CPP-GMR Technology for Future High-Density Magnetic Recording

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To realize a Current-Perpendicular-to-Plane Giant Magnetoresistance (CPP-GMR) magnetic read head, we have enhanced the CPP magnetoresistance of fully metallic spin-valves by developing two groups of new magnetic materials for each magnetic layer. The first group are spin-blocking materials that control the spin-dependent transport through the synthetic ferrimagnet pinned layer using impurities. Pinned layers of these new materials do not have the low magnetoresistance disadvantage of the synthetic pinned layer in CPP spin-valves. The other group are high-resistivity magnetoresistive materials that contain a relatively high resistivity metal and have spin-dependent scatterings. These materials expand the possibility of improving the output of the CPP-GMR, which has a small resistance, and enable recording densities in excess of 300 Gbit/in^2. Because a high output, high signal-to-noise ratio, and low resistance are required in read sensors for high-density recording and fast data-transfer, CPP-GMR technology will be indispensable for the future system of high-density magnetic recording.

1. Introduction

The read head technology for magnetic recording is changing. Read heads that use tunneling magnetoresistance (TMR) sensors have been replacing read heads that use current-in-plane (CIP) spin-valves, which have been in wide use.

Although the TMR head has a high output signal, its high resistance is a critical obstacle to downsizing sensors for future high-density recording. **Figure 1** shows the trends of data transfer rate for high-end hard disk drive (HDD) systems and allowed resistance-area product (*RA*) of read head sensors with a current-perpendicular-to-plane (CPP) structure versus areal density. As can be seen, the *RA* of the CPP type sensor must be reduced in order to increase the data transfer rate for higher areal density recording. These trends indicate that the TMR head, whose minimum achievable *RA* value is thought to be about 1 Ωμm^2, will face the *RA* limit at about 300 Gbit/in^2.

On the other hand, in terms of sensor resistance, the CPP-GMR (giant magnetoresistance) sensor, which also has a CPP structure, can be applied to much higher areal densities because it uses a metallic spin-valve film and therefore has quite a low *RA* of around 0.1 Ωμm^2. The CPP-GMR film can be applied to a sensor that is several 10s of nanometers long. Moreover, the CPP structure has advantages such as a short read gap and good thermal contact with the electrodes. Therefore, the CPP-GMR is expected to replace the TMR head and enable densities exceeding 300 Gbit/in^2.[1)-4)]

However, the performance of CPP-GMR sensors that use spin-valves made of conventional materials is limited by their less than 1 mΩμm^2 (**Figure 2**) specific magnetoresistance change (Δ*RA*: resistance-change x area). This value is small because of the small change in film

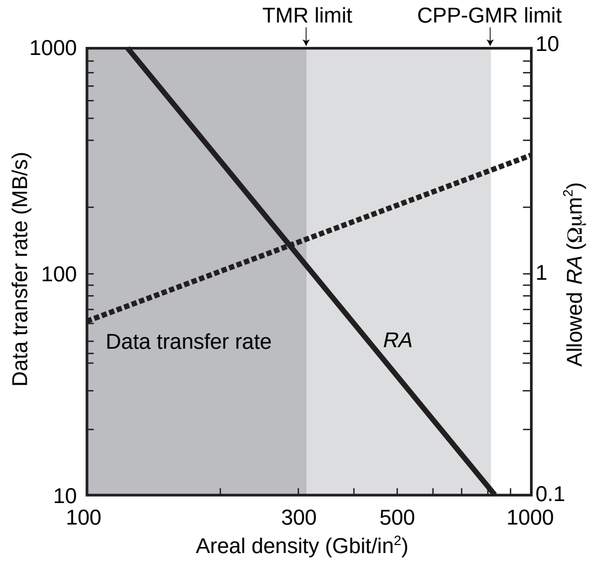

Figure 1
Trends of data transfer rate for high-end HDD systems and allowed resistance-area product (*RA*) of read head sensors with current-perpendicular-to-plane (CPP) structure versus areal density.

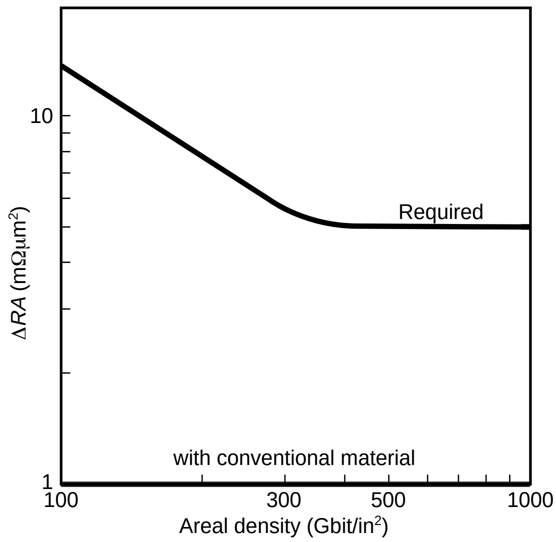

Figure 2
Estimated required ΔRA of CPP-GMR for higher recording densities for output signal voltage = 1.5 mV, head efficiency = 30%, sense current density = 100 MA/cm^2, and power consumption of sensor element = 0.6 mW.

resistance that occurs when the relative angle between magnetizations of two magnetic layer materials is changed. The moderate intrinsic magnetoresistance value and the minuscule CPP resistance of spin-valves result in a ΔRA that is too small to achieve a sufficiently high signal-to-noise ratio (SNR). Figure 2 shows the required ΔRA of the CPP-GMR for recording densities as estimated using the following conditions: output signal voltage for sufficient SNR = 1.5 mV, head efficiency = 30%, sense current density = 100 MA/cm^2, power consumption of sensor element = 0.6 mW.

One of the special features of the CPP-GMR is that the absolute ΔR value increases as the sensor is downsized. Because of this feature, the required ΔRA becomes smaller as the recording density approaches 300 Gbit/in^2, where the power consumption of the sensor is the dominant factor in limiting the sense current. On the other hand, the current density limit becomes dominant over 300 Gbit/in^2, which makes the required ΔRA constant, and we found from this estimation that a ΔRA of at least 5 m$\Omega\mu$m^2 is needed. A great deal of effort has therefore been made to improve the ΔRA value of CPP spin-valve sensors for practical applications.[5)-9)]

In this paper, we describe several methods for enhancing the CPP-GMR. One is to use a novel synthetic ferrimagnet pinned-layer structure in CPP spin-valves that effectively enhances the ΔRA while maintaining a high magnetic pinning field. The other method is to use newly developed high-resistivity ferromagnetic alloys for the free and reference layers. We then describe how we improved the performance of CPP spin-valves by applying these methods.

2. Enhancing *ΔRA* of CPP-GMR

By assuming the spin-diffusion is much longer than the layer thickness, *RA* and ΔRA of the CPP structure can be described by a simple two-current model[10),11)] derived from Boltzmann's equation. The ΔRA of the CPP configuration, which has a synthetic ferri-coupled magnetic pinned-layer structure for obtaining a strong pinning field (**Figure 3**), can be expressed as follows:

Equation 1

$$\Delta RA = \frac{4(\beta_F \rho_F^* t_F + \gamma R^*A)(\beta_R \rho_R^* t_R - \beta_P \rho_P^* t_P + \gamma R^*A)}{\rho_F^* t_F + \rho_R^* t_R + \rho_P^* t_P + 2R^*A + R_{Para}}$$

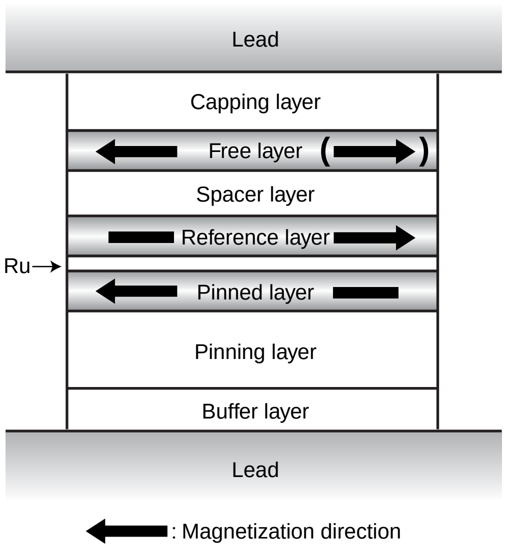

Figure 3
CPP-GMR structure used for calculating ΔRA. Spin valve film is a bottom type with a synthetic ferrimagnet pinned layer.

Here, β and γ are, respectively, the bulk and interface spin-asymmetry coefficients; t is the thickness of each magnetic layer; $\rho^* = \rho/(1-\beta^2)$; and ρ is the resistivity of the magnetic layer. The suffixes F, R, and P indicate, respectively, the free, reference, and pinned layers. $R^*A = RA/(1-\gamma^2)$, and RA is the resistance-area product at the interface between the magnetic and non-magnetic layers. R_{Para} is a parasitic resistance in the CPP structure and includes the resistances of the terminals, contacts, anti-ferromagnetic pinning layer, and other elements and also the crowding resistance. The effects of ruthenium (Ru) in the synthetic ferri-coupled magnetic pinned-layer structure were ignored for simplicity. Equation 1 shows there are several methods of enhancing the ΔRA, for example, we could use a material with a high $\beta\rho^*$ and γR^*A, thicken the free and reference layers (although this is not practicable because it reduces the free layer sensitivity and effective strength of the pinning field), or decrease the parasitic resistance. It is also quite effective to use a small or negative β material for the pinned layer. Although it is difficult to use all of these methods in combination because, for example, a high-resistivity material shows little or no spin-dependent scattering, this is the key approach for improving the CPP-GMR. In this paper, we introduce some of the advances we have made using new materials for the pinned, free, and reference layers.

3. Spin blocking material for synthetic ferrimagnet pinned layer

3.1 Synthetic ferrimagnet pinned-layer structure

The synthetic ferrimagnet (SyF) pinned-layer structure used in commercial CIP and TMR heads consists of the pinned, Ru, and reference layers (**Figure 4**). This structure is also used in the CPP-GMR because the anti-ferromagnetic exchange couplings of the magnetizations of these layers reduces the magnetostatic edge coupling between the free and reference layers and increases the effective strength of the pinning field.

In the case of CPP spin-valves, however, the antiparallel magnetization configuration of the pinned and reference layers leads to a reduction of the ΔRA. The perpendicular magnetoresistance originates from the spin-asymmetry of the electron scattering in the magnetic layers and interfaces,[10),11)] and the higher asymmetry leads to a higher ΔRA. In the SyF pinned-layer structure, the spin-asymmetry of the total perpendicular resistance is degraded because the spin-asymmetries of the bulk scattering in the pinned and reference layers are opposite to each other. The ΔRA can be enhanced by thickening the reference layer, but this is undesirable because it reduces the effective strength of the pinning field.

3.2 Spin blocking layers and calculated CPP-GMR

According to the theory discussed above, we can increase the effective spin-asymmetry of the total perpendicular resistance of the SyF Pinned-layer structure by decreasing the spin-

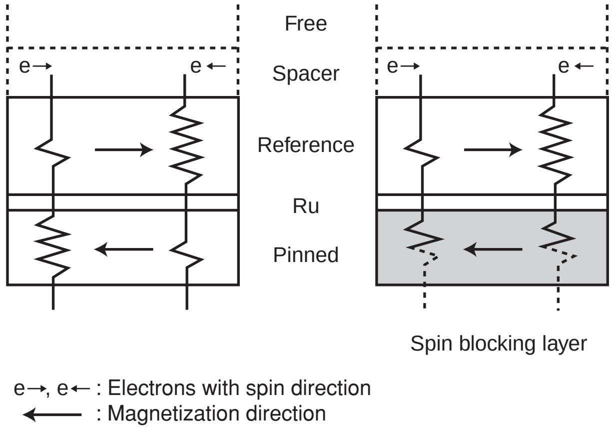

Figure 4
Synthetic ferrimagnet (SyF) pinned layers in CPP spin valves without and with a spin blocking layer.

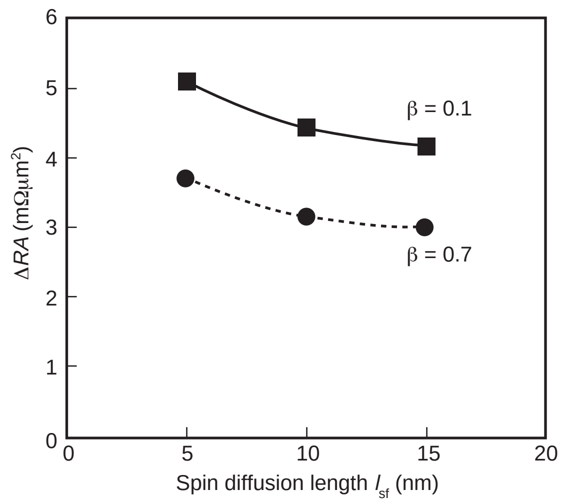

Figure 5
Calculated ΔRA of dual spin valves for various values of spin-asymmetry coefficient β and spin diffusion length l_{sf} of pinned layers.

asymmetry of the bulk scattering of the pinned layer and/or by reducing the spin-diffusion length in the layer. This is because such a pinned layer blocks the undesirable spin-dependence of the electronic transport outside the reference layer. Therefore, in this paper, we hereafter refer to this layer as the spin-blocking layer (Figure 4).

In order to quantitatively estimate the effect of the spin-blocking layer, we calculated it using the Valet-Fert theory,[10),11)] which describes the CPP-GMR of spin-valves. First, we derived the material parameters of our ordinary CPP spin-valves by fitting a Valet-Fert calculation to the experimental results. Then, we calculated the ΔRA of dual CPP spin-valves having spin-blocking layers with various values of bulk spin-asymmetry coefficient β and spin-diffusion length l_{sf}. **Figure 5** shows the results.

The ΔRA increases as β and l_{sf} decrease, and the increase reaches about 70% when β and l_{sf} are reduced, respectively, from 0.7 and 15 nm (typical values for Co-Fe alloys) to the much smaller values of 0.1 and 5 nm. As will be discussed later, we succeeded in decreasing β experimentally to nearly zero by introducing impurities. We therefore expected such an increase in the ΔRA in our experiment.

3.3 Experimental results of pinned layer material

To experimentally observe the effects of the spin-blocking layer, it is necessary to decrease the spin-asymmetry and/or spin-diffusion length while keeping the materials ferromagnetic. We found that introducing impurities such as Ru into ferromagnetic compounds could satisfy these requirements. When a ferromagnetic Co-Fe alloy with Ru impurities is used for the free and reference layers of CPP spin-valves, the magneto-resistance becomes almost zero irrespective of their thickness. This strongly suggests that β of ferromagnetic Co-Fe-Ru materials is close to zero. In addition, the increase in resistivity due to the impurities suggests there is a shortening of the spin-diffusion length.

We have fabricated dual CPP spin-valves using Co-Fe based SyF pinned-layer structures with and without Ru impurities in the pinned layers. These spin-valves were sputter-deposited in ultra-high-vacuum chambers. Several tens of CPP elements of various sizes were patterned on each wafer using photolithography and ion-milling.[1),6)] Between the anti-ferromagnet and Co-Fe-Ru layers, a thin Co-Fe layer was inserted to obtain a stronger pinning field. For comparison, we also fabricated dual CPP spin-valves with single (i.e., not SyF) pinned layers.

By using Co-Fe-Ru instead of Co-Fe for some of the pinned layers in the SyF pinned-layer structures, the ΔRA was increased from 3.4 to 4.2 m$\Omega\mu$m^2, which is a more than a 20% increase. Because there was no difference except for the impurities in the pinned layers, the effect of the spin-blocking layers was confirmed. A similar effect has been observed using Co-Fe-Ta alloys. The experimental results also suggest that spin-scattering (spin-flip) by the Ru layer, which we neglected in the previous discussion, is not as strong because it eliminates this effect.

The effective strength of the pinning field (i.e., unidirectional anisotropy field Hua) of an SyF pinned layer with a spin-blocking layer can be similar to that of a conventional SyF pinned layer and higher than that of a single pinned layer having the same thickness as the reference layers in the SyF pinned layer (with a spin-blocking layer). **Figure 6** shows the relative ΔRAs of spin-valves having different pinned-layer structures. Approximately half of the loss in ΔRA in the SyF pinned-layer structure is compensated for by the

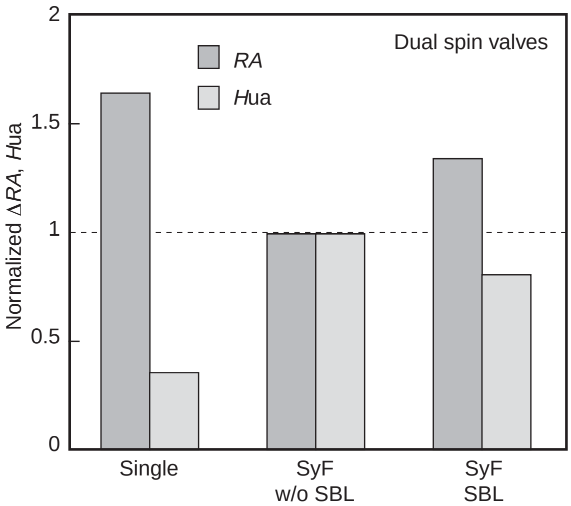

Figure 6
Effect of pinned-layer structure on ΔRA and unidirectional unisotropy field Hua. Pinned-layer structures are single ferromagnetic, SyF with conventional Co-Fe pinned layer (without spin blocking layer SBL), and SyF with SBL.

effect of the spin-blocking layers, while the effective strength of the pinning field stays about the same.

It should also be mentioned that, theoretically, pinned-layers with a negative β would work more effectively. In this case, the pinned layers would enhance the total spin-asymmetry of the SyF pinned-layer structure rather than block the spin-dependence of the transport in the pinned layers and should be called “spin-enhancing” layers. Some ferromagnetic materials are known to show inverse GMR and therefore a negative β at low temperatures.[12] We are currently searching for effectively negative β materials for the pinned layers.

4. High-resistivity magnetic materials for free and reference layers

4.1 Free and reference layer materials

In addition to the methods used for the pinned layer that were described in the previous section, the use of high $\beta\rho^*$ and γR^*A materials is effective for enhancing the ΔRA of the free and reference layers. We focused on developing a magnetic material that has a high $\beta\rho^*$; that is, a high resistivity and spin-dependent scattering. First, we fabricated CPP spin-valves using many different types of magnetic alloys that were based on conventional Co-Fe materials for the free and reference layers. Then, we estimated their $\beta\rho^*$ and γR^*A values by fitting the experimental results to a Valet-Fert calculation. Although most of these alloys did not satisfy the properties we were seeking, we finally found an excellent magnetic alloy. Details of this new alloy are given in the following paragraphs.

Table 1 shows the resistivity and spin-asymmetry coefficients of some of the magnetic alloys we used. Co-Fe is a conventional magnetic material and has an fcc crystalline structure. Co-Fe-Cu has almost the same resistivity as Co-Fe, but its spin-asymmetry coefficients are much higher — partly due to the bcc crystalline structure of

Table 1
Spin asymmetry coefficients and resistivity of magnetic alloys used in pinned and free layers.

	Material	β	ρ (μΩcm)	γ
1	Co-Fe	0.55	12	0.62
2	Co-Fe-Cu [7)]	0.77	12	0.72
3	Co-Fe-Al	0.50	130	0.35

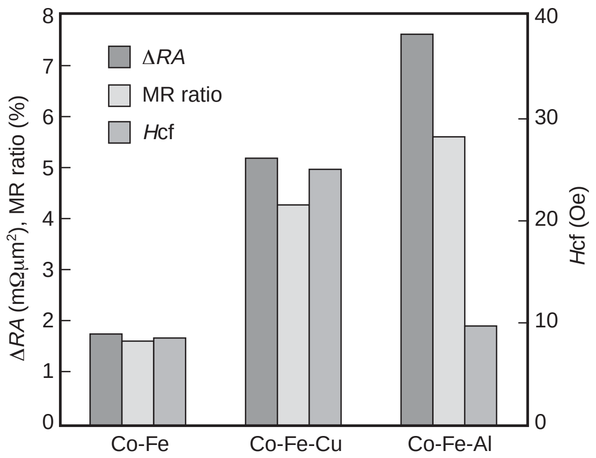

Figure 7
Effect of free and pinned layer magnetic materials on *ΔRA*, MR ratio, and *H*c of free layer *H*cf. Magnetic materials are those shown in Table 1.

Co-Fe-Cu. Cu's action as an impurity is also important for realizing the high spin-asymmetry coefficients.[7)]

However, the important point here is the film property of the third magnetic material, Co-Fe-Al. This material showed spin-asymmetry coefficients similar to those of the conventional Co-Fe, even though its resistivity is around 130 μΩcm, which is about 10 times higher than that of other materials. Magnetic materials that have a high resistivity such as the material used for the spin-blocking layer mentioned above usually show little or no spin-dependent scattering. However, selecting an appropriate material, for example, Al, for the magnetic layers enables us to obtain both a high resistivity and high spin-asymmetry coefficients, although an elucidation of the compromising mechanism is desired.

4.2 Improving *ΔRA* and other properties of CPP structure using high-resistivity materials

Following the above experiments, we examined the *ΔRA*s of each magnetic material we used in the pinned and free layers of the dual type CPP structures (**Figure 7**). The *ΔRA* was improved to 5.2 mΩμm^2 due to the high spin-asymmetry coefficients of the Co-Fe-Cu compared to the conventional Co-Fe, which has a *ΔRA* of 1.8 mΩμm^2. The CPP-GMR that used the Co-Fe-Al, however, showed the highest *ΔRA*, achieving a value of 7.7 mΩμm^2 in a fully metallic CPP-GMR element with a total thickness of 52 nm, which is 50% higher than the *ΔRA* of the Co-Fe-Cu high spin-dependent scattering material.

Although the spin-asymmetry coefficients of the Co-Fe-Al material are not so high, the combination of these coefficients with the high resistivity, which until recently has not been possible in ferromagnetic metals, strongly enhanced the *ΔRA*. Compared to the conventional Co-Fe material, the Co-Fe-Al material has more than four times the *ΔRA*.

The *RA* of the Co-Fe-Al material was only about 0.1 Ωμm^2, which is one tenth that of the TMR sensors. In CPP-GMR magnetic read sensors fabricated using current technology, the relatively high resistivity of these magnetic materials is not a significant factor in increasing the total *RA* because these sensors have parasitic resistances. The resistance of the TMR will restrict a downsizing of magnetic sensors in spite of improvements in the head integrated circuit. Therefore, the low resistance of the CPP sensors will be a great advantage in future high-density recording. Moreover, in contrast to the Co-Fe-Cu, when the high-resistivity Co-Fe-Al material was used as a free layer, it showed a coercivity of around 10 Oe, which is small enough for high-sensitivity magnetic sensors. Also, the pinning field *H*ua has the sufficiently high value of more than 2 kOe, which is the same as that of conventional magnetic materials.

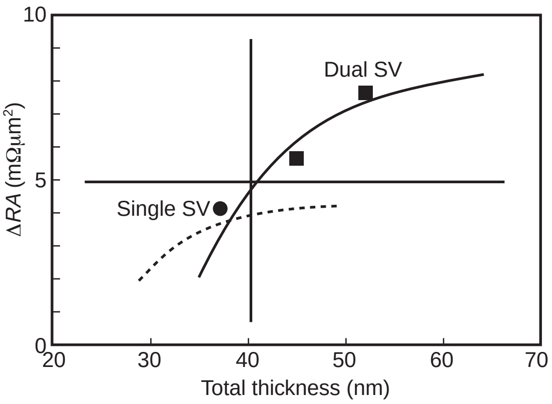

Figure 8
ΔRA vs. total thickness of CPP-GMRs with dual and single type spin-valves. Symbols indicate experimentally obtained results. Lines indicate results calculated using two-current series resistor model with experimentally obtained parameters.

Although, from the viewpoint of sensor output, the achieved *ΔRA* of 7.7 mΩμm^2 is applicable for densities exceeding 200 Gbit/in^2, the total thickness of 52 nm is slightly too thick for the read gap. However, due to the improvement of the *ΔRA*, the thickness of the magnetic layers can be reduced: for example, a *ΔRA* of 5.7 mΩμm^2 can be achieved with a total thickness of only 45 nm (**Figure 8**). This value is sufficient for recording densities in excess of 300 Gbit/in^2, for which the TMR head might not be applicable. Moreover, from these experimental results and from estimations made using a previous theory, we expect to achieve the minimum target *ΔRA* of 5 mΩμm^2 with a total thickness of only 40 nm. One of the choices for a magnetic head with an even narrower read gap is the single type spin-valve, which has a smaller total thickness than the dual type spin-valve and thin anti-ferromagnetic pinning and ferromagnet pinned layers that do not contribute to the change in resistance. In the future, further magnetic material improvements to make up for a lower *ΔRA* and the consideration of spin-transfer induced noise[13)] are required, especially for the single type spin-valve.

5. Conclusion

We have successfully enhanced the *ΔRA* of the CPP-GMR sensor, whose small resistance makes it attractive for future magnetic read heads, by introducing innovative materials such as spin-blocking materials and high-resistivity materials with high spin-asymmetry. The spin-blocking layer in the SyF pinned layer increases the *ΔRA* by decreasing the undesirable spin-asymmetry of the bulk scattering in the pinned layer without a significant reduction in the effective strength of the exchange pinning field. This novel effect was experimentally confirmed using Co-Fe-Ru, Co-Fe-Ta, and other materials in the spin-blocking layer. We also developed new magnetic materials for the free and pinned layers that enable both a high resistivity and high spin-asymmetry coefficients. The high *ΔRA* of 7.7 mΩμm^2 was achieved in a fully metallic CPP-GMR element with an *RA* of around 0.1 Ωμm^2 by using high-resistivity, high spin-asymmetry coefficient materials such as Co-Fe-Al. This high *ΔRA* enables the total film thickness to be reduced: for example, *ΔRA* = 5.7 mΩμm^2 at a total thickness of only 45 nm. These materials, therefore, can be used to achieve densities in excess of 300 Gbit/in^2. A combination of the proposed spin-blocking effect (including the spin-enhancing effect using the negative β materials we propose) with the newly developed high-resistivity ferromagnetic alloys in the free and reference layers will lead to further increases in the CPP-GMR effect. There are several remaining problems, for example, the total film thickness needs to be reduced for the narrower read gap of the future. However, we are certain that CPP-GMR technology will open the door to the future ultra-high-density magnetic recording world.

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