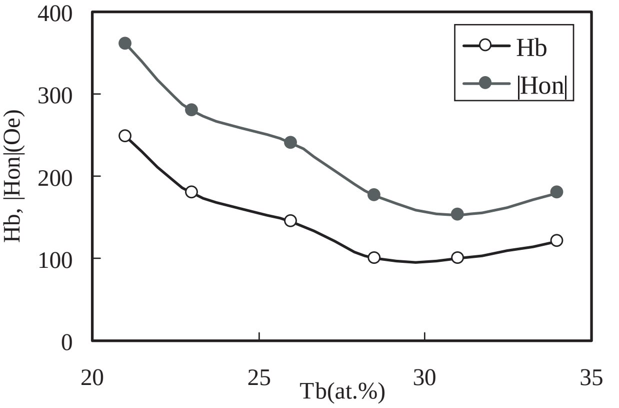

Fig. 7. H_b and H_{on} as functions of recording layer composition of ECDL disks in the structure of poly-carbonate substrate/SiN$_x$/Tb$_x$(FeCo)$_{100-x}$/TbFeCo(TM-rich)/SiN$_x$/Al/SiN$_x$.

respectively. Figure 7 reveals the dependence of H_b and H_{on} on the composition of the recording layer of ECDL disks. H_b decreases from 250 to 100 Oe and the absolute value of H_{on} ($|H_{on}|$) decreases from 350 to 150 Oe when the recording layer Tb content increases within $21 < x < 31.5$. In contrast, H_b and $|H_{on}|$ of single-layer disk with magnetization of 300 emu/cm^3 are 250 and 400 Oe, respectively.

These experimental results are in agreement with those derived from the modified nucleation field model: a lower H_b and $|H_{on}|$ are required for A-type ECDL disks. The bias and onset field are determined by the demagnetizing field and exchange coupling effect of ECDL disks. According to the modified nucleation field model, H_d was reduced and the slope of $H_n(A)$ was increased in A-type ECDL films. In other words, the existence of interface wall energy at the interface during the recording process could reduce the probability of the formation subdomains within the recorded marks. Therefore, lower H_b and $|H_{on}|$ are required in order to prevent subdomains from occurring during the switching process as a result of the exchange coupling.

H_d, H_n and $H_n(A)$ are functions of recording mark size. The simulated results of the radial dependence of H_d, H_n and $H_n(A)$ when $r_c = 0.15$, $0.05\,\mu$m are shown in Figs. 8(a) and 8(b), respectively. The intersections of H_d and H_n for single-layer/A-type ECDL are about 490/120 and 310/80 Oe for $r_c = 0.15$ and $0.05\,\mu$m, respectively. The temperature profile for thermomagnetically writing smaller marks is less sharp than that of larger marks, thus a smoother magnetization temperature profile is obtained near the Curie radius position. Therefore, the values of the intersection of H_d and H_n for both single-layer and A-type ECDL disks become smaller as the recorded mark size decreases. Consequently, H_b and $|H_{on}|$ of smaller marks of A-type ECDL disks become lower than those of larger marks.

Due to the exchange-coupling effect, we found that A-type ECDL films possess low H_b and $|H_{on}|$, a larger H_c for a stable recording domain and high magnetization for a high flux density. The magnetization of the readout layer can be increased to 370 emu/cm^{3}12) by adjusting the composition and configuration of MO media. Moreover, A-type ECDL films with lower H_b are suitable for high-speed magnetic field modulation (MFM) direct overwriting.

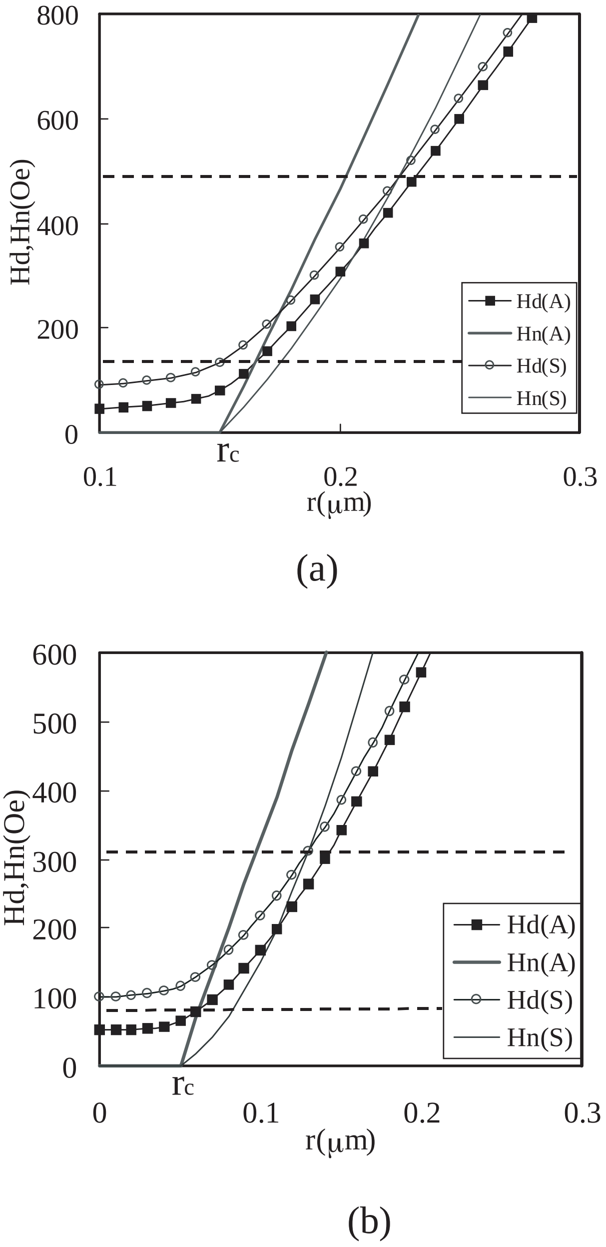

Fig. 8. Radial dependence of the demagnetizing field (H_d) and the nucleation field (H_n) when (a) $r_c = 0.15$, and (b) $r_c = 0.05\,\mu$m, where "S" and "A" denote single-layer and A-type ECDL films, respectively.

5. Conclusions

A series of exchange coupled double-layer disks consisting of a TM-rich TbFeCo readout layer with magnetization more than 300 emu/cm^3 and a recording layer were studied for magnetic flux reading optical recording. Through exchange coupling between the TM-rich readout and RE-rich recording layers, H_c of A-type ECDL films could be greatly enhanced from 1.7 to 7.6 kOe. Moreover, a lower H_b (100 Oe) and $|H_{on}|$ (150 Oe) of A-type ECDL disks can suppress the formation of sub-domains during the switching process by exchange coupling, which is in agreement with the analytic results of the modified nucleation field model. Therefore, A-type ECDL disks with magnetization over 300 emu/cm^3, high stability and low H_b are potentially applicable for magnetic flux readout toward high-density recording at a high writing rate.

Acknowledgements

We would like to thank Dr. W. K. Hwang of RITEK Company, Taiwan for fruitful discussions and valuable suggestions. This work was supported by the National Science Council of the Republic of China under contract "Photonics Science and Technology for Tera Era" Center of Excellence, under contract No. 89-E-FA06-1-4.

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