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Synthetic Ferrimagnetic Media

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The thermal stability and read-write performance of longitudinal magnetic recording media with antiferromagnetically coupled layers were investigated. The thermal stability is strongly dependent on the interaction between layers and the anisotropy energy of the stabilizing layer or layers. For media with two coupled layers, the energy barrier is increased by 30% to 80% of the anisotropy energy of the stabilizing layer, depending on the strength of the interaction. Although the total thickness is larger compared to a conventional medium with the same remanence magnetization and thickness product $M_r\delta$, the resolution is higher and depends on the difference in thickness between the layers. With these "synthetic ferrimagnetic" structures, thermally stable, low $M_r\delta$ and high-resolution media are made possible with an areal density advantage of at least 1.75 times that of conventional longitudinal recording media.

1. Introduction

The high areal densities realized today in commercial rigid disk drives are the results of scaling made possible by significant developments in media, head, channel, and coding technologies. The number of grains per bit has been approximately maintained to obtain the necessary signal-to-noise ratio (SNR) for adequate bit error rates at a specified areal density. As the magnetic grain volume is decreased, the energy barrier E_b to thermal agitation is lowered.[1] By increasing the medium coercivity H_C, E_b is increased as well as the medium SNR. However, this process cannot be continued indefinitely because head fields are limited by the availability of high moment materials and by the reduction in write head width. Much gain has been achieved by reducing the magnetic spacing, which increases the resolution and therefore the ability to write higher linear densities. However, success with this approach is obviously limited by how safely and reliably the flying height can be reduced.

Methods proposed to improve thermal stability in longitudinal media aside from increasing the magnetic anisotropy include keepered media, which employ a soft magnet "keeper layer" to reduce the demagnetizing field H_d inside bits;[2] thermally-assisted writing schemes similar to what is being used for magneto-optic recording;[3] and media with antiferromagnetic (AFM) underlayers.[4] A variation of the latter but with the use of artificial antiferromagnets such as Co/Ru/Co multilayers[5] has recently been introduced.[6)-9)] Greater exchange coupling between the stabilizing layer (or layers) and the recording layer can be realized compared to the use of natural AFM. In this paper, we will borrow from the terminology used for synthetic antiferromagnets and use the term "synthetic ferrimagnetic media" (SFM) for these antiferromagnetically coupled layer structures. Compared to conventional media, we have observed a significant improvement in thermal stability as well as read-write performance, especially at high densities.[6)-9)] In this paper, we describe the microstructure, magnetic properties, thermal stability, and read-write properties of synthetic ferrimagnetic media.

2. Media

2.1 Layer structure

Figures 1 (a) and **(b)** show the layer and magnetic structures of SFMs with two and three magnetic layers, respectively. Conventional underlayer structures are employed which consist of a seed layer such as oxidized NiP and a Cr-based underlayer. Disposed between the magnetic layers are thin layers of Ru to induce antiparallel coupling.[5] The product $M_r\delta$ of the effective remanence magnetization and the thickness is reduced due to the layer magnetization cancellation, but the effective grain volume is larger compared to a conventional medium of the same $M_r\delta$. Therefore, greater thermal stability is expected without a significant degradation in linear density resolution caused by the larger total magnetic layer thickness of the structure.

The subsequent discussion focuses on SFM with two magnetic layers, the stabilizing layer L1, and the main layer L2. The notation [t_{L2}/Ru/t_{L1}] will be used for the structure, where t_L is the layer thickness in nm.

2.2 Fabrication

The media are deposited using an in-line magnetron-sputtering machine similar to what is used for mass-production. NiP-coated disks are first heated, then the Cr underlayer, CoCr intermediate layer, and CoCrPtB-based magnetic layers and Ru layers are sputtered. (Although the SFM reported here are made on NiP seed layers, they can also be easily fabricated on other seed layers that promote the magnetic layer c-axes to be in-plane.) Cr films grown on oxidized NiP at elevated temperatures (~200°C) develop a (002) fiber texture on which subsequent hcp layers such as CoCr-based alloys grow with a $(11\bar{2}0)$ orientation. The Ru deposition time is kept to about 4 seconds, as in a typical mass-production process. Adequate thickness control in the optimum range of 0.6 to 0.8 nm is readily achieved. A sputtering unit that can yield 5% Ru thickness control over a 3.5-inch disk is sufficient to ensure uniformity in the magnetic and read-write (R/W) properties.

2.3 Microstructure

Figure 2 shows a high-resolution cross-sectional transmission electron microscopy (TEM) image of an SFM with two magnetic layers on an NiP/Al-Mg substrate. The thin dark band is a Ru layer which grows coherently on the Co-alloy layers. Bulk Ru has an hcp structure but

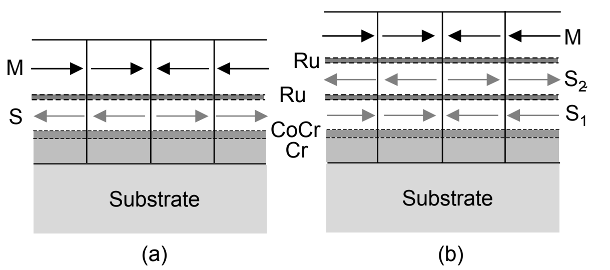

Figure 1
Schematics of the SFM structure with (a) one (S = L1) and (b) two (S_1 and S_2) stabilizing layers disposed between the main magnetic layer (M = L2) and the CoCr and Cr seed layers. Interlayer antiferromagnetic coupling is mediated by the thin Ru layers.

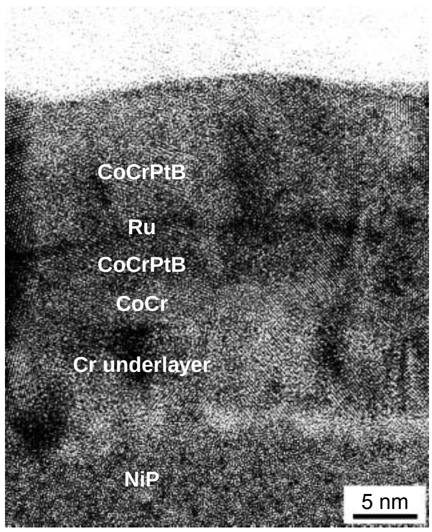

Figure 2
Cross-section TEM image of an SFM with two CoCrPtB layers separated by 0.8 nm of Ru (dark band).

with larger lattice parameters (a = 0.271 nm, c = 0.428 nm) compared to the Co-based layers ($a \approx 0.25$ nm, $c \approx 0.41$ nm). This lattice mismatch does not adversely affect the in-plane c-axis orientation of the succeeding magnetic layers, because they maintain the $(11\bar{2}0)$ texture. This is not surprising since the spacer thickness is less than 1 nm. The $M_r\delta$ value was as expected, indicating that the c-axes of layers L1 and L2 within a grain are parallel. Hysteresis loops evaluated perpendicular to the film revealed a perpendicular coercivity of ~ 0.1 × the circumferential H_C, which is typical of media with good in-plane alignment. Comparison of the grain sizes using plan-view TEM images showed that the average grain sizes are very similar, which demonstrates that the grain growth through the Ru layer is columnar. Clear lattice fringes were observed, especially for layer L2, which suggest epitaxial growth onto the first three hcp layers: the CoCr-alloy intermediate layer, L1, and the Ru spacer.

3. Magnetic properties

3.1 Magnetization

Figure 3 shows the magnetization major loop and a minor loop for a [12.5/Ru/5] medium on a glass substrate measured using an alternative gradient field magnetometer (AGFM) at room temperature. The c-axes are isotropic in the plane because the substrates were not textured. The magnetization configuration of the layers is also shown at saturation and at remanence (H = 0). At sufficiently high fields ($H \geq 6$ kOe) [Oe = (1000/4π)A/m], the magnetizations of the L1 and L2 layers are parallel. As the field is reduced from positive saturation, the magnetization of layer L1 is reversed. This occurs in the range of 1000 Oe, suggesting the presence of antiferromagnetic coupling between the layers. A minor loop taken from H = –1000 Oe to 2000 Oe reveals almost no hysteresis, indicating the negligible H_C (80 Oe) of layer L1.

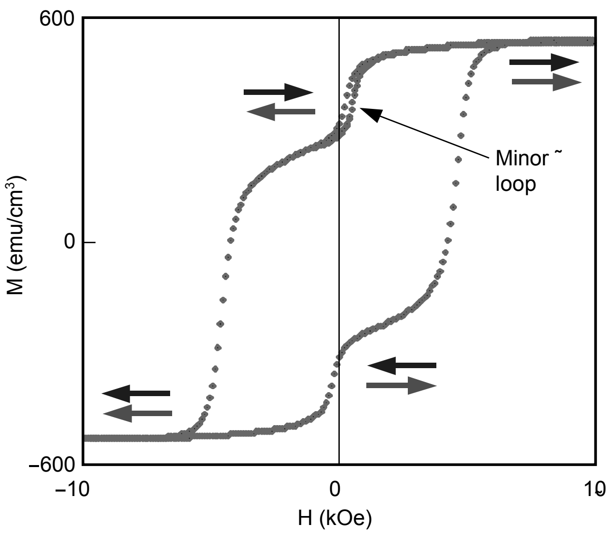

Figure 3
Magnetization and minor loop for a [12.5/Ru/5] medium. The magnetization configuration for the two layers is also shown at saturation and remanence.

The average exchange field H_{ex} (on layer L1) corresponds to the field at the center of the minor loop. H_{ex} is approximately 190 Oe, which is low for this particular medium. The usual values are greater than 500 Oe,[8)-10)] which, with the insertion of a thin (~ 1 nm) Co-rich magnetic layer between Ru and L1, is easily enhanced to greater than 1000 Oe.[11)] The DC remanence curves are similar for SFM and conventional media.[6),7),9),12)] Therefore, the recording process is roughly as follows: the head field aligns the magnetization of the portion directly under the head gap of layers L1 and L2 in one direction and, as the write head is moved away, the magnetization of layer L1 is reversed due to H_{ex}. The writing of the next bit may actually assist in the quick reversal of L1 because the field has a component along the reversed direction of L1 magnetization. When reading, the head senses a remanent state similar to that of a single magnetic layer medium. Therefore, no special writing or signal processing are necessary beyond what are already being employed for conventional media. Regarding the read head, because low $M_r\delta$ values are preferred for high linear density recording and are feasible with SFM, sensitivity development is very important.

3.2 Coercivity

The coercivity H_C of SFM is usually several hundred Oersteds larger than that of a single layer medium of the same thickness as layer L2. This variation is mainly thermal in origin because the difference is greatest in the low $M_r\delta$ range. Coercivity tends to increase with t_{L1}, and dynamic H_C measurements showed that the difference is more pronounced at longer field time exposures.[10] For the same t_{L2}, torque magnetometer measurements of the magnetic anisotropy K_u revealed the same value regardless of t_{L1}. Since $H_{ex} \sim (M_{L1}t_{L1})^{-1}$, the switching field H_0 (~1/2 of magnetic anisotropy field H_K) of SFM does not significantly change. H_0 is expected to increase by a fraction of H_{ex}: $\Delta H_0 \approx t_{L1}/t_{L2} \times H_{ex}$. ΔH_0 is usually within 250 Oe (3.5% of H_0) and it is a small investment to make for the huge gain in thermal stability.

4. Thermal stability

4.1 Signal decay

Thermal stability measurements were made on a spinstand with a Guzik controller and an analog HP8655 spectrum analyzer in zero frequency span. The head is a commercial head used for a 7.3 GB/platter 10 krpm enterprise drive. The measured signal was the fundamental Fourier component. All measurements were made at room temperature. As a guide for estimating decay rates at 65°C, measurements of the remanence magnetization M_r decay in the presence of a reversing field were made using a superconducting quantum interference device (SQUID) magnetometer at room temperature and at 65°C. The reversing field used at 65°C was lower to account for the decrease in $M_r\delta$.[11] There was approximately a two-fold increase in M_r decay at elevated temperatures compared to that at room temperature.

Figure 4 shows the signal decay of 300 kFCI (k flux change per inch) bits in media with structure [12/Ru/4] and in a single layer medium (solid diamonds). For this particular single layer medium, a 0.7 nm-thick Ru layer was deposited between the magnetic layer and the CoCr layer. This was done to make it as similar as possible to the [12/Ru/4] medium (open squares), which has antiferromagnetically coupled L1 and L2 layers. The single magnetic layer medium has the same CoCrPtB composition as layers L1 and L2.

The antiferromagnetically coupled medium reveals the most stable behavior, while the medium with t_{Ru} = 1.4 nm (open circles) shows the same decay behavior as the single layer medium. For Co/Ru/Co systems, the exchange coupling oscillates in sign and the coupling energy decays rapidly with the spacer thickness.[5] Positive coupling is expected for t_{Ru} = 1.4 nm; however, its effect on the stability is insignificant, indicating that the coupling energy is negligible. At 4 nm, layer L1 has a very low H_C and by itself cannot sustain 300 kFCI bits. Its effect on the decay is not observed for the t_{Ru} = 1.4 nm case but is dramatic for the coupled case.

The laminated structure of SFM may lead to higher magnetic anisotropy values for layer L2. The coercivity of conventional media is known to be improved by insertion of an hcp CoCr alloy layer (1 to 3 nm) between the Cr-based underlayer, which has a bcc structure and a Co-based magnetic layer, which is hcp.[12] Energy dispersive x-ray

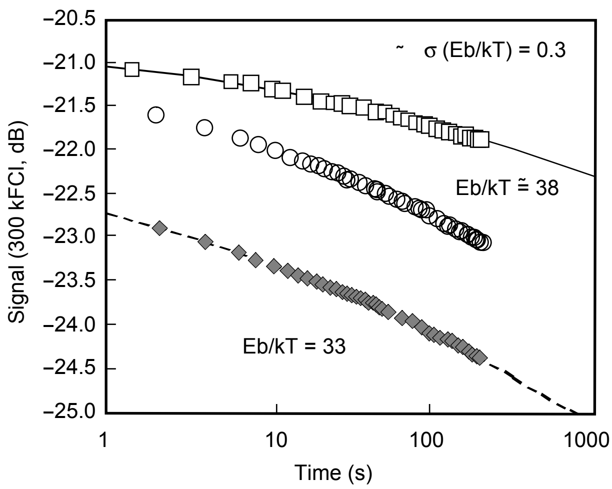

Figure 4
Signal decay at room temperature for 300 kFCI bits in various SFM: [12/Ru/4] (open squares), [12/Ru/4] (open circles), and 12 nm-thick single layer (solid diamonds). Lines are fitted to a model.

spectrometer (EDS) data shows that an interlayer minimizes Cr diffusion from the underlayer into the magnetic layer, which reduces the thickness of the initial non-magnetic layer.[13] The above results for t_{Ru} = 1.4 nm show that the effect of lamination on the thermal stability is not significant. Whatever can be gained in terms of magnetic anisotropy increase may have been already achieved by use of a 3 nm-thick CoCr intermediate layer. Any further increment in the CoCr layer thickness does not usually result in significant improvements in H_K.

The lines in Figure 4 are for a fit using a simple model for the decay.[14] A log-normal distribution in energy barriers E_b was assumed. With $\sigma/(E_b/kT) = 0.3$, the best fit to the signal decay was obtained with $E_b/kT = 38$ for the [12/Ru/4] medium and with $E_b/kT = 33$ for the single layer medium, where k is Boltzman constant and T is absolute temperature. Adding an L1 layer increases the magnetic grain volume by 33% but enhances the average E_b by only 15%, revealing a "stabilization efficiency" of approximately 45%. With a moderate increase in H_{ex} to ~ 1000 Oe, surprising efficiencies greater than 80% have been achieved[10] showing that the coupling need not be as large as those found in Co/Ru/Co systems, which would result in significant increases in H_0.

4.2 Stabilization layer contribution

The stabilizing layer thickness has been observed to affect the thermal stability. **Figure 5 (a)** shows the effect of increasing the effective volume. The figure shows the signal decay rate as dB/decade·time (0.1 dB ≈ 1.1%) for two-layer SFM with different t_{L1} vs. $M_r\delta$ values. The signal decay rate for single (solid triangles) and dual magnetic layer (open circles) conventional media are shown for comparison.[15),16] The rate of decay decreases for media with thicker stabilizing layers. **Figure 5 (b)** shows the rate of decay for a series of SFM with t_{L2} fixed at 12.7 nm and t_{L1} varied. As t_{L1} is increased, the stability improves, but $M_r\delta$ is reduced.

The K_u of the L1 layer has also been observed to affect the thermal stability. This favors low Cr and high Pt content magnetic alloys. Interestingly, the SNR of SFM is not as strongly dependent on the composition of layer L1 as it is on layer L2, which permits more freedom in the choice of layer L1 compositions. However, the magnetic anisotropy energy K_uV_g of layer L1 cannot be in-

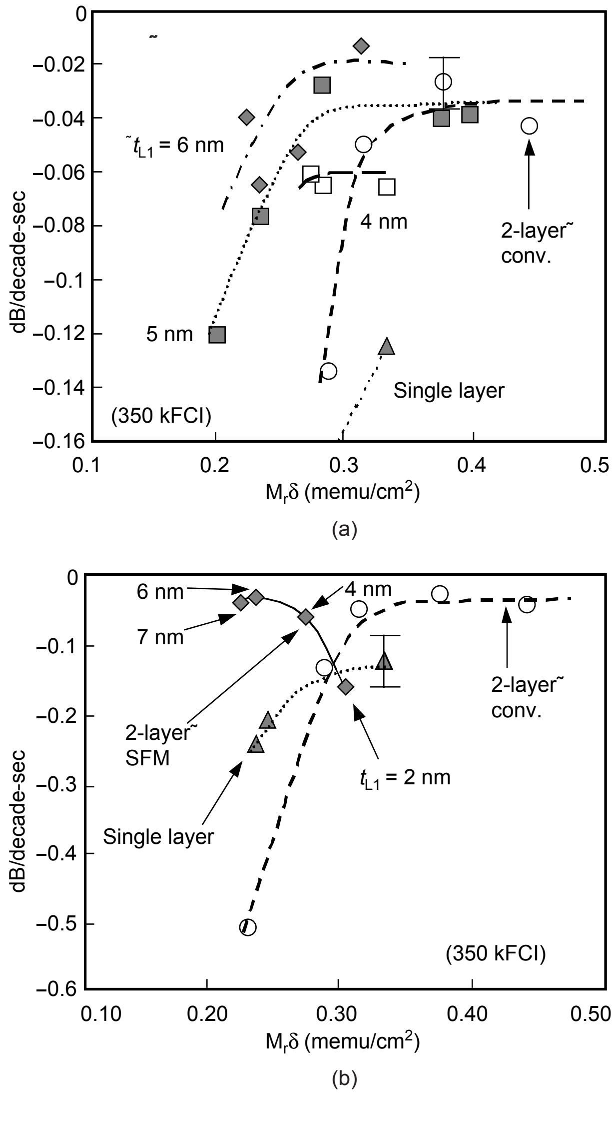

Figure 5
Signal decay rate for 350 kFCI tracks in various media. (a) Decay rates for two-layer SFM with t_{L1} = 4 nm (open squares), 5 nm (solid squares), and 6 nm (♦) compared with conventional media with one (solid triangles) and two (open circles) magnetic layers. (b) Decay rates for two-layer SFM (♦) with different t_{L1} (2, 4, 6, and 7 nm) but fixed t_{L2} = 12.7 nm. The two-layer and single layer media are the same as in (a). The measurement resolution is ±0.01 dB/dec. Lines are guides to the eye.

creased arbitrarily to obtain the desired thermal stability. The extent to which K_uV_g can be increased is limited by H_{ex}.

For the following discussion,[17] the media are made on glass substrates but the seed layers are made of NiP; the layer structure and compositions are very similar to media deposited on Al-Mg substrates. Two different compositions, A and B, are used for the L1 layer. The Pt concentration is increased from A to B at the expense of Co, while the other additives are kept the same. All of the SFM are made with an L1 layer from 0 to 10 nm thick and an L2 of constant thickness and composition. The saturation magnetization $M_{S\text{-}L1}$ and magnetic anisotropy $K_{u\text{-}L1}$ were evaluated for 10 nm-thick single layers. These values are expected to degrade by ~25 % when the thickness is decreased to 5 nm. For an increase in Pt concentration, $M_{S\text{-}L1}$ decreases from 380 (L1 = A) to 350 emu/cm^3 (L1 = B), but $K_{U\text{-}L1}$ increases from 2.5 to 3×10^6 erg/cm^3 (erg = 10^{-7}J) when the composition is changed from A to B.

Figure 6 shows the coercivity of SFM with t_{L1} for [L2/Ru/(A)] (open squares) and [L2/Ru/(B)] (solid circles). H_C increases as a function of t_{L1} up to a thickness t_{max} that varies slightly with the L1 composition. [L2/Ru/C] has the largest H_C among the media for $t_{L1} < t_{max}$. This is consistent with layer B having the largest stability factor K_uV/kT. At and above t_{max}, the magnetization of some grains in L1 and L2 are parallel, because $H_{C\text{-}L1} \geq H_{ex}$. H_{ex} destabilizes such a parallel state and hence the decrease in H_C. **Figure 7** shows the dependence of K_uV/kT for the same films with t_{L1} below the corresponding t_{max} values. The stability factor clearly increases as a function of t_{L1} and magnetic anisotropy. As mentioned earlier, the switching field H_0 is not expected to significantly increase. Estimates from dynamic coercivity measurements show an increase of 200 to 250 Oe. This increase comes from the exchange field and not the anisotropy of L1. The ~3.5% increase in H_0 is small compared with the 30% increase in K_uV/kT as shown in Figure 7. Indeed, for a constant $M_r\delta$, the increase in the stability factor can be larger than 70%.

When an L1 was employed with $K_u < 0.5 \times 10^6$ erg/cm^3, the increase in stability factor with t_{L1} was significantly smaller. This result is similar to the results of Lohau *et al.*,[18] who reported that the thermal stability arises primarily from the magnetic anisotropy energy of the top layer L2. Therefore, significant improvements in thermal stability, limited only by the requirement that $H_{ex} > H_{C\text{-}L1}$, can be made by properly choosing the L1 layer. These stability factor results have also

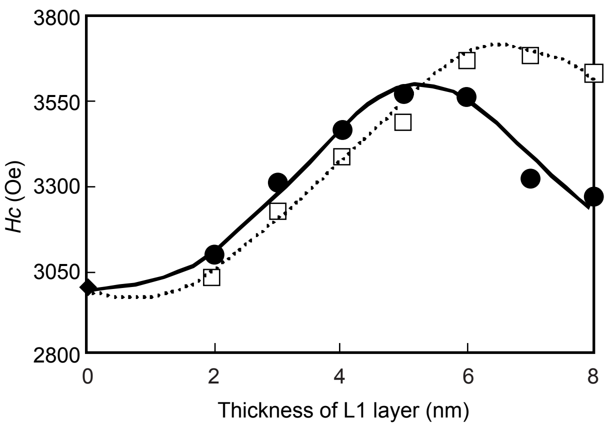

Figure 6
Dependence of coercivity on L1 layer thickness for SFM structures [L2/Ru/A] (open squares) and [L2/Ru/B] (solid circles).

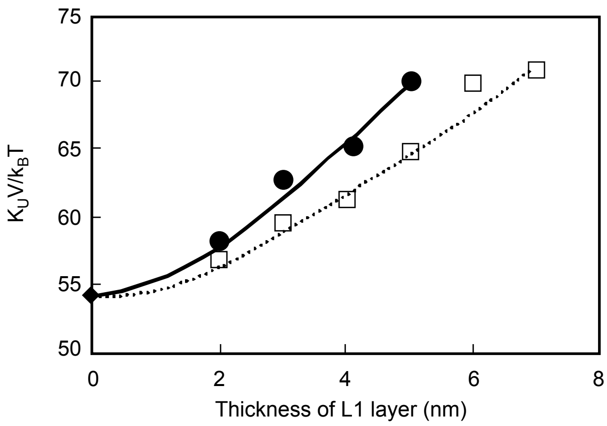

Figure 7
Plot of stabilization factor K_UV/k_BT vs. thickness of L1 layer for SFM structures [L2/Ru/A] (open squares) and [L2/Ru/B] (solid circles).

been confirmed by direct signal decay measurements of 270 kFCI patterns.[17)]

5. Read-write properties

5.1 PW_{50}

The R/W performance of SFM is similar to that of conventional media having a similar $M_r\delta$ value. Analysis of the full-width-at-half-maximum of an isolated pulse (PW_{50}) and its amplitude showed an effective $M_r\delta$ that is approximately the difference in the $M_r\delta$ values of the layers.[8),9)] Multilayered SFM exhibit small PW_{50} values which depend more on the effective thickness than the total magnetic layer thickness. No significant resolution decrease was observed compared to single layer media with similar $M_r\delta$ values.

5.2 Medium signal-to-noise ratio

Figure 8 shows the SNR performance of dual-magnetic layer conventional media[16)] and that of two magnetic layer SFM on NiP/Al-Mg. The underlayer structures are similar, and t_{L1} = 5 nm. The integrated medium noise N_m and signal S were measured at 350 kFCI and are plotted relative to a medium designed for a 20 GB/platter drive. For $M_r\delta$ > 0.3 memu/cm^2, the S_{iso}/N_m is slightly better for the conventional medium (open triangles) but the high-density S/N_m is better for the SFM (solid squares), especially at the lower $M_r\delta$ values. This difference is due to the lower effective thickness of SFM compared to conventional media. The data in Figure 8 is typical of CoCrPtB alloys; many different composition combinations of layers L1 and L2 exhibit a similar trend.

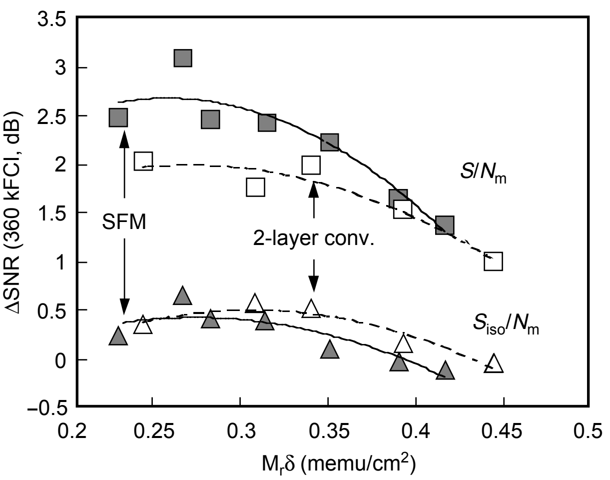

Figure 8
Medium SNR of two-layer SFM (solid symbols) compared with two magnetic layer conventional media (open symbols). The values given are relative to a medium on NiP/Al-Mg used for a 20 GB/platter drive.

5.3 Overwrite

Because the total thickness of SFM is greater than that of an equivalent conventional medium, overwrite (O/W) degradation sometimes occurs. This is especially the case for SFM with large effective $M_r\delta$ values (> 0.4 memu/cm^2) and those with more than one stabilization layer. Aside from the limitations imposed by H_{ex}, O/W considerations also limit the thickness of the stabilization layers. As discussed in the section on coercivity, the anisotropy fields of the stabilization layers are much weaker than those of layer L2 itself and H_K for SFM is independent of t_{L1}. The SFM O/W degradation may arise mainly from the increased magnetic spacing. For the range of $M_r\delta$ values designed for over 20 Gbit/in^2, there is no systematic difference in O/W performance between SFM and conventional media. This has also been confirmed recently by Bertero.[12)] Note that the comparisons made here are between a stable SFM and a less stable conventional media. To achieve thermal stability characteristics similar to those of the SFM, the coercivity of conventional media must be increased, and since H_K is usually increased in the process, the O/W performance is expected to worsen. High data rate testing has also been done for the SFM ($M_r\delta$ = 0.39 memu/cm^2) used in a demonstration of 56.1 Gbit/in^2 recording.[6)] The disk was spun at 10 000 rpm, and tracks were written at a radius of 34.4 mm. At 550 Mb/s and a linear density of 412 kFCI, an adequate on-track bit error rate has been achieved, indicating that there are no O/W problems for this three-layer SFM.[18)]

Many other advantages were observed in the SFM, especially those arising from the increased coercivity (or reduced $M_r\delta/H_C$) with no significant increases in H_K. For some values of t_{L1}, O/W is improved and nonlinear transition shift is reduced.[19] Side erasure of neighboring tracks due to head side fringing fields is also reduced.[20]

6. Over 100 Gbit/in² demonstration and SFM areal density advantage

The large improvements in thermal stability arising from the use of stabilization layers extend the areal density capability of conventional longitudinal recording media. A demonstration of 106 Gbit/in² recording has been made with a thermally stable two-layer SFM with $H_0 < 8000$ Oe, which is well within the capabilities of present write head technology.[21] The demonstration was made at a data rate of 16.1 Mbyte/s with a track density of 141.9 kTPI and a linear density of 750 kBPI (796 kFCI), which correspond to a track pitch of 0.179 µm and a bit length of ~32 nm. The medium had a coercivity of 3970 Oe and an Mrt value of 46.5 G µm (0.37 memu/cm²) (G = 10^{-4}T). The write head track width was 0.162 µm, and the double specular spin-valve read width was 0.124 µm. The spin-valve sensitivity was greater than 8 mVpp/µm for a sense current of 1.8 mA. The flying height was 12 nm.

Simple SFM areal density advantage estimations can be made by assuming a minimum thickness t_C (and grain area) for conventional media at which thermal stability can be maintained. For the same $M_r\delta$, an SFM can be made with $t_{L2} - t_{L1} \approx t_C$. For an L1 layer with $t_{L1} = 5$ nm and the same K_u as that of layer L2, the anisotropy energy is ~ (t_C + 5 nm + 2.5 nm)/t_C that of the conventional medium. The sum of the first two terms is t_{L2} and the last term (2. 5 nm) assumes a 50% stabilization efficiency from L1. Therefore, the SFM grain area can be reduced by the same factor while still retaining the same thermal stability performance as the conventional medium. This capability to further reduce the area gives SFM an areal density advantage. For $t_C = 10$ nm, the advantage is ~ 1.75 times.

The thermal stability and read-write performance of SFM have been established and have been introduced in the HN-15L 2.5-inch mobile drive, which began shipping this Fall.

7. Conclusion

Synthetic ferrimagnetic media show improved thermal stability compared to conventional media. The enhancement of thermal stability is due to an increase in the media's effective grain magnetic anisotropy energy arising from the antiferromagnetic exchange coupling between the magnetic layers. The read-write properties were not significantly affected by the addition of layers but were improved at low $M_r\delta$ values compared to conventional media.

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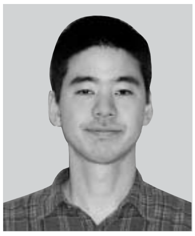

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