TbFeCo as a Perpendicular Magnetic Recording Material

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Abstract- TbFeCo perpendicular magnetic recording media were developed by employing a NiP underlayer to control the magnetic properties of TbFeCo magnetic layer. With the NiP underlayer the magnetization reversal changed from the wall motion to the rotation mode. Dynamic write-read characteristics of a single-layer medium were examined using a conventional merge-type GMR head with a write core width of 1 μm that was designed for longitudinal magnetic recording. A clear magnetic pattern of 450 kFCI, high media SNR and acceptable overwrite properties were obtained. It was shown the thermal stability of the TbFeCo medium is good enough for practical applications. A double-layer medium with a soft-magnetic backlayer exhibited a practical overwritability for a narrow track pitch of 0.4 μm .

Key words: magneto-optical recording media, amorphous RE-TM alloy film, TbFeCo, perpendicular magnetic recording, GMR head, merge type head

1. Introduction

Co-Cr based alloy films have been investigated as materials for perpendicular recording media. The films have a structure composed of segregated grains and the main media noise source is in-bit reversed magnetic domain ¹⁾. To decrease the noise, both of the reversed domain formation and the reversed domain size must be reduced. Honda *et al.* ²⁾ showed that the squareness ratio ($M_r/M_s = S$) in the perpendicular M-H loop must be increased to suppress the reversed domain formation, and the magnetic exchanging coupling between adjacent grains must be reduced to reduce the reversed domain size. The smaller exchange coupling leads to a smaller loop slope in M-H loop. Large S is also required to prevent thermal fluctuation of perpendicular recording media at lower linear density due to higher demagnetization field ³⁾. However, larger S and smaller loop slope are in a tradeoff relationship and very high coersivity (H_c) is required to satisfy both of them for an appropriate M_s value, which makes it difficult to fabricate media.

On the other hand, Rare Earth - Transition Metal (RE-TM) alloy films that are widely used as magneto-optical (MO) recording materials have an amorphous and continuous structure. Recently new recording technologies combining thermo-magnetic or thermally assisted magnetic writing on MO media and magnetic flux

reading by GMR sensor were proposed to achieve higher density recording ^{4), 5)}.

From these backgrounds and seeking another approach, it seems a good way to apply RE-TM alloy films for perpendicular magnetic recording media because reversed domains formation can be suppressed according to their high squareness ratio and low media noise is expected according to their amorphous continuous structure. In addition, they have features preferable to magnetic recording such as; a rather large perpendicular magnetic anisotropy, K_u , easily controllable magnetic properties and fabrication at room temperature. Figure 1 shows the dependence of K_u and M_s of TbFe film on the composition for example, which are calculated using the molecular field model. Because of the characteristics of ferrimagnetic material, there exists the composition of zero net magnetization, which is called the compensation composition. This means that M_s is tunable over a wide range by composition. The value of K_u is $3.5 - 5 \times 10^6 \text{ erg/cm}^3$, which is larger than that of Co-Cr alloy film (about $2 \times 10^6 \text{ erg/cm}^3$ at the maximum).

Indeed, investigations have already been done about perpendicular magnetic recording on RE-TM alloy films. Jenniot *et al.* ⁶⁾ and Bernstein *et al.* ⁷⁾ demonstrated perpendicular recording on TbGdFe, TbFe, and GdFe thin films. Ohtani *et al.* examined the relationship between film fabrication conditions and read-write properties ⁸⁾. However, desirable recording characteristics were not obtained in any experiments and amorphous RE-TM media with strong exchange interaction in film have been believed to be unsuitable for magnetic recording because

Fig. 1 Composition dependence of anisotropy constant, K_u , and saturation magnetization, M_s , of TbFe calculated using the molecular field model.

of the distortion of magnetic transition induced by domain wall motion. However, we think issues in recording performance might have also caused these results. For example, a sensitive GMR reading head was not yet available, and the sputtering technique was not sophisticated at that time.

In this paper, we demonstrate the capabilities of high recording density on perpendicular magnetic recording media composed of a TbFeCo film by controlling the magnetization reversal mode and improving a sputtering process. Dynamic write-read characteristics of a single-layer medium were examined using a conventional merge type GMR head designed for longitudinal recording media. A double-layer medium with a soft-magnetic backlayer was also evaluated using a head with a narrow core width.

2. Preparation of single-layer media

2.1 Structure and basic properties

Single-layer perpendicular media with the structure shown in Fig. 2 were fabricated by a conventional DC magnetron sputtering at room temperature on 2.5inch size glass substrates. A thin SiN layer was formed on the glass substrate as an adhesive layer, and on top of that, a NiP underlayer with a thickness of 10 nm was sputtered. Then, 40nm thick TbFeCo with TM-rich composition was sandwiched between protection layers of amorphous carbon. A lubricant was spin-coated on the top carbon layer for dynamic write-read measurements. Figure 3 shows the Kerr rotation hysteresis loop. The medium has a squareness ratio of 1 and a coercivity squareness S^* of over 0.7 without compensation for demagnetizing field. The H_c of the samples are 2.9 kOe, and the product of film thickness and saturation magnetization, tM_s , is about 1.0 memu/cm^2 .

2.2 Effect of NiP underlayer

The NiP underlayer plays an important role to control the magnetic properties of the media⁹⁾. In order to investigate the magnetization reversal mode, the angular dependence of H_c of TbFeCo films with a NiP underlayer and without a NiP underlayer were measured. As shown in Fig. 4, the H_c of a film with a NiP underlayer decreases with varying magnetic field direction from normal (0 degree) to parallel (90 degree) to a film plane, but the H_c of a film without a NiP underlayer increases with changing magnetic field direction on the contrary. The result suggests that the magnetization of TbFeCo film without a NiP underlayer reverses by the domain wall movement mode, but the magnetization of TbFeCo film with a NiP underlayer reverses mainly by the rotation mode¹⁰⁾.

Figure 5 shows the morphology of a media surface observed with an atomic force microscope. Without NiP, the surface roughness is 0.2 nm, but with the NiP underlayer, the roughness is 0.3 nm. Figure 6 shows the effect of the NiP underlayer on the shape of perpendicular

Lubricant	
Protection layer (10 nm)	Carbon
Recording layer (40 nm)	TbFeCo
Protection layer (5 nm)	Carbon
Underlayer (10 nm)	NiP
Adhesive layer (10 nm)	SiN
Substrate	Glass

Fig. 2. Structure of the TbFeCo single-layer perpendicular recording media

Fig. 3. Kerr rotation hysteresis loop.

Fig. 4. Angular variation of H_c for the samples with and without NiP underlayer.

Fig. 5. Surface morphology of the samples (a) with and (b) without NiP underlayer.

Fig.6. Effect of NiP underlayer on the shape of hysteresis loop

hysteresis loop. Without NiP underlayer the slope of the loop is very steep. With NiP the slope of the loop decreases and the coercive force increases as the thickness increases, while the squareness ratio remains 1. We believe the difference in the surface morphology of the bottom carbon layer brought about by the NiP layer introduces wall motion pinning sites in the TbFeCo film, which changes the magnetization reversal mode.

3. Evaluation results of single-layer media

Dynamic properties of the single-layer medium were measured with a spin stand tester equipped a merge type GMR head (write core width: 1.0 μm , write gap length: 0.3 μm , read core width: 0.8 μm , read gap length: 0.12 μm) designed for longitudinal recording media. The linear velocity at writing and reading was 12 m/s.

3.1 Magnetic transitions

Figure 7 shows the magnetic force microscope images of the written magnetic patterns on the TbFeCo medium. Reversed domains, which are often observed on Co-Cr based alloy perpendicular recording media, do not take place inside the written domains even for long marks (53kFCI). The distortion of magnetic transitions is very small and clear magnetic patterns can be observed even at 450 kFCI, although the edge of the write head has a "percolation.". This indicates that high linear density recording is possible, even on films having rather large

exchange couplings

3.2 Dynamic properties

Figure 8 (a) shows the reproduced waveform of an isolated pattern, which has a shape typical of single-layer perpendicular media. The dipulse ratio is 1, which means that recording is free of demagnetization at the trailing edge of the write head because the media has a high coercivity squareness. Figure 8 (b) shows the waveform of a random pattern. The waveform of 330 kFCI is clearly resolved. We observed a signal even at 650 kFCI.

Figure 9 shows the media signal-to-noise ratio, media SNR, and Fig. 10 shows the peak-to-peak signal amplitude, S_{pp} , of the TbFeCo medium and the longitudinal medium with a capability of 15 Gb/in². The

Fig. 8 The reproduced waveforms of (a) isolated pattern and (b) random pattern.

Fig. 7 Magnetic force microscope images of magnetic patterns recorded by a ring-type write head with a core width of 1.0 μm and a gap length of 0.3 μm .

media SNR is defined as $SNR=20\log_{10}(S_{pp}/N_{rms})$, in which N_{rms} denotes the media noise that was derived by subtracting system noise and head noise from total noise. Even though media SNR of TbFeCo media is smaller than that of longitudinal media, total SNR including system noise and head noise is not different in each media because we used TbFeCo media with a large signal amplitude.

Figure 11 shows the dependence of signal amplitude and overwrite properties on a write current, I_w . The signal

Fig. 9 The linear density dependence of media signal to noise ratio.

Fig. 10 The linear density dependence of signal amplitude.

Fig. 11. Write current dependence of signal amplitude and overwriteability.

amplitude was measured for 81 kFCI and 326 kFCI. Without recording demagnetization, the amplitude became saturated as I_w increased. Overwrite properties were examined by measuring the residual signal level of 81 kFCI after overwriting at 490 kFCI. The overwriteability value is -30 dB, which is at an acceptable level for practical use.

3.3 Thermal stability

Static thermal stability of the TbFeCo medium was measured. A sample of the medium was saturated, and the temporal change in residual magnetization M_r without applying a magnetic field was measured using SQUID. Figure 12 shows the change of M_r/M_s against time at 25°C and 65°C. M_r/M_s has no decay at 25°C, even after 10^4 seconds have elapsed. But at a high temperature of 65°C, M_r/M_s decreased at a rate of 1.3 %/decade because of the reduction of H_c . This rate is not so big, and moreover this would be improved by using high-Curie-point media or RE-rich media

The changes of recorded signal output voltage were also measured against time using a spin stand tester for 42 kFCI, 200 kFCI, and 400 kFCI at 25°C. It is known that perpendicular recording is subject to thermal agitation at lower linear density because of higher demagnetization field. As shown in Fig. 13, all linear densities did not have

Fig. 12 Time dependence of M_r/M_s for the TbFeCo perpendicular recording media.

Fig. 13 Time dependence of output signal voltage for different linear densities.

significant decay although the measurement time was not long enough, which corresponds to the result of Fig. 12.

4. Double-layer media

4.1 Media and head

Perpendicular magnetic recording media often have a soft magnetic back-layer to increase the perpendicular writing field in the recording layer by in-plane magnetization in the back-layer. We tried the double-layer media configuration to enhance overwrite performance for a narrow track width.

The media structure is shown in Fig.14. We used a CoZrNb amorphous film with a thickness of 500 nm as a soft magnetic back-layer. The layer structure with TbFeCo, NiP, and C in the double-layer media is the same as that of the single-layer media explained in section 3.1 and the H_c of the double-layer medium is 2.9 kOe.

Figure 15 shows the bottom-view of the head that we prepared to evaluate the double-layer medium. A merge-type GMR head having a very narrow write track width of 0.4 μm was FIB trimmed from the air bearing surface. As shown in the figure, there are two FIB trimmed depressions. One is to make a wide gap length, and another is to get the straight trailing edge. The obtained configuration resembles a single-pole head for perpendicular recording. On the other hand, a non-trimmed head with the write core width of 0.5 μm was used to evaluate the single-layer medium described in section 3 for comparison.

Lubricant	
Protection layer (10 nm)	Carbon
Recording layer (40 nm)	TbFeCo
Protection layer (5 nm)	Carbon
Underlayer (10 nm)	NiP
Soft magnetic layer (500 nm)	CoZrNb
Substrate	Glass

Fig. 14 Structure of the TbFeCo double-layer media with a soft magnetic back layer.

Fig. 15 Bottom-view of the FIB trimmed head for evaluation of the double-layer media

4.2 Dynamic properties

Figure 16 is the readout waveforms of the double-layer medium, which shows the typical shape of perpendicular recording using a single pole head. Overwrite properties of each medium were examined using the residual signal of 81 kFCI after overwriting at 490 kFCI as shown in Fig. 17. Overwrite performance of the single-layer medium is poor for the narrow track width. Conversely, overwritability of the double-layer medium, even for 0.4 μm track width, is good enough for practical applications. Figure 18 shows the media SNRs of each medium. Unfortunately, the media SNR of the double-layer medium is smaller than that of the single-layer medium, because the write noise of the double-layer

Fig. 16. Reproduced waveforms of the double-layer media.

Fig. 17 Write current dependence of overwritability of the double-layer media and the single-layer media for narrow track pitch.

Fig. 18 Media signal to noise ratio of the double-layer media and the single-layer media for narrow track pitch.

medium is rather high. Decrease of the write noise is the next issue for research and the media structure must be optimized for double-layer media.

5. Conclusion

We have developed TbFeCo perpendicular magnetic recording media by controlling the magnetic properties. Especially we found that the existence of a NiP underlayer changed the magnetization reversal to the rotation mode, suppressed the distortion of magnetic transition and elevated the recording resolution. The single-layer TbFeCo perpendicular medium exhibited clear magnetic transitions of 450 kFCI and high media SNR using a conventional merge-type GMR head. And the thermal stability of the medium is good enough for practical applications. The double-layer medium with a CoZrNb soft-magnetic backlayer has practical overwritability for a narrow track pitch of 0.4 μ m, yet the media structure must be improved for double-layer media to achieve a higher media SNR.

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