Advanced Technologies in Synthetic Ferrimagnetic Media

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Recently, synthetic ferrimagnetic media (SFM) have been widely employed as high-density recording media for hard disk drives (HDDs). The signal-to-noise ratio (SNR) and thermal stability of magnetically written bits have been improved by three new SFM technologies. The first technology greatly improves the SNR in the lower areal magnetization region by increasing the magnetic anisotropy energy of the stabilizing layer without degrading the thermal stability. The second is an exchange enhancement technology that uses a Co-based layer adjacent to the Ru exchange coupling layer to improve the thermal stability without degrading the SNR. On SFM media that incorporate this second technology, stable, non-percolating high-density patterns of up to 900 kfci were clearly observed using high-resolution magnetic force microscopy (MFM). The third technology uses a separated recording layer with a Ru/CoCr/Ru exchange-coupling layer (separated-SFM) to provide a more than 50% reduction of medium noise power with the same or better thermal stability than that of conventional SFM. These technologies enable the design of practical media for recording densities over 150 Gbit/in^2. This paper introduces these new SFM technologies.

1. Introduction

Thermal degradation of the magnetically written bits of a hard disk drive (HDD) has been recognized as a fundamental limiting factor for high-density longitudinal recording.[1] To circumvent the limitations caused by thermal degradation, synthetic ferrimagnetic media (SFM) were proposed in 1999 and 2000 by Fujitsu[2),3)] and in 2000 by IBM.[4] SFM capable of densities around 100 Gbit/in^2 have been demonstrated in laboratories[5)-7)] and used in commercial 2.5-inch HDDs at 35 Gbit/in^2.[8] With 60 to 100 Gbit/in^2 areal densities now being targeted for commercial applications and SFM technologies being put to practical use,[9] it is important to develop media technologies for densities exceeding 100 Gbit/in^2 that will also act as a bridge to perpendicular recording technology. Furthermore, SFM technology can be used to improve the performance of not just longitudinal media, but also perpendicular media.[10]

In this paper, we introduce three newly developed SFM technologies. The first provides thermal stability and improves the signal-to-noise ratio (SNR) by increasing the magnetic anisotropy of the stabilization layer of SFM. The second enhances the exchange coupling energy between the stabilization and recording layers of SFM to improve the thermal stability without degrading the SNR. The third uses an exchange-coupled separating layer to half the medium noise power. These new technologies improve the SNR performance of SFM while maintaining the thermal stability.

2. Structure of SFM

Figure 1 shows the layer and magnetic structures of SFM with two and three magnetic

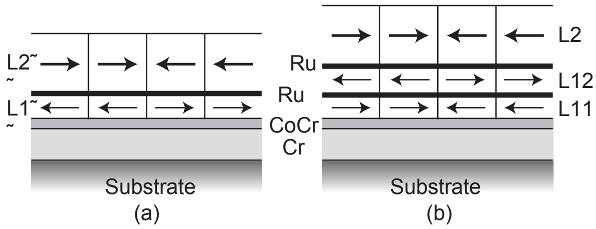

Figure 1
SFM structure with (a) one (S = L1) and (b) two (S1 and S2) stabilizing layers between main magnetic layer (M = L2) and CoCr and Cr seed layers. Interlayer antiferromagnetic coupling is mediated by 0.7 nm Ru layers.

Table 1
Media structures.

Media	Thickness (nm) L1	Thickness (nm) L2	K_u of L1 (10^6 erg/cm^3)	M_s of L1 (emu/cm^3)
SL	–	9 to 15	–	–
SFM-1	5	9 to 15	1.9	325
SFM-2	5	8 to 14	1.3	250
SFM-3	3 to 7	12	1.3	250

note) Same alloys were used for SL and L2 for all SFM.

layers. Conventional underlayer structures are employed that consist of a seed layer such as oxidized NiP and a Cr-based underlayer. Thin layers of Ru are added between the magnetic layers to introduce antiparallel coupling.[11] Each magnetic layer is antiparallel-coupled by an exchange coupling mechanism created by the insertion of a thin Ru (about 0.7 nm) layer. The effective areal magnetization (remanence magnetization × thickness) $M_r\delta$ is reduced due to the layer magnetization cancellation. However, the effective grain volume is larger than in a conventional medium of the same $M_r\delta$ because the stabilizing layer and recording layer are magnetically coupled. Therefore, greater thermal stability is realized without significant degradation in linear density resolution due to the total thickness.[3]

3. SNR and thermal stability improvement of SFM

According to longitudinal magnetic recording theory, a thinner medium or lower $M_r\delta$ with a higher coercivity in higher density recording results in a higher SNR.[6),9)] To secure thermal stability at a lower $M_r\delta$, we used CoCrPtB alloys for the L1 and L2 layers.

A series of conventional media with a single magnetic layer (SL) and three series of SFM were used in this study (**Table 1**). All the media were made using the same L2 composition, underlayer, intermediate layer structures, and sputtering conditions. A CoCrPtB alloy with good intergranular segregation was used for the SL. This alloy shows bulk magnetization (M_s) and magnetic anisotropy (K_u) values of 325 emu/cm^3 and 1.9 × 10^6 erg/cm^3, respectively. The $M_r\delta$ values of the SL were varied between 0.26 and 0.45 memu/cm^2 by changing the magnetic layer thickness, and the coercivity (H_c) values correspondingly changed between 1800 and 3400 Oe.

For SFM-1 and SFM-2, the thickness of L1 was fixed and $M_r\delta$ was varied by changing the thickness of L2. The distinction between SFM-1 and SFM2 is that their L1s have different CoCrPtB alloy compositions with different M_s and K_u values (Table 1). For SFM-1, $M_r\delta$ was varied between 0.15 and 0.35 memu/cm^2, and the H_c values correspondingly changed between 2600 and 3900 Oe. For SFM-2, $M_r\delta$ was varied between 0.18 and 0.37 memu/cm^2, and the H_c values correspondingly changed between 2000 and 3600 Oe. For SFM-3, L2 was fixed and $M_r\delta$ was varied between 0.29 and 0.37 memu/cm^2 by changing L1.

Figure 2 shows the signal decay coefficient of the media at 300 kfci for various $M_r\delta$ values as evaluated using a read-write tester. The readout voltage from the read head decayed linearly against a logarithmic time scale, and the signal decay coefficient was defined as the gradient of this linear decay. For SL, the decay coefficient is worse than –0.1 dB/decade for $M_r\delta < 0.33$ memu/cm^2. SFM show better thermal stability, and the thermally-stable region (defined where the decay coefficient is better than –0.05 dB/decade) is shifted to lower $M_r\delta$ values. SFM-1, which have a higher K_u-L1 (K_u of L1) than SFM-2,

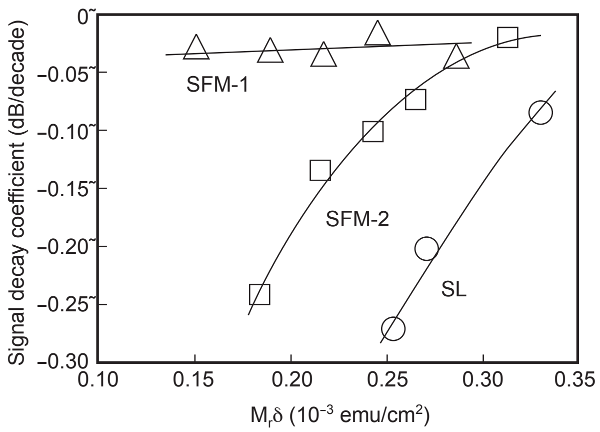

Figure 2
Signal decay coefficient of SFM and single magnetic layer media at 300 kfci at various $M_r\delta$.

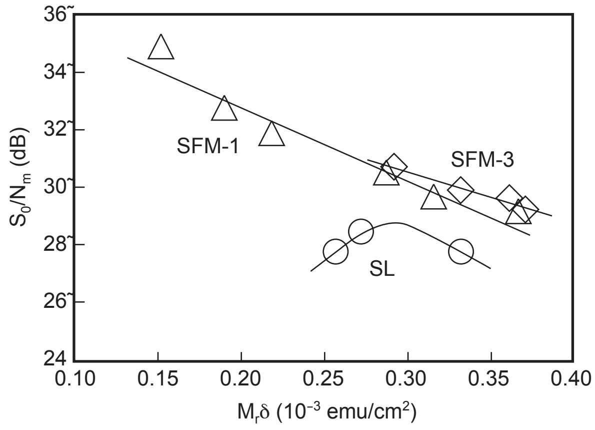

Figure 3
S_0/N_m of SFM and single magnetic layer media at 450 kfci for various $M_r\delta$. S_0 is isolated base-to-peak signal, and N_m is media noise.

show the best thermal stability performance, with a signal decay coefficient better than –0.05 dB/decade, even at $M_r\delta$ = 0.15 memu/cm^2. The L1 layer of SFM-1 has a higher M_s (M_s-L1) than that of SFM-2; therefore, for any particular tL2, a lower $M_r\delta$ is obtained. However, at any particular tL2, where the thermal energy barrier of L2 is constant, SFM-1 show better thermal stability than SFM-2 due to the contribution from K_u-L1. The signal decay was also measured at higher linear densities, and the media with $M_r\delta$ = 0.15 memu/cm^2 showed a decay rate better than –0.04 dB/decade at 400 kfci. A signal decay coefficient of –0.05 dB/decade at half of the maximum usable linear density is usually acceptable in commercial drives. For both SFM-1 and SFM-2, the switching field is about 7500 Oe and is only 200 to 300 Oe higher than that for the SL; therefore, no significant degradation in overwrite (OW) is expected.

With thermal stability secured at very low $M_r\delta$ values, it is important to investigate whether SNR improvements are also observed. **Figure 3** shows the SNR of SFM-1, SFM-3, and SL media at 450 kfci for a wide range of $M_r\delta$ values. For both SFM series, the S_0/N_m improves as $M_r\delta$ is reduced. The SNR of the SFM-1 is improved by 5.7 dB when $M_r\delta$ is reduced from 0.36 to 0.15 memu/cm^2. The SNR values for SL are lower due to the lower $M_r\delta/H_c$ values. When similar $M_r\delta/H_c$ values are considered, S_0/N_m for SFM and conventional media could be made similar.[12] However, to obtain similar $M_r\delta/H_c$ values at low $M_r\delta$ values in conventional media, the switching field must be increased substantially.

4. Improvements in thermal stability by enhancement layer

In this section, we report on another scheme for improving the thermal stability of SFM that uses an exchange field enhancement layer (E layer).[13] To achieve the high K_u-L1 value required for thermal stability, a significant J is imperative to maintain the antiparallel moment configuration at remanence. That is, H_{ex} must be greater than H_c-L1, where H_{ex} is the exchange field experienced by L1, and H_c-L1 is the coercivity of L1).[3),14)] To offset the increase in H_c-L1 due to a higher K_u-L1, H_{ex} values greater than the typical 500 Oe are necessary.[14)]

Due to antiferromagnetic (AF) coupling, the L1 layer experiences an exchange field H_{ex} that is proportional to the interlayer AF exchange coupling strength J and inversely proportional to the thickness and saturation magnetization M_{S1} of the L1 layer; therefore, $H_{ex} = J / t_1 M_{S1}$. The value of t_1

M_{S1} cannot be arbitrarily reduced to increase H_{ex} because it is used to cancel a portion of the magnetization of L2. Therefore, a larger H_{ex} improvement must be thought through the enhancement of J. SFM structures have been reported[4),14)] that have a very small J of approximately 0.05 erg/cm^2 compared to the 5 erg/cm^2 of pure Co/Ru multilayers.[11)] The small J observed in previous SFM structures is likely due to the effect of additives such as Cr, B, Pt, which comprise at least 30 at.% of the magnetic layers.[15),16)] These additives are essential for obtaining the necessary anisotropy values, grain size, and segregation properties in a medium with good recording properties. It is not trivial to reduce these additives without adversely affecting recording performance. Instead, we modified the interfaces by inserting thin (about 1 nm) exchange enhancement layers (E layers) between the Ru nonmagnetic spacer and the magnetic layers.

Figure 4 shows a media structure with the usual high-performance CoCrPtB L1 and L2 layers and two enhancement layers: E1 and E2. E1 is inserted between Ru and L1, and E2 is inserted between Ru and L2. These E layers are composed of hcp magnetic materials such as Co, CoCr, and CoCrX, with the latter having the lowest Co content and X being a transition metal.

Figure 5 (a) shows the exchange-coupling field H_{ex} as a function of E layer thickness. The thickness of L1 and L2 were kept constant. H_{ex} was determined from the center of a minor loop.[14)] The figure shows that H_{ex} is dramatically increased by using very thin E layers of 0.5 or 1 nm and this enhancement strongly depends on the material used. An H_{ex} of 4 kOe is attained with a 1 nm E layer of pure Co. This value is eight times larger than the H_{ex} without E layers. The H_{ex} obtained with CoCr is smaller than that obtained with pure Co, and the 1.2 kOe value obtained with CoCrX is even smaller. We also confirmed that $M_r\delta$ does not change when E layers are used, which indicates complete antiparallel coupling in the remanent state.

Table 2 shows J values for 1 nm E layers composed of different materials. The largest among these values is 0.73 erg/cm^2 for pure Co. The J value tends to be smaller with larger concentrations of additives. Just 1 nm of Co on both sides of the Ru can multiply J by 15 with no E layer. Therefore, the coupling strength J seems to be strongly determined by the Co concentration at the interface.

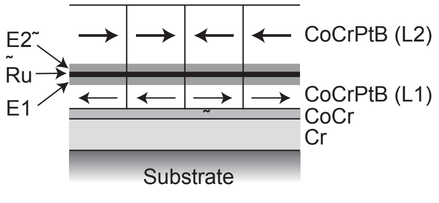

Figure 4
Structure of synthetic ferrimagnetic media with E layers.

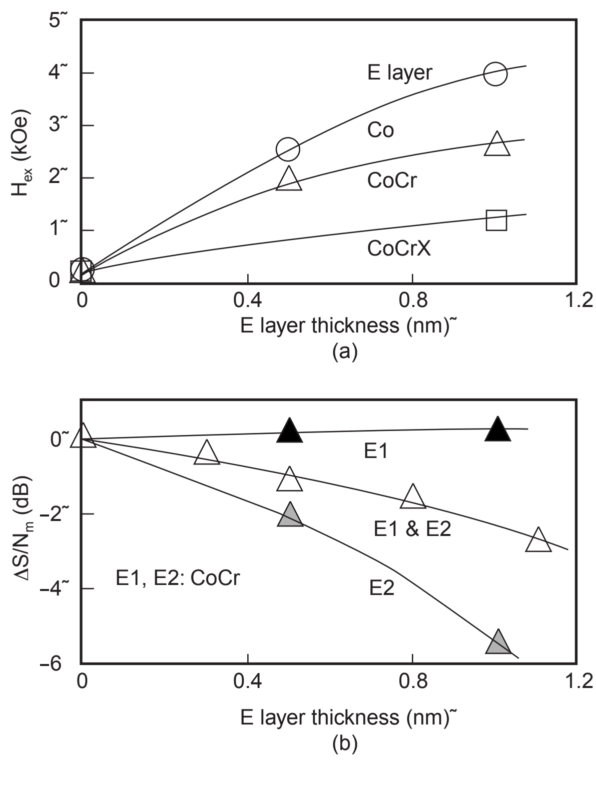

Figure 5
(a) Exchange coupling strength H_{ex} for L1 at various E layer thicknesses. Same E layers are on both sides of Ru. (b) Change in SNR for various E layer thicknesses when E1, E2, and both E layers are used. Values are relative to SFM with no E layer. E layers are CoCr alloy.

Figure 5 (b) shows the SNR dependence on CoCr E-layer thickness of media with E1, E2, and both E layers as compared to the case with no E layer. When both E1 and E2 are used, the SNR degrades by 2.0 dB at 1 nm. The SNR degrades more rapidly when only E2 is used; for example, it degrades by 6 dB at 1 nm. On the other hand, the SNR does not change or slightly improves when only E1 is introduced. When only E1 is used, the H_{ex} is 1001 Oe, which is 400 Oe better than when no E layer is used. The J is 0.14 erg/cm^2, and this value is 3 times larger than when no E layer is used.

Figure 6 shows the thermal stability factor K_uV/kT as a function of the stabilization layer thickness of L1 for SFM with and without an E1 layer. An intrinsic character of SFM is that, even without an E layer, the stability factor is increased from 59 to 67 by increasing the L1 thickness from 3 to 5 nm. When an E1 layer is used, K_uV/kT is further increased because of the enhanced J.[17] The contribution of L1 to the overall thermal stability is increased from earlier reported values of 30 to 50% [12),18] to over 80%.

Table 2
J values with various E layer materials.

Materials	Co	CoCr	CoCrX	No E layer
J (erg/cm^2)	0.73	0.59	0.24	0.05

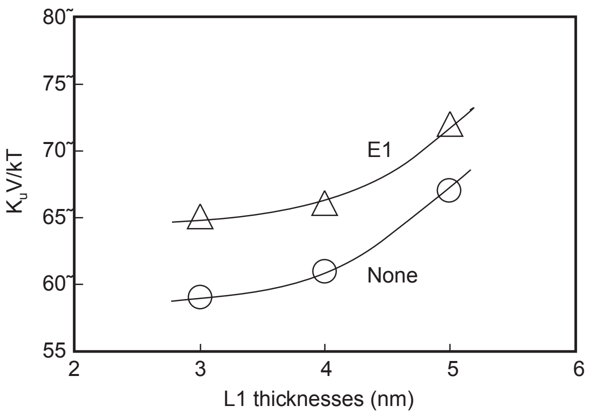

Figure 6
Stability factor of SFM with E1 layers and no E layer at various L1 thickness.

Therefore, an E1 layer improves the performance of SFM in two ways: 1) it increases the contribution that the stabilization layer makes towards improving the thermal stability and 2) it increases H_{ex}, which allows the use of higher K_u-L1 materials to further improve the thermal stability. The 106 Gbit/in^2 demonstration medium consists of an L1 layer with relatively low anisotropy ($<2.5 \times 10^6$ erg/cm^3) and $H_{ex} < 500$ Oe; however, it also exhibited an excellent thermal stability coefficient of –0.01 dB/decade at room temperature.[5),19)] With a single E1 layer, at least from the media thermal stability point of view, higher densities seem more accessible in the longitudinal recording mode.

Enhancement of the exchange coupling strength and thermal stability while maintaining the SNR is made feasible by employing an E layer between the Ru and stabilization layers. This provides added flexibility when tuning thermally stable media to obtain the optimum read-write properties. We submit that the combination of a high anisotropy stabilization layer and enhanced antiferromagnetic layer coupling will ensure stability at recording densities over 100 Gbit/in^2.

5. Direct observation of high-density bit patterns on SFM

In the previous sections, we showed that an SFM, which is thermally stable in the lower $M_r\delta$ region, can be used for high-density recording because of the sharper bit transitions. To confirm this ability, magnetic force microscopy (MFM) observation was performed on SFM.[20)] The sample investigated was a thermally stable medium with a CoCr L1 layer of thickness 1.5 nm, $M_r\delta$ = 0.22 memu/cm^2, and H_c = 4400 Oe. **Figure 7 (a)** shows MFM images of clearly identifiable 800, 900, and 1000 kfci bit patterns. **Figure 7 (b)** shows the amplitude of the force gradient (or line profile) corresponding to the bits and transitions. Improvements of the media and the high resolu-

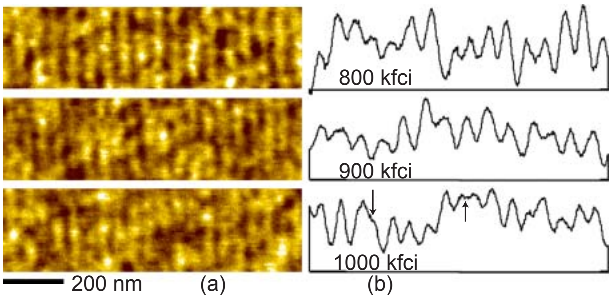

Figure 7
(a) 800 to 1000 kfci patterns imaged using a high-sensitivity MFM and (b) corresponding amplitude of force gradient (in A.U.) against scan length. Transitions correspond to positions of peaks or valleys.

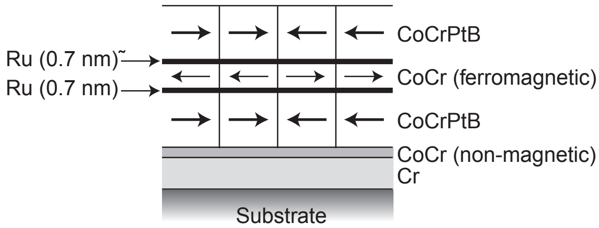

Figure 8
Configuration of separated-SFM (s-SFM). Medium has multiple ferromagnetic layers separated by thin Ru layers.

tion of the MFM system, made this observation possible. It is clear from these two figures that the 800 kfci patterns are well resolved and the peak/valley positions corresponding to the transitions can be well quantified. This is true for the 900 kfci patterns as well. For the 1000 kfci patterns, however, there are regions in which neighboring bits are not well-resolved (black arrows), and an analysis[21] of the data further clarified this observation. Therefore, the percolation density is close to or above 1000 kfci for this media. From the frequency analysis of the data shown in Figure 7 (b), average bit lengths of 34, 30, and 26 nm are obtained, which are in close agreement with the written patterns of 800, 900, and 1000 kfci, respectively.

A fine bit pattern was observed without percolation up to a linear density of 900 kfci. A track density of 170 ktpi can be realized on the basis of a 5.5 bit aspect ratio (fci/tpi). As a result, it may be possible to extend recording densities beyond 150 Gbit/in^2 by using low-$M_r\delta$ and thermally-stable SFM.

6. New noise reduction technology: separated SFM

A medium layer with a separation structure containing a non-magnetic layer has been studied as a technology for reducing medium noise.[22), 23)] However, this type of media could not be put to practical use because its separation structure halves the grain volume, and as a result, the thermal stability is insufficient at the lower $M_r\delta$ values needed for high-density recording.[24)]

To improve the thermal stability of this type of media without degrading its low-noise properties, we employ an exchange coupling structure instead of a non-magnetic breaking layer.[25)] An exchange-coupling layer consisting of a CoCr ferromagnetic layer laminated with a thin Ru layer on both sides was employed to separate the recording layers (separated-SFM: s-SFM) in longitudinal HDD media as shown in **Figure 8**. The CoCrPtB recording layers, which are divided into sections of equal thickness, are ferromagnetically coupled via the antiferromagnetically coupled CoCr layer by a function of the thin Ru layers.

Figure 9 shows the hysteresis loops of SFM and s-SFM. The magnetization of s-SFM's CoCrPtB layers are synchronously rotated; therefore, s-SFM's hysteresis loop is similar to that of the SFM. The exchange field H_{ex} of the CoCr layer in s-SFM is enhanced compared to that of SFM because the exchange fields from the upper and lower interfaces with the Ru simultaneously act on the CoCr layer.

Figure 10 shows the energy of normalized medium noise power $(N_m/S_0)^2$ versus the recording density. The $(N_m/S_0)^2$ was greatly reduced by the s-SFM structure over a wide range of recording densities. Above 500 kfci, the medium noise

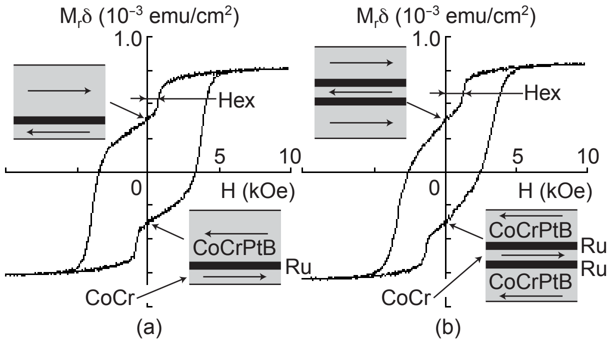

Figure 9
Hysteresis loops of (a) SFM and (b) separated-SFM (s-SFM). Magnetic moment coupling state at remanent magnetization state and exchange field H_{ex} for CoCr layer are shown.

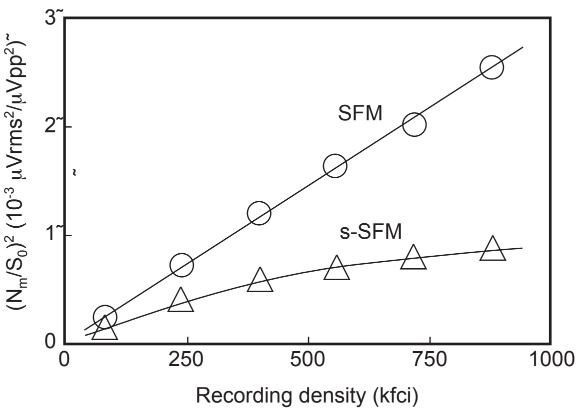

Figure 10
Normalized medium noise power $(N_m/S_0)^2$ of SFM and separated SFM (s-SFM) at various recording densities.

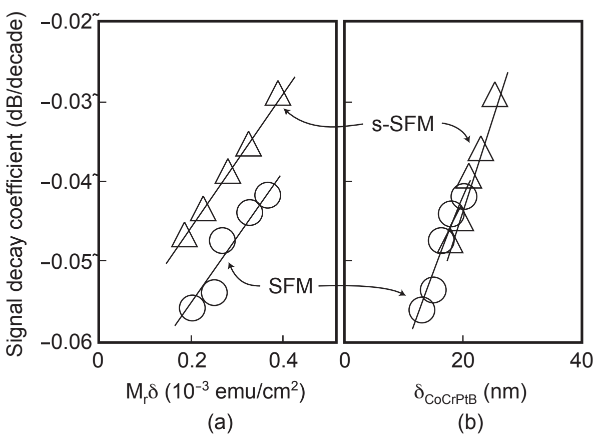

Figure 11
Signal (350 kfci) decay coefficient at room temperature of SFM and separated SFM (s-SFM) at (a) various areal magnetizations and (b) various total thicknesses of recording layer.

power of s-SFM was more than 50% less than that of SFM, which is a promising improvement of SNR performance for high-density recording.

If we compare both media on the basis of areal magnetization, s-SFM have better thermal stability than SFM [**Figure 11 (a)**]. Also, when the s-SFM thickness is the same as the total thickness of the CoCrPtB layer, the SFM and s-SFM have similar thermal stabilities [**Figure 11 (b)**] because the top and bottom CoCrPtB layers are coupled by a magnetic exchange interaction via the Ru/CoCr/Ru layer. It can be concluded that s-SFM provide low medium-noise properties with no degradation of thermal stability.

7. Conclusion

A new synthetic ferrimagnetic media (SFM) shows improved thermal stability and SNR compared to a simple-structured SFM. The magnetic anisotropy and exchange coupling energy of this media's stabilization layer improve the thermal stability. A separated recoding layer structure with a Ru/CoCr/Ru exchange coupling layer greatly reduces the medium noise without degrading the thermal stability. The potential of this SFM for high-density recording was confirmed with the observation of 900 kfci magnetic bits. Recording densities exceeding 150 Gbit/in^2 can be achieved by integrating new SFM technologies. These technologies will not only act as a bridge to perpendicular recording technology but will also be applied to perpendicular media.

References

1) S. H. Charap, P. L. Lu, and Y. He: Thermal stability of recorded information at high densities. *IEEE Trans. Magn.*, **33**, p.978-983 (1997).
2) E. N. Abarra, H. Sato, A. Inomata, I. Okamoto, and Y. Mizoshita: Magnetic recording medium with exchange coupling underlayers. in Magnetics Soc. Japan Conf., Kita Kyushu, September 1999.
3) E. N. Abarra, A. Inomata, H. Sato, I. Okamoto, and Y. Mizoshita: Longitudinal magnetic recording media with thermal stabilization layers. *Appl. Phys. Lett.*, **77**, p.2581-2583 (2000).

4) E. E. Fullerton, D. T. Margulies, M. E. Schabes, M. Carey, B. Gurney, A. Moser, M. Best, G. Zeltzer, and H. Rosen: Antiferromagnetically coupled magnetic media layers for thermally stable high-density recording. *Appl. Phys. Lett.*, **77**, p.3806-3808 (2000).
5) J. Hong, J. Kane, J. Hashimoto, M. Yamagishi, K. Noma, and H. Kanai: Spin-valve head with specularly reflective oxide layers for over 100 Gbit/in^2. *IEEE Trans. Magn.*, **38**, p.15-19 (2002).
6) B. R. Acharya, A. Ajan, E. N. Abarra, A. Inomata, D. Hasegawa, and I. Okamoto: Synthetic ferrimagnetic media for over 100 Gbit/in^2 longitudinal magnetic recording. in Joint Eur. Magnetism Symp., Grenoble, France, August 2001.
7) Z. Zhang, Y. C. Feng, T. Clinton, G. Badran, N.-H. Yeh, G. Tarnopolsky, E. Girt, M. Munteanu, S. Harkness, H. Richter, T. Nolan, R. Ranjan, S. Hwang, G. Rauch, M. Ghaly, D. Larson, E. Singleton, V. Vas'ko, J. Ho, F. Stageberg, V. Kong, K. Duxstad, and S. Slade: Magnetic recording demonstration over 100 Gb/in^2. *IEEE Trans. Magn.*, **38**, p.1861-1866 (2002).
8) Press Release by Fujitsu Ltd., October 2001.
9) E. N. Abarra, B. R. Acharya, A. Inomata, A. Ajan, and I. Okamoto: Synthetic ferrimagnetic media. *FUJITSU Sci. Tech. J.*, **37**, 2, p.145-154 (2001).
10) E. Girt and H. J. Richter: Antiferromagnetically coupled perpendicular recording media. *IEEE Trans. Magn.*, **39**, p.2306-2310 (2003).
11) S. S. P. Parkin: Systematic variation of the strength and oscillation period of indirect magnetic exchange coupling through the 3d, 4d, and 5d transition metals. *Phys. Rev. Lett.*, **67**, p.3598-3601 (1991).
12) E. N. Abarra, B. R. Acharya, A. Inomata, and I. Okamoto: Synthetic ferrimagnetic media. *IEEE Trans. Magn.*, **37**, p.1426-1431 (2001).
13) A. Inomata, B. R. Acharya, E. N. Abarra, A. Ajan, D. Hasegawa, and I. Okamoto: Advanced synthetic ferrimagnetic media (invited). *J. Appl. Phys.*, **91**, p.7671-7675 (2002).
14) A. Inomata, E. N. Abarra, B. R. Acharya, and I. Okamoto: Exchange coupling strength in synthetic ferrimagnetic media. *IEEE Trans. Magn.*, **37**, p.1449-1451 (2001).
15) M. T. Johnson, M. T. H. van de Vorst, P. J. H. Bloemen, R. Coehoorn, A. Reinders, J. aan de Stegge, and R. Jungblunt: Phase shifts in the oscillatory interlayer exchange coupling across Cu layers. *Phys. Rev. Lett.*, **75**, p.4686-4689 (1995).
16) R. Ranjan: Presented at Joint MMM-Intermag Conference, San Antonio, January 2001 (unpublished).
17) J. P. Wang, Z. S. Shan, S. N. Piramanayagam, and T. C. Chong: Anti-ferromagnetic coupling effects on energy barrier and reversal properties of recording media. *IEEE Trans. Magn.*, **37**, p.1445-1448 (2001).
18) B. R. Acharya, A. Ajan, E. N. Abarra, A. Inomata, and I. Okamoto: Contribution of the magnetic anisotropy of the stabilization layer to the thermal stability of synthetic ferrimagnetic media. *Appl. Phys. Lett.*, **80**, p.85-87 (2002).
19) B. R. Acharya, E. N. Abarra, A. Inomata, A. Ajan, and M. Shinohara: Signal-to-Noise ratio and thermal stability issues in extending synthetic ferrimagnetic media technology over 100 Gb/in^2. *IEEE Trans. Magn.*, **39**, p.645-650 (2003).
20) E. T. Yen, H. J. Richter, G. L. Chen, and G. Rauch: Quantitative MFM study on percolation mechanisms of longitudinal magnetic recording. *IEEE Trans. Magn.*, **33**, p.2701-2703 (1997).
21) A. Ajan, E. N. Abarra, A. Inomata, M. Shinohara, and W. Yamagishi: Percolation studies in synthetic ferrimagnetic recording media. *IEEE Trans. Magn.*, **40**, p.2431-2433 (2004).
22) H. Hata, T. Fukuichi, K. Yabushita, M. Umesaki, and H. Shibata: Low-noise media using double-layer CoNiCr thin films for longitudinal recording. *J. Appl. Phys.*, **67**, p.4692-4694 (1990).
23) R. Ranjan, M. S. Miller, P. K. George, and M. Lu: Magnetic, recording, and crystalline properties of multilayered longitudinal thin-film media. *J. Appl. Phys.*, **69**, p.4727-4729 (1991).
24) Pu-L. Lu and S. H. Charap: Thermal instability at 10 Gbit/it/in^2 magnetic recording. *IEEE Trans. Magn.*, **30**, p.4230-4232 (1994).
25) T. Gouke, I. Okamoto, Y. Kitamoto, and S. Ishida: Noise property of Co-Cr-Pt-B longitudinal media separated by a Ru/Co-Cr/Ru exchange-coupling layer. *J. Magn. Soc. Jpn.*, **28**, p.797-801 (2004).

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