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Recent Developments in Magnetic Recording Heads

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ABSTRACT

Recently developed and future magnetic head technologies are reviewed. Scaling of dimensions brought about significant increases in recording densities in the last decade. On the recording head aspect, as the read head is narrowed, large improvements in sensitivity are required. Therefore, spin-valve read heads have been improved by introducing synthetic ferromagnetic pinned layers, a spin filter back layer and a specular scattering layer. The current perpendicular to plane (CPP) structure is now being adopted instead of the current in plane (CIP) structure which is the present magnetic head structure. Under heads with a CPP structure, tunneling magnetoresistance (TMR) devices and multilayer GMR are candidates. In CPP mode, we can make better use of "spintronics" or spin-dependent conduction phenomena because device character depends more directly on the spin-dependent electronic states of the materials. Future technologies of read head are also discussed.

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 mobile disk drive products with magnetoresistive (MR) heads and giant magnetoresistive (GMR) spin-valve heads. High annual growth rates of 80% or more have been achieved in areal recording density during this period. Areal recording density is approaching 70 Gbit/in2 this year. Figure 1 also shows demonstrations made over several years at international magnetic conferences, including Intermag, MMM, and TMRC. These densities were achieved by combining advanced head technology with low-noise disk media [1-5]. The 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 recent developed GMR read head technologies are reviewed and promising future technologies of current-perpendicular-to-plane (CPP) are also mentioned.

GMR READ HEAD

Figure 2 summarizes the evolution of the spin-valve structure we have developed. The spin-valve films are classified as follows:

a) Bottom type spin-valve
b) Bottom type synthetic ferrimagnetic spin-valve with back layer
c) Bottom type double specular spin-valve

The bottom type spin-valve film (Figure 2 (a)) has a simple structure consisting of four layers: a free layer, a Cu spacer layer, a pinned layer, and an antiferromagnet pinning layer. The resistance versus field R-H curve of the bottom type spin-valve in the early development stage is shown in Fig. 3(a). The film structure is Sub./Ta(5 nm)/NiFe(5)/ PdPtMn(25)/CoFe(3.5)/Cu(3.5)/ CoFe(5.5)/ NiFe(2.5). The MR ratio is ~ 6.0% [4]. For the bottom type synthetic ferromagnetic spin-valve, two magnetic layers antiferromagnetically couple to each other

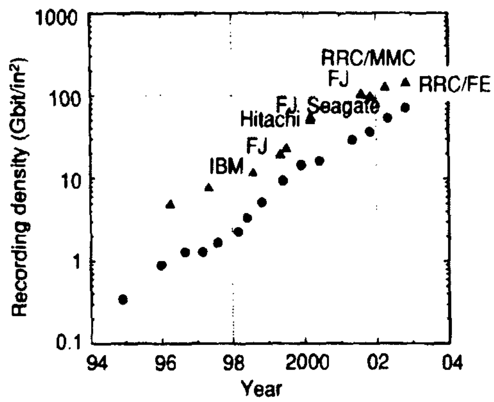

Figure 1. Trend of the recording density of hard disk drive (HDD). Circles indicate the evolution of mobile HDD products. Triangles indicate recording densities of demonstration reported at the major conferences.

through a very thin Ruthenium layer. This is an artificial antiferromagnetic state; this structure is called synthetic antiferromagnet (SAF) [6]. In this structure, the static magnetic field experienced by the free layer arising from the pinned layer is reduced and useful in keeping the proper magnetic bias point, especially when the sensor stripe height is reduced down to half a micron. Moreover, the magnetic moments stabilize each other, such that the effective exchange bias field from the antiferromagnet is enhanced and the pinning layer can be made thinner than in a conventional spin-valve.

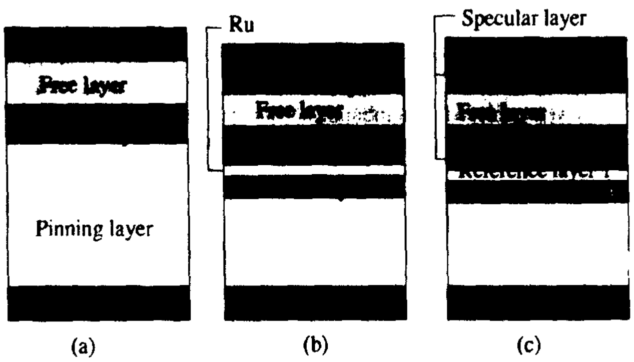

Fig. 2 Evolution of spin valve films. (a)bottom type spin valve, (b) synthetic ferrimagnetic spin valve with Cu back layer, (c) synthetic ferrimagnetic spin valve with double specular layers.

Fig. 2(c) shows a synthetic ferromagnetic double specular spin valve with an MR ratio of 15% MR as shown in Fig. 3(b). The film structure is Buffer (7 nm)/ PdPtMn(10)/CoFeB(1.6)/Ru(0.75)/CoFeB (1.25)/Oxide/CoFeB(1.5)/Cu(2.3)/CoFeB(2)/Fe2O3(2)/Al2O(32). The pinning layer is 10 nm thick and the magnetic state was stable with a very small hysteresis. This thin pinning layer was enabled by the synthetic ferrimagnetic structure and the film growth condition (background pressure < 2×10^{-7} Pa) [7]. The MR ratio of the double specular spin-valve is two times larger than that of a simple bottom type spin-valve. A larger signal output can therefore be expected.

CPP READ HEAD

Ultra-high density recording over 100 Gbit/in^2 requires a much higher sensitivity and a narrower read-core-width read head. To satisfy these requirements, the CPP heads have been extensively investigated and developed as CPP heads have several advantages compared to current in plane (CIP) heads, which are currently being used for recent hard disk drives (HDDs). Table I shows a comparison between CIP and CPP structure heads. If we assume the current density is limited at a constant value, the output voltage of the CIP heads is proportional to the core width and higher sensitivity sensor materials are required as the core width becomes narrower. On the other hand, expected output voltage is constant for a CPP head.

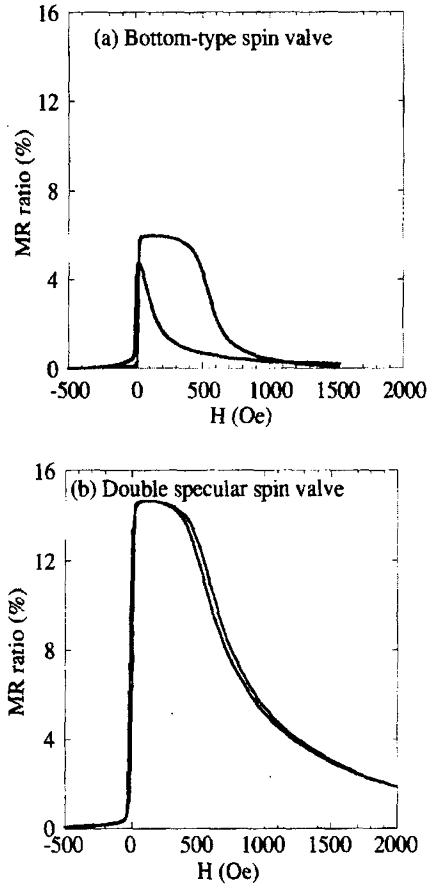

Fig. 3 R-H curves of the conventional bottom type spin valve (a), and double-specular spin valve (b).

If the power consumption of the sense current is limited to avoid a temperature rise, the output voltage of the CPP head is roughly inversely proportional to the square root of the sensor area. For the CPP head structure, only the sensor film is in the read gap and is suitable for higher linear density recording. Higher heat conduction, which is important for stable head operation, can be expected for the CPP structure than for the CIP structure. The CPP structure therefore shows several advantages as the sensor size is reduced. However, the device resistance increases as the sensor area decreases and this resistance increase is the main problem in ultra high density CPP head.

Figure 4 shows the target properties for a 0.01 μm^2 CPP element for 150 Gbit/in2 read head application [8]. The area is estimated by considering the power consumption, electron migration of the element, and data transfer rate. A tunneling magnetoresistance (TMR) head is one of the candidates for realizing high sensitivity. However, TMR heads have large resistances, which lead to ESD (electrostatic discharge) problems, limit the operating frequency, and make the Johnson and Shot noise high. It is very difficult to make low-resistance barrier-layers and significant progresses in fabrication technology are needed. Another candidate for ultra-high densities is a CPP head using GMR films.

Several researchers have studied GMR properties in the CPP mode, and they have demonstrated magnetoresistance changes at room temperature twice as large as those in the CIP mode in calculation [9] and experiment [10]. CPP heads using GMR multilayers have also been investigated [11]. Although multilayer CPP heads are expected to obtain large output signals, they show problems such as hysteresis generation and difficult magnetic domain control of the read element. This is aggravated by the requirement for thinner read gaps. In contrast, a CPP element using a spin-valve (SV) film can be rid of such problems of GMR multilayers. We have studied the GMR properties of SV film in CPP mode and tried to improve their magnetoresistance change.

The MR ratio of conventional spin valve films in CPP mode is about 0.5 % as shown in Fig. 4. The MR ratio must be increased to 8%, if the product of sensor resistance and its area, *RA*, is to be kept constant. But this is difficult to realize by increasing ΔRA only, the product of sensor resistance change and its area. However, at the largest allowed *RA*, an MR ratio of only 3% is needed. This is an easier path to reach the target area as *RA* is also increased. However, for the corresponding sensor size at a 150Gbit/in^2 design, calculations show that the amplitude of the output voltage is still insufficient as shown in Fig. 4. In this study, we tried to improve the magnetoresistive properties of CPP-SV heads for 150 Gbit/in^2 recording.

Table I. CIP vs. CPP heads

	CIP head	CPP head
Output signal current density limit power consumption limit	 Proportional to core width Constant	 Constant Inversely proportional to square root of sensor area
Read gap	Sensor and two gap layer thicknesses	Sensor thickness
Heat radiation	Mainly through terminals at both ends of the sensor	Direct heat connection to top and bottom terminals
Device resistance	Constant	Increase as sensor area decreases

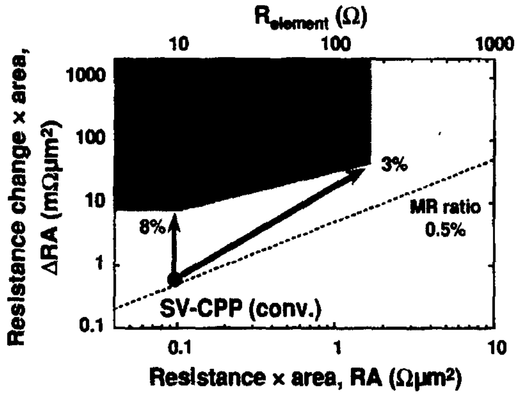

Fig. 4 Target region of 150Gbit/in^2 read head is shown as a function of RA and ΔRA. The required ΔRA is determined with the condition that the output signal >1 mV. The head efficiency is assumed to be 13.5%. Limitations due to data transfer, power consumption, and migration are also considered [8].

GMR PROPERTIES IN CPP MODE OF SPIN-VALVE FILMS

CPP properties were measured using a four-terminal technique. The spin-valves were sputter-deposited in an ultrahigh vacuum chamber and patterned by a photolithography and ion-milling processes. The element size was varied from 0.1 μm² to 1.0 μm². Details of the fabrication process are published elsewhere [12]. The film structure of the single spin-valve was buffer/ PdPtMn (13 nm) / CoFeB(1.5, 3)/Cu(4)/ CoFeB(1.5, 3)/ capping layer, and the dual spin valve films was buffer/PdPtMn(15)/ CoFeB(1.5, 3)/ Cu(4)/ CoFeB(3,6)/ Cu(4)/ CoFeB(1.5, 3)/ PdPtMn(15)/ capping layer. Both resistance (R) and resistance change (ΔR) are inversely proportional to the GMR size (A) of the CPP elements. As an example, for the single spin-valve with thinner magnetic layers, the RA was 81 $\text{m}\Omega\mu\text{m}^2$ and the ΔRA was 0.35 $\text{m}\Omega\mu\text{m}^2$; the MR ratio of the element was 0.43%. The RA and ΔRA are plotted

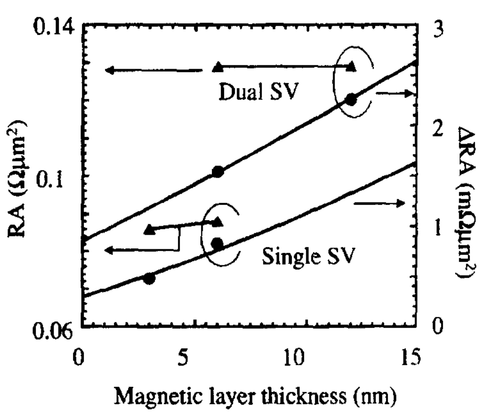

Fig. 5 The RA and ΔRA of single and dual spin valve films in CPP mode. The RA is almost constant for magnetic layer thickness. The behavior of the ΔRA was well described by the two-current series-resistor model [13].

for single and dual spin-valves in Fig. 5. The magnetic layer thickness is the total thickness of the free and reference layers. *ΔRA* increases as the magnetic layer thickness is increased. The dual spin valve shows a larger *ΔRA* than a single spin-valve due to the increase of magnetic/ nonmagnetic interfaces. These can be explained by increments in the spin-dependent bulk and interface scattering, respectively. Each layer thickness is smaller than the spin diffusion length and the behavior of *ΔRA* is well described by the two-current series-resistors model [13].

GMR-PROPERTIES IN CPP MODE OF SPIN-VALVE FILMS WITH OXIDE LAYER

Even for dual-type SV films, *ΔRA* remains in the order of several $m\Omega\mu m^2$. Therefore, it is difficult to obtain sufficient output voltage using conventional spin-valve read heads. We tried to enhance *ΔRA* by inserting nano-oxide layers (NOL). The nano-oxide layer has highly conductive and resistive regions due to inhomogeneous oxidation. The effective element area is smaller than the physical size and leads to a "confined current path". If the confined path is in the vicinity of the free/Cu spacer/reference layers, then we can expect larger *ΔRA* while the *RA* does not increase so much.

The stacking structure of the film was Buffer/ PdPtMn/ CoFeB/ Ru/ CoFeB/ Cu/ CoFeB/ Cu/ CoFeB(t nm)-NOL/ capping layer. The CoFeB under the capping layer was oxidized just after the deposition by oxygen gas at a controlled pressure. Fig. 6 shows *RA*, *ΔRA*, and MR ratio as a function of the thickness of the oxidized CoFeB. *RA* as well as *ΔRA* increase when $t < 0.9$ nm and the MR ratio is kept less than 1%. *ΔRA* increases more rapidly when the CoFeB is thicker than 1 nm and the MR ratio is enhanced to 1.5%. This MR ratio increment is thought to be due to the confined current path structure of CoFeB on the Cu back layer. The enhancement of MR is much clearer if the nano-oxide layer of the CoFeB is located between the reference and free layers [14]. In this structure, a ratio of more than 5% was observed in the range of $0.6\ \Omega\mu m^2 < RA < 1.5\ \Omega\mu m^2$. This GMR property is inside the target region for 150 Gbit/in^2 recording.

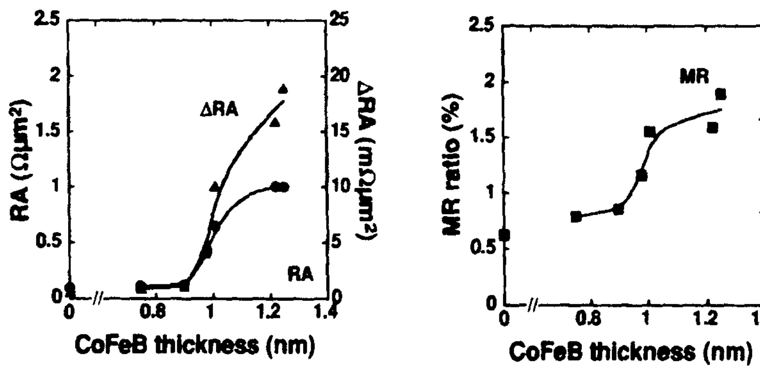

Fig 6. The GMR properties in the spin valve film with nano-oxide layer in CPP mode. MR enhancement was observed $t>1$ nm, where t is the thickness of the oxidized CoFeB under the capping layer.

PROSPECTS OF SPINTRONICS HEAD

Spin-valve heads are already a kind of "spintronic" devices because they utilize spin-dependent electron conduction. However, CPP structure devices such as TMR and CPP-GMR are closer to being "full-pledged" spintronic device. In CPP mode, the conduction electrons pass through all the multilayers, and conduction and valence band levels show abrupt changes according to the band structure of each material. Therefore, we can make better use of the spin-dependent conduction in CPP structure devices than CIP ones.

Here, one of our recent breakthroughs which may be applicable for head devices are mentioned [15]. Though highly spin-polarized materials such as half metals enable significant enhancements of the magnetoresistance ratio [16], it is difficult to fabricate practical GMR devices using such novel materials.

We have tried to enhance the magnetoresistance by inserting a nonmagnetic thin Cu layer into the free layer, which is hereafter called a laminated free structure [15]. When a Cu layer is inserted in the free layer, the number of magnetic/nonmagnetic interfaces increases from three to five (see Fig. 7). The modification makes the difference between spin up and down resistance increase due to the additional interfaces, i.e., the inserted interfaces act as spin filters in the layer. The effect can be interpreted phenomenologically in the framework of the two-current series-resistor model [17, 15]. Figure 8 shows the enhancement of ΔRA due to the laminated free structure. It elucidates the role of the interfaces in the spin valves in the CPP mode, and the physics of CPP GMR.

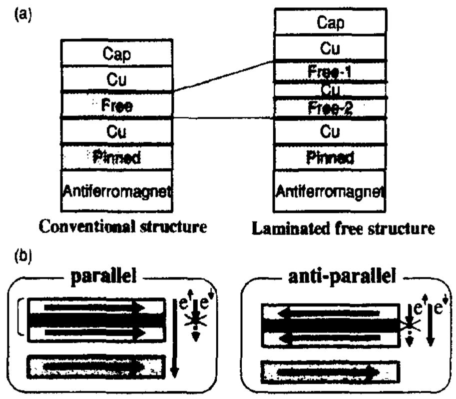

Fig. 7 (a) Schematic structure of the conventional (left) and laminated free-layer (right) spin-valves. Thick lines indicate magnetic/non,magnetic interfaces. (b) Configuration of the magnetic moment of the laminated free layer. The Cu spacer between the free layers is less than 1 nm and the laminated free layer rotates in phase. The figure schematically shows the filtering effect of the laminated free layer.

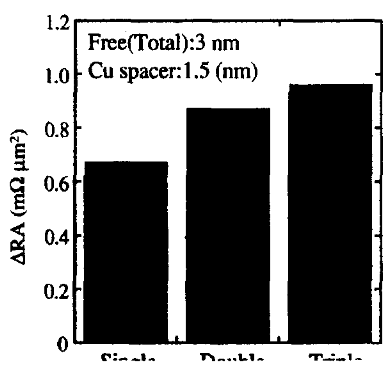

Fig. 8 The ΔRA of laminated free spin-valves. Double refers to two free layers with one Cu spacer; ΔRA increases by 30% compared to a conventional spin-valve. Triple refers to three free layers and two Cu spacer layers.

CONCLUSIONS

Spin valve read heads have been improved year by year, taking advantage of advancements in our knowledge of physics, as in the introduction of the synthetic ferrimagnetic structure and use of specular electron scattering at the interface of metal/oxide layers. The MR ratio of spin-valves has been improved beyond 15% and is now approaching 20%. However, with present materials and known techniques, the MR ratio can hardly be increased. Continuous growth of the recording density requires a new type of device instead of the current-in-plane (CIP) head. The current-perpendicular-to-the-plane (CPP) structure heads are more suitable for high density recording than CIP heads and both CPP-GMR and TMR are promising candidates for future read head over 150 Gbit/in^2. Single spin-valve heads with a nano-oxide layer exhibited an MR ratio of 5% and its GMR properties are sufficient for 150 Gbit/in^2 recording. We may simply be entering the vast world of "spintronics" through TMR and CPP-GMR. The layered structure and artificial junction technology consisting of magnetic and nonmagnetic metals, semiconductors, and insulator will provide us very high sensitive devices which may just work for future terabit recording.

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