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Advanced Spin-Valve GMR Head

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Information and communication systems increasingly handle huge amounts of data, placing heavy demands on hard disk storage capacity and performance. Progress in the development of giant magnetoresistive (GMR) spin-valve materials and high-sensitivity spin-valve read heads has allowed a continuous increase of areal recording density in hard disk drives. This paper describes our advanced spin-valve head technology. This technology features a bottom type synthetic ferrimagnet spin-valve with low magnetostriction. It comprises a magnetic layer, Ru interlayer, and magnetic layer sandwich as a pinned layer. It also has a specular spin-valve with specular reflection layers consisting of a layer of natural oxide or another oxide material. The synthetic ferrimagnet spin-valve and the specular spin-valve enable increased read-back output of the spin-valve head. This paper also describes our demonstration of over 100 Gbit/in^2 technologies at areal recording densities achieved by a high-sensitivity, double-specular spin-valve head on synthetic ferrimagnet media.

1. Introduction

Information and communication systems increasingly handle huge amounts of data, placing heavy demands on hard disk storage capacity and performance. **Figure 1** shows the development of areal recording densities for Fujitsu's mobile disk drive products with magnetoresistive (MR) heads and giant magnetoresistive (GMR) spin-valve heads. High compound annual growth rates of 80% or more have been achieved in areal recording density. Areal recording density will approach 40 Gbit/in^2 this year. Figure 1 also shows demonstrations made over several years at international magnetic conferences, including Intermag, MMM, and TMRC. These demonstrations came before the shipment of commercial models and showed the higher areal recording densities achieved using state-of-the-art spin-valve heads. In 1996, we were the first in the world to demonstrate an areal recording density of 5 Gbit/in^2 using the spin-valve head.1) We demonstrated 8 Gbit/in^2 using a thermally stable spin-valve head in 1997, 20.4 Gbit/in^2 using a synthetic ferrimagnet spin-valve head in 1998, 56.1 Gbit/in^2

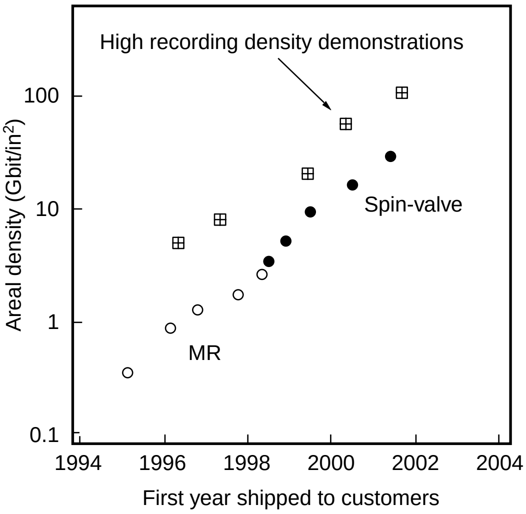

Figure 1
Increase in areal densities for Fujitsu's mobile disk drive products with MR heads and spin-valve heads and high recording density demonstrations using spin-valve heads.

using a specular spin-valve head in 2000, and 106.4 Gbit/in^2 using a double specular spin-valve head in August 2001. These densities were achieved by combining our advanced head technology with low-noise disk media.$^{2)-6)}$ We have clarified that progress in developing spin-valve materials and high-sensitivity spin-valve read heads could enable us to achieve a continued increase in areal recording density in hard disk drives.

In this paper, we review the evolution of spin-valve films and spin-valve heads and discuss other issues such as synthetic ferrimagnet structure and specular GMR properties. We also review our demonstration of over 100 Gbit/in^2 densities achieved by a double specular spin-valve head.

It has been thought that 100 Gbit/in^2 is the maximum possible magnetic recording density in hard disk drives because of the existence of random telegraph noise (RTN) due to the thermally activated domain instability in spin-valve heads with ultra-thin free layers.$^{7)}$ However, we have demonstrated over 100 Gbit/in^2 densities using high-sensitivity, double-specular spin-valve technology without ultra-thin free layers.

2. Spin-valve head structure and GMR spin-valve effect

Figure 2 shows the concept of a typical merged type inductive write/spin-valve read head. The spin-valve film consists of four laminated metal layers: an anti-ferromagnet pinning layer, a pinned layer whose magnetization is fixed by an exchange-coupling field from the anti-ferromagnet layer, a Cu interlayer, and a free layer whose magnetization rotates according to the signal field from the disk media. The electrical resistance of the spin-valve film is low when magnetizations from the pinned layer and free layer are parallel and high when they are antiparallel. The spin-valve film is patterned to form a rectangular element with a sub-micron height and track-width. Domain control hard magnet layers, such as CoCrPt films, are attached to the end of the spin-valve element as magnetic and electrical contacts. This is done to stabilize the domain structure in the free layer and completely suppress the Barkhausen noise produced by the biasing field from the hard magnet layers. Sense current flows into the spin-valve element through the leads, and the change in resistance is transferred

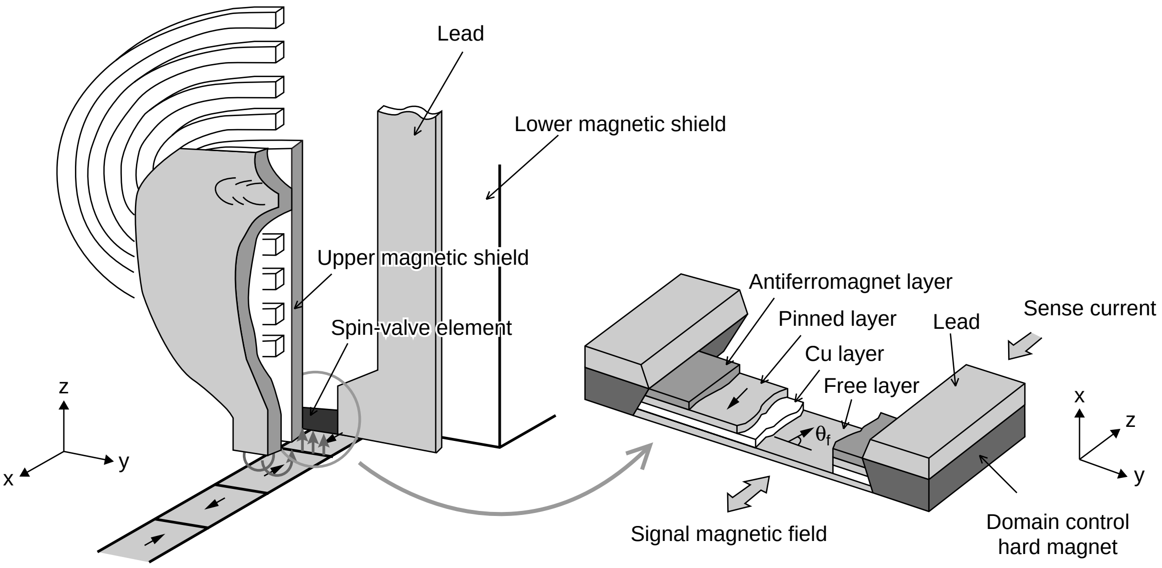

Figure 2
Typical merged type inductive write/spin-valve read head.

to the readback voltage. To achieve high-resolution reading, the spin-valve element, the hard magnet layers, and the leads were placed through insulator gaps between two magnetic shields. The length of the spin-valve element (distance between both leads) defines the physical read track-width.

3. Spin-valve technology

3.1 Evolution of the spin-valve

Figure 3 summarizes the evolution of the spin-valve structure we developed. The spin-valve films are classified as follows:

1) Top type spin-valve
2) Bottom type synthetic ferrimagnet spin-valve
3) Bottom type single specular spin-valve
4) Bottom type double specular spin-valve

The top type spin-valve film (Figure 3 (a)) has a simple structure consisting of four layers: a free layer, Cu interlayer, pinned layer, and anti-ferromagnet layer. The bottom type double specular spin-valve film (d), however, has over 10 thinner layers. Thickness must be controlled to within ±0.1 nm in each layer.

Achieving a high recording density requires a narrow head track-width while maintaining the readback voltage output. This means the spin-valve head must be highly sensitive. The synthetic ferrimagnet spin-valve and specular spin-valve technologies enable us to achieve the needed high sensitivity and high MR change. The following sections explain these technologies in detail.

3.2 Film preparation and experiment

We deposited spin-valve films on glass and silicon substrates using an ultra high vacuum (UHV) sputtering system operating below a base pressure of 2×10^{-7} Pa. During deposition, we applied a magnetic field of 100 Oe [Oe = (1000/4π) A/m] to induce anisotropy. We used a PdPtMn anti-ferromagnet for the pinning layer and NiFe and CoFe or CoFeB magnetic films for the pinned and free layers. The spin-valve films were annealed to crystallize the PdPtMn anti-ferromagnet and to fix the direction of unidirectional anisotropy in the pinned/anti-ferromagnet bilayer. MR response curves in the spin-valve films were measured along their easy-axis using an in-line four-point probe with applied magnetic fields of ±100 Oe or ±2 kOe. The magnetic properties in the spin-valve films were investigated using a vibrating sample magnetometer (VSM) system.

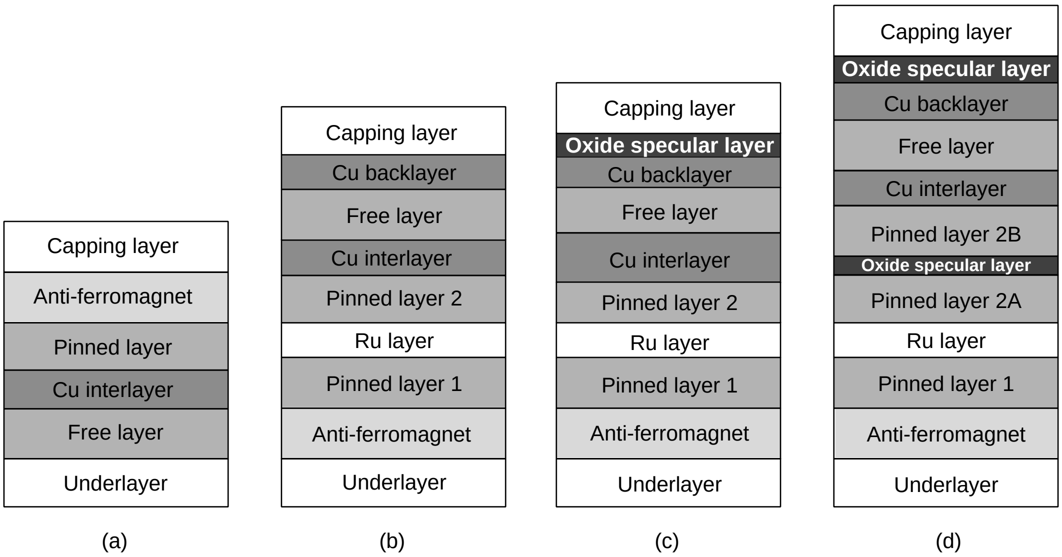

Figure 3
Evolution of spin-valve films. (a) Top type spin-valve, (b) bottom type synthetic ferrimagnet spin-valve, (c) bottom type single specular spin-valve, and (d) bottom type double specular spin-valve.

3.3 Bottom type synthetic ferrimagnet spin-valve

Synthetic ferrimagnet spin-valve film comprises a magnetic layer, Ru interlayer, and magnetic layer sandwich as a pinned layer (Figure 3). When the Ru thickness is optimized, strong anti-ferromagnetic coupling is produced between the magnetic layers and their magnetizations are antiparallel.8) We used CoFe/Ru/CoFe or CoFeB/Ru/CoFeB sandwiches, although a Co/Ru/Co sandwich has been widely used as a synthetic ferrimagnet material.9) The reason we used CoFe/Ru/CoFe or CoFeB/Ru/CoFeB sandwiches was that the CoFe and CoFeB films show the possibility of inducing better uniaxial anisotropy than a Co film. The dependence of magnetic properties on the Ru thickness was investigated in a CoFeB (2.5 nm)/Ru/CoFeB (2.5 nm) ferrimagnet. The maximum anti-ferromagnetic coupling field between the CoFeB layers was around 7 kOe when an 0.8 nm - thick Ru interlayer was used.10) This exchange-coupling field was almost the same as that in a Co (2.5 nm)/Ru/Co (2.5 nm) sandwich with an identical magnetic layer thickness. Clearly, the CoFeB/Ru/CoFeB ferrimagnet showed a strong exchange coupling, as did the Co/Ru/Co ferrimagnet. An exchange-coupling field in a CoFeB (3 nm)/Ru (0.8 nm)/CoFeB (3 nm) ferrimagnet sandwich was also investigated as a function of the temperature at which the exchange-coupling field was measured. The exchange-coupling field gradually decreases as the temperature increases, but no abrupt reduction was observed up to 330˚C. Exchange coupling between both CoFeB layers was thermally very stable.

Figure 4 shows a comparison of MR response curves in a synthetic ferrimagnet spin-valve and a conventional spin-valve film with a single pinned layer. The effective pinning field Hua* of the synthetic ferrimagnet spin-valve film and the pinning field Hua of the conventional spin-valve film is defined as the center point of half-maximum amplitude in the forward and reverse loops at the higher side of the applied field. The MR response curve of the synthetic ferrimagnet spin-valve film has a smaller coercivity Hc in the pinned layer; however, the Hc of the conventional spin-valve film is larger. The exchange-pinning field between the pinned CoFeB layer and PdPtMn anti-ferromagnet layer displays hysteresis. Therefore, the synthetic ferrimagnet spin-valve film has a large pinning field from the anti-ferromagnet layer because the net moment of the pinned trilayer is very small. Consequently, the demagnetization field from the pinned trilayer can be reduced. The synthetic ferrimagnet spin-valve heads have advantages over conventional spin-valve heads with single pinned layers. These advantages include higher output and a smaller readback amplitude asymmetry, even with a thin free layer, and the possibility of reducing the thickness of the anti-ferromagnet layer.10),11)

Magnetostriction of the free layer in the spin-valve film is an important factor that determines the read performance of a spin-valve head. The large magnetostriction of the free layer produces an unstable read response because it induces undesirable anisotropy in the free layer.12)

Figure 5 shows a comparison of saturation

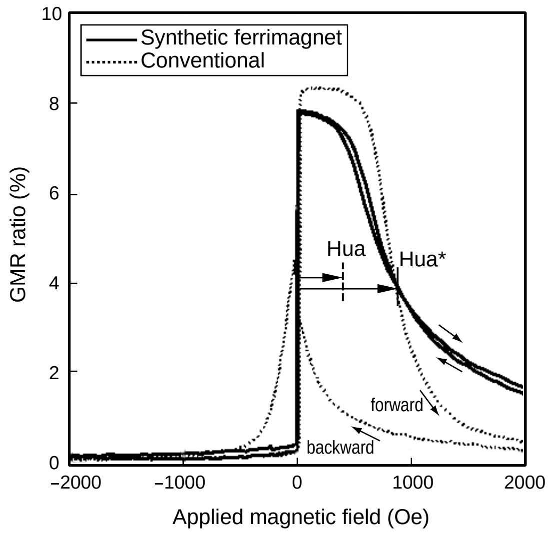

Figure 4
MR response curves of synthetic ferrimagnet spin-valve and conventional spin-valve films.

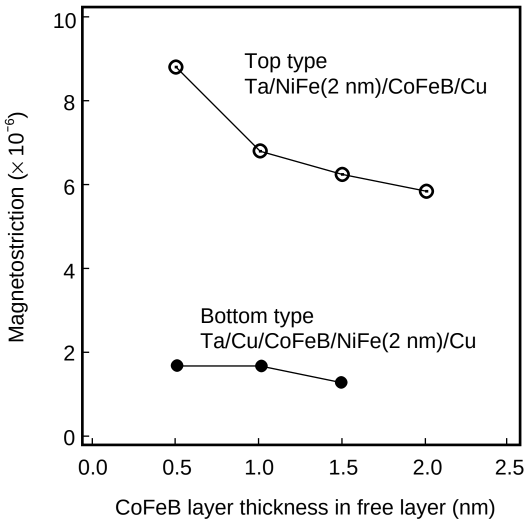

Figure 5
Magnetostriction as a function of CoFeB layer thickness in free layer for top type and bottom type spin-valve films.

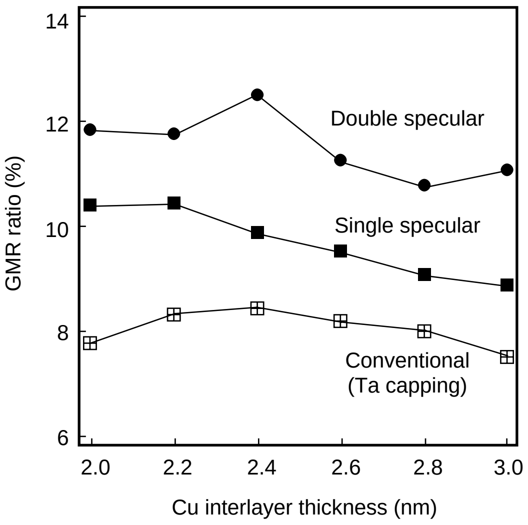

Figure 6
Enhancement in GMR ratio when oxide specular layers are incorporated into spin-valve film.

magnetostriction as a function of CoFeB layer thickness in the free layer for the top type and bottom type spin-valve films. To achieve a high readback sensitivity in the spin-valve head, the free layer thickness must be reduced. Magnetostriction, however, increases as the free layer thickness is reduced in the top type spin-valve film. This causes unstable responses in the spin-valve head. The increase in magnetostriction is probably due to increased surface magnetic anisotropy.[13] On the other hand, magnetostriction of the free layer in the bottom type spin-valve was not significantly changed when the thickness of the CoFeB free layer was reduced and is smaller than in the top type spin-valve. Using X-ray Photoelectron Spectroscopy (XPS), we confirmed that intermixing between the Cu interlayer and CoFeB free layer in the bottom type spin-valve is much larger than in the top type spin-valve. We also found a negative aspect: saturation magnetostriction of the CoFeB increases when we add Cu to CoFeB.[14] Therefore, the small magnetostriction in the bottom type spin-valve might result from the contribution of negative magnetostriction in the Cu-CoFeB intermixing layer.

3.4 Specular spin-valve

Shunt loss of sense current has been decreased by making the free layer, Cu layer, and pinned layer thinner in the spin-valve film in order to increase the readback output of the spin-valve head. Electron scattering loss, however, is increased at the capping layer, underlayer, and anti-ferromagnet layer. This occurs because the thicknesses of the free, Cu, and pinned layers are reduced in conventional spin-valve films, which causes a small increase in GMR change. In specular spin-valve film, a specular reflection layer of Ag, Au, or oxide layers placed between the free layer and the capping layer or inserted into the pinned layers, can suppress this scattering loss and increase the GMR change.[15] This effect occurs because, as in a super-lattice GMR multilayer, electrons are reflected several times at the interfaces between the free layer, Cu interlayer, and pinned layer.

We prepared single specular spin-valve films and double specular spin-valve films consisting of a layer of natural oxide or another oxide material. **Figure 6** shows the GMR ratio as a function of Cu interlayer thickness for the single and dou-

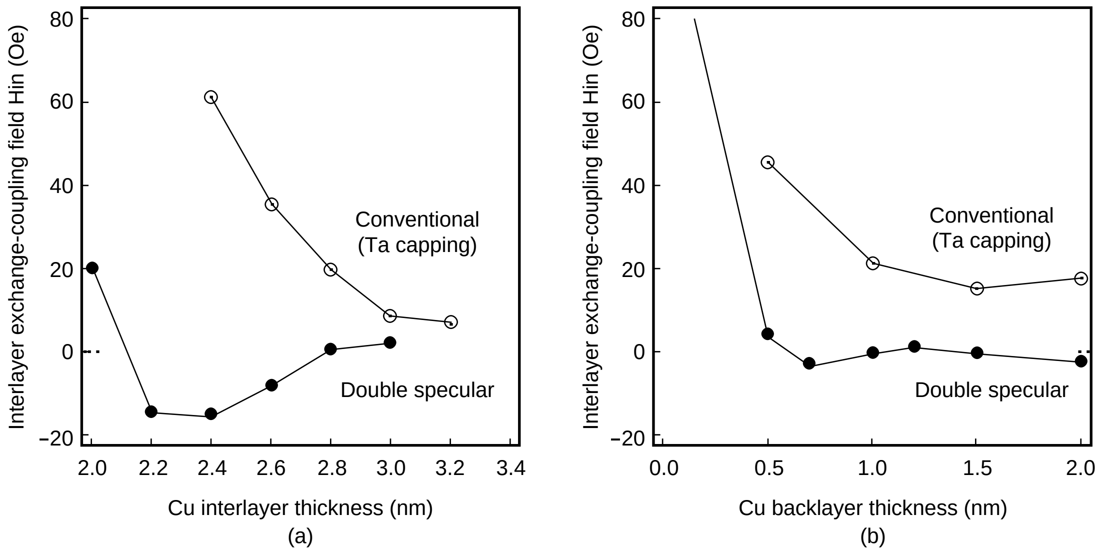

Figure 7
Oscillation of interlayer exchange-coupling field as a function of Cu interlayer thickness (a) and Cu backlayer thickness (b) in double specular spin-valve film and conventional synthetic ferrimagnet spin-valve film.

ble specular spin-valve films and for a conventional bottom type synthetic spin-valve film with a Cu backlayer between the free layer and the capping layer. At a Cu interlayer thickness of 2 nm, for example, the GMR ratios of the single and double specular spin-valve films are higher by about 30% and 50%, respectively. This increase is bigger than that of the conventional spin-valve film with a Cu backlayer and capping layer. Clearly, the specular spin-valve film has a greatly improved GMR performance, thanks to enhanced specular reflection at the oxide interface. In addition, the reflection effect in the double specular spin-valve film is higher than in the single specular spin-valve film.

Figure 7 shows interlayer exchange-coupling field Hin as a function of the Cu interlayer thickness (Figure 7 (a)) and the Cu backlayer thickness (Figure 7 (b)) in the double specular spin-valve film and conventional synthetic ferrimagnet spin-valve film. The Hin monotonically increases as the Cu interlayer thickness is reduced in the conventional spin-valve film. However, as the Cu interlayer thickness is changed, the Hin oscillates in a way similar to the RKKY-like oscillation observed in the super-lattice GMR multilayer (Figure 7 (a)). We think this occurs because of the flatness effect at the oxidized pinned layer interface[14] and reduced electron scattering at the capping layer and anti-ferromagnet layer. Further, note that the Hin oscillates as the Cu backlayer thickness is changed as well as when the Cu interlayer is changed (Figure 7 (b)). We believe this indicates that specular reflection at the capping oxide layer is also effective.

The specular spin-valve was expected to show a dramatic increase in GMR when the specularity of electrons at the interfaces is increased, because it simulates a multilayered super-lattice with infinite boundaries. However, the GMR values seem to reach their maximum at around 13% in the spin-valve. Therefore, the specularity at the oxide specular layers is much smaller. This means that there is a significant chance to enhance the specularity by engineering the specularly reflective layers of the spin-valve. In fact, we have recently succeeded in developing a double specular spin-valve with a GMR ratio of 20% by modifying the capping layer.[16] The GMR is the largest value ever reported for a spin-valve with a single Cu spacer, irrespective of the kind of anti-ferromagnet. This spin-valve also showed a practical exchange-coupling field of over 1000 Oe and soft magnetic properties, which are essential for obtaining a high spin-valve head output.

4. Double specular spin-valve heads for 106.4 Gbit/in^2 densities

We fabricated spin-valve heads with a double specular spin-valve film having the following structure: underlayer/PdPtMn/CoFe/Ru/CoFe/specular-layer/Cu/CoFe/NiFe/Cu/specular-layer. We used electroplated NiFe for the bottom and top shields. The read-gap length was 0.07 µm. The GMR ratio of the spin-valve film was 12.4%, and the exchange-biasing field of the pinned layers was greater than 1000 Oe. The magnetic pole material of the write head is a high Bs NiFe-alloy.

We tested the read performance of the spin-valve heads on a low-noise CoCrPt-based quaternary alloy media with an Mrt of 0.36 memu/cm^2. The readback waveform was taken at a sense current of 2 mA. The waveform was stable and quiet, and no Barkhausen noise was observed **(Figure 8)**. The readback output increased approximately linearly up to a sense current of ±2 mA and started to saturate at a sense current of about ±3 mA. The output showed good asymmetry in the sense current range of ±3 mA, irrespective of the polarity. The asymmetry was near zero at a sense current of +2 mA and stayed within ±5% in the sense-current range from –3 mA to +3 mA. We tested the read track-width on a microtrack narrower than 0.02 µm. The effective read track-width was estimated to be less than 0.14 µm, which was determined from the half-width of the microtrack profile. **Figure 9** shows that the normalized readback peak-to-peak output was 8.6 mVpp/µm with an asymmetry of 0.5% at a ±2 mA sense current. The sensor height of the head was estimated to be around 0.1 µm by transmission electron microscopy (TEM). We also tested the error rate performance using an advanced EPR4ML channel on a low noise CoCrPt-based quaternary alloy synthetic ferrimagnet media$^{4)}$ with an Mrt of 0.37 memu/cm^2 and an Hc of 3972 Oe. The effective read track-width of the spin-valve head was just 0.124 µm. The effective write track-width of the inductive write head was 0.162 µm, as determined by an off-track profile. The readback output of the head was 9.3 mVpp/µm. A bit error rate of less than 1×10^{-5} was obtained without error correction at a

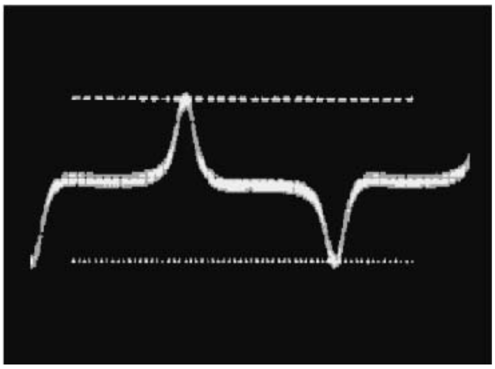

Figure 8
Readback waveform of double specular spin-valve head.

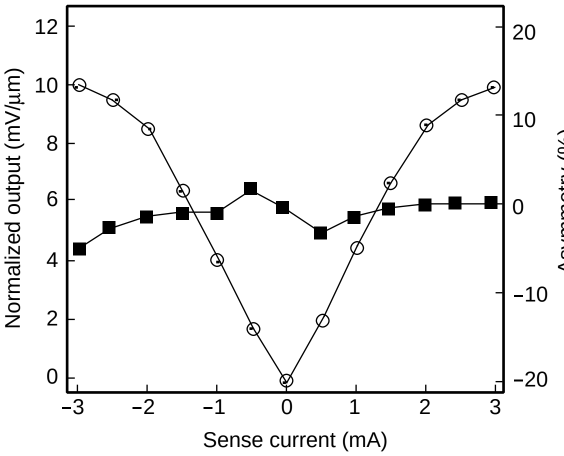

Figure 9
Normalized readback output and asymmetry as a function of sense current. The open circles correspond to the output, and the closed squares correspond to the asymmetry.

linear density of 750 kBPI and a magnetic spacing of 12 nm. **Figure 10** shows a 747 curve of the spin-valve head, with the off-track performance as a function of the squeeze track-pitch. The off-track performance at a track-pitch of 0.179 µm is still the same as that in the isolated track limit. This means that our spin-valve head is usable at 0.179 µm, which corresponds to 141.9 kTPI. We can, therefore, achieve an areal recording density of 106.4 Gbit/in^2 (with 750 kBPI × 141.9 kTPI) using double specular spin-valve heads.

5. Conclusion

This paper introduced the advanced spin-valve technology that we developed. It showed that the bottom type synthetic ferrimagnet spin-valve includes such advantages as a large pinning field from the PdPtMn anti-ferromagnet layer and low magnetostriction of the free layer, which produce a higher and more stable output with smaller readback amplitude asymmetry. The paper also indicated that the specular spin-valve enables an enhanced GMR ratio thanks to enhanced specular reflection at the oxide interface and an interesting oscillation of the interlayer-coupling field. As in a super-lattice GMR multilayer, this oscillation is a function of the thicknesses of the Cu interlayer and the Cu backlayer. We have fabricated highly sensitive, narrow-track spin-valve heads with double specular spin-valves and tested their read performance and bit error rate performance on low-noise CoCrPt-based quaternary alloy synthetic ferrimagnet media. Test results show that we achieved an areal recording density of 106.4 Gbit/in^2 using a double specular spin-valve head, low-noise synthetic ferrimagnet media, and advanced integration techniques. We strongly believe that the spin-valve with specularly reflective layers is an excellent candidate as an advanced read head for magnetic recording beyond 100 Gbit/in^2. We will continue to increase areal recording density by engineering the specularly reflective layers of the spin-valve heads in hard disk drives.

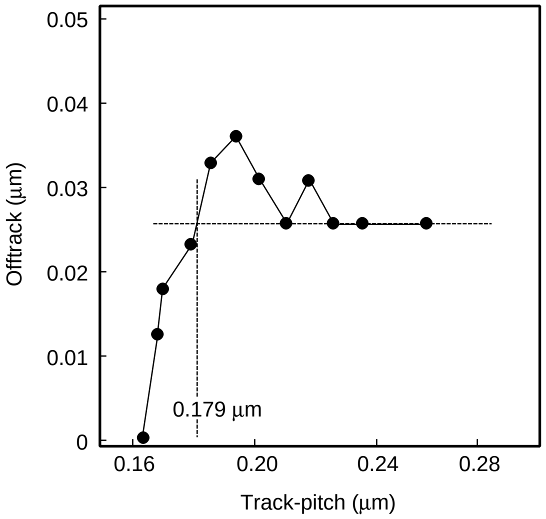

Figure 10
Error rate squeeze curve of double specular spin-valve head in the demonstration of 106.4 Gbit/in^2 areal recording density.

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