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Enhanced Current-perpendicular-to–plane Giant Magnetoresistance in Single Spin-valve with Synthetic Antiferromagnet Free layers

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Micron to submicron sized current-perpendicular-to-plane geometrical giant magnetoresistance single spin-valves (CPP-GMR SPV) with synthetic antiferromagnet (SyAF) as a free layer were fabricated. We demonstrate that a SyAF free layer dramatically enhances CPP-GMR ratio of the single SPV structure from 0.83% to 3.56% even at room temperature. Calculation by Valet-Fert model shows that the enhancement of CPP-GMR by SyAF originates from the high spin-dependent interface resistance induced by larger spin anisotropy between $Co_{90}Fe_{10}$ and Ru layers. A study of the magnetic switching behavior by both experiment and single-domain thermal activation modeling shows that the CPP-GMR SPV with SyAF structure approaches single-domain magnet even with the low aspect ratio of 1, provided that its size diminishes to ~0.18μm^2. The single-domain structure brings a size-independent magnetic switching field when the aspect ratio is 1. Large GMR ratio at room temperature, single-domain structure and size-independent magnetic switching field demonstrate the great potential of CPP-GMR SPV with SyAF free layers to be used in future ultrahigh density magnetic storage devices.

Key words: CPP GMR, Single Spin-valve, SyAF, Single-domain

1. INTRODUCTION

It was predicted that 100 Gbits/in^2 is the maximum possible magnetic recording density in hard disk drives because of too large random telegraph noise in current-in-plane (CIP) giant magnetoresistance spin-valve (GMR SPV) read head with ultra-thin free layer [1]. Ultra-high recording density over 100Gbits/in^2 needs a higher sensitive read head material. It has already been proved that current-perpendicular-to-plane (CPP) geometrical GMR (i.e. CPP-GMR) is the best candidate for next generation magnetic head [2]. First, the intrinsic magnetoresistance (MR) ratio of CPP-GMR is higher than that of CIP-GMR; second, downsizing of element size causes the resistance change or output voltage to increase with increasing recording density. Even though CPP-GMR has many advantages, too low resistance-area product (RA) and MR of conventional CPP-GMR multilayer restrict its usage as ultra-high density head. Another difficulty in realizing CPP magnetic read head is the controlling of the domain structure when element size shrinks below submicron dimensions. Complex domain configurations depending on aspect ratio tend to be formed, when element size decreases into submicron or nanometer scale because of large demagnetizing field arising from the poles at the edge of element. Higher aspect ratio brings a large switching field, while lower aspect ratio induces multi-domain structures, which hamper the development of ultra-high density magnetic recording. We have already theoretically and experimentally found that synthetic antiferromagnet (SyAF) facilitates to form a single-domain structure [3] even with low aspect ratio ~1 and also the coercivity force of SyAF is independent of the interlayer coupling in large scaled element [4]. In this paper, we apply SyAF in CPP-GMR SPV structure as free layers, and demonstrate that SyAF dramatically enhances CPP-GMR. Also CPP-GMR SPV with SyAF free layers exhibits single-domain magnetic switching behavior, when its size shrinks below 0.18 μm^2 and size-independent magnetic switching field with the low aspect ratio of 1.

2. EXPERIMENT

The structure of our samples is Cu(20nm)/IrMn(10nm)/$Co_{90}Fe_{10}$(3nm)/Cu(d nm)/free layer/Cu(5nm)/Ta(2nm). Two kinds of free layers are studied. One is single $Co_{90}Fe_{10}$ layer and another is SyAF layers $Co_{90}Fe_{10}$(5 nm)/Ru(0.45 nm)/$Co_{90}Fe_{10}$ (3 nm), which exhibits AF coupling as reported before [4]. Here we label the samples with single $Co_{90}Fe_{10}$ free layer "conventional CPP-GMR" and those with SyAF "CPP-GMR with SyAF". The interlayer thickness d ranges from 2.5 nm to 6 nm. Our fabrication process is "subtractive". The multilayer was first deposited on a Si/SiO_2 substrate in an ultrahigh-vaccum sputtering system with a base pressure below ~5×10^{-9} Torr. A 200 Oe magnetic field was applied in order to induce an easy-axis during the sputtering. Then bottom electrode Cu and top electrode Cu/Ta were patterned using electron beam lithography and subsequent ion milling etching. After this, GMR SPV element was etched out followed by SiO_2 sputtering. A thick capping layer Cu was then coated using lift-off process. Elements sizes vary from 4×1 μm² to 0.2×0.2 μm². Four probes measurements of transport properties were carried out in CPP geometry at room temperature with magnetic fields applied along easy axis. The measuring current was kept below 1 mA to avoid any other effect induced by current.

3. RESULTS AND DISCUSSION

Figure 1 (a) and (b) show the resistance R and resistance change ΔR as a function of element size A for conventional CPP-GMR and CPP-GMR with SyAF with interlayer Cu thickness 2.5 nm, respectively. Here ΔR is defined as $\Delta R = R_{AP}-R_P$, i.e. the resistance change between antiparallel and parallel magnetization configurations of SPV films.

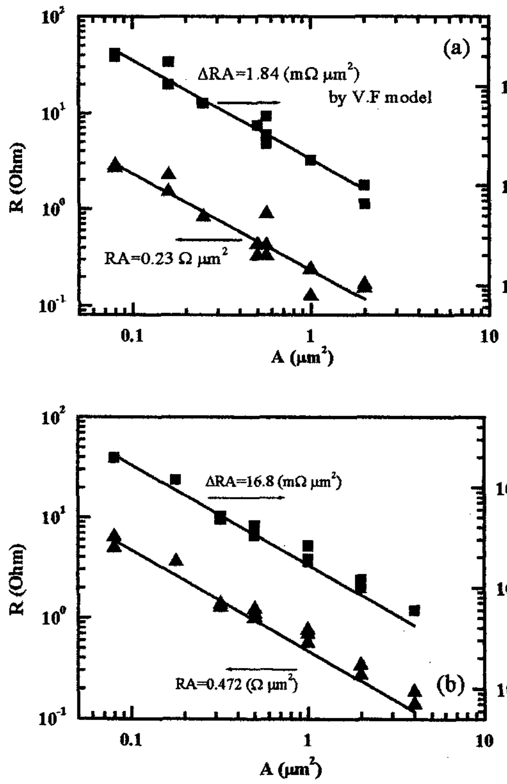

Fig.1. Resistance R and resistance change ΔR as a function of element size for (a) conventional CPP-GMR and (b) CPP-GMR with SyAF structures, while interlayer Cu thickness is 2.5 nm. Solid lines are the fitting lines using V-F model equations.

From Fig 1, both R and ΔR are inversely proportional to A. For conventional CPP-GMR, ΔRA fits well with Valet-Fert (V-F) model [5], using the bulk spin asymmetry coefficient β_{CoFe}~0.42 and the interface spin asymmetry coefficient $\gamma_{CoFe/Cu}$ ~0.75. Here we use the interface resistances reported elsewhere and bulk resistivity measured by us. According to V-F model, we get $\Delta RA \approx 1.84$mΩ μm² and $RA \approx 0.23$ Ω μm². Thus conventional CPP-GMR possesses the obtain MR value of ~0.83%. For CPP-GMR with SyAF, fitting to experimental data results in $\Delta RA \approx 16.8$mΩ μm² and $RA \approx 0.472$ Ω μm², i.e. MR of CPP-GMR with SyAF reaches as high as ~3.56%, which means SyAF as free layers dramatically enhances CPP-GMR in our system. SyAF also doubles the RA, from 0.23 Ω μm² to 0.472 Ω μm². As predicted by Campbell and Fert [6], Ru impurity in Co will scatter majority spins more strongly than minority ones, and leads to large spin anisotropy in the Co/Ru interface. Applying V-F model in CPP-GMR with SyAF, one obtains the spin-dependent interface resistance between $Co_{90}Fe_{10}$ and Ru layers (i.e. $AR^*_{CoFe/Ru}$) to be around 5.19 fΩ m², which is much higher than that between Co_9Fe_1 and Cu layers ($AR^*_{CoFe/Cu} \approx 1$ fΩ m²). We think the enhancement of the MR by SyAF is because of this high interface resistance induced by large spin anisotropy. Detailed theoretical and experimental study of the mechanism for this enhancement will be reported elsewhere. Referring to the simulation works by Takagishi et al.[2], the higher MR justifies that CPP-GMR with SyAF can be used as a read head material with areal density as high as 200 Gbits/in².

The magnetic switching behaviors under different field sweep rates are also studied. The sweep rates of magnetic field vary from 1 Oe/s to 40 Oe/s. The switching field H_{SW} decreases with decreasing field sweep rate. If the element bit forms single-domain, the field sweep rate dependence of H_{SW} can be described by a single-domain thermal activation model [7]:

$$R_H = \frac{\gamma_0}{2C(H_k - H_{SW})} \exp[-C(H_k - H_{SW})^2], \qquad (1)$$

where $C = K / k_B T H_k^2$; H_k is the zero-temperature anisotropy field as determined by the shape anisotropy; R_H is the field sweep rate; γ_0 is attempt frequency; $K = 0.5mH_k$ is the uniaxial anisotropy energy.

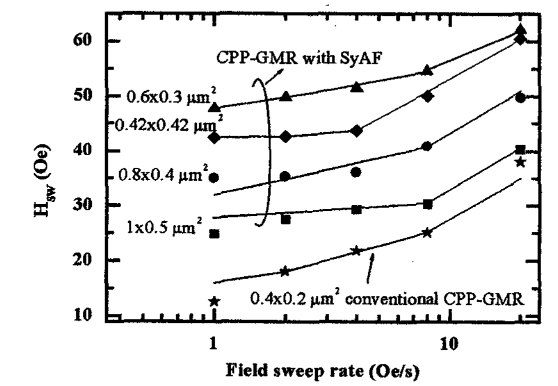

Fig.2. Experimental results of field sweep rate dependence of magnetic switching field H_{SW} (scatter symbols) compared with single-domain model calculation (solid lines) for different sized elements.

Figure 2 gives the experimental and modeling results of H_{SW}-R_H curves for different sized

CPP-GMR with SyAF elements. Results of conventional CPP-GMR element with size 0.4×0.2 μm^2 are also shown for comparison. For the conventional CPP-GMR, the switching behavior is far from single-domain modeling result even though the element size decreases to as small as 0.4 by 0.2 μm^2. For CPP-GMR with SyAF, on the other hand, when the element size decreases to around 0.6 by 0.3 μm^2, the variation of switching field under different magnetic field sweep rate fits well with one calculated from the single-domain thermal activation model. Keeping the element area 0.18 μm^2 and changing aspect ratio into 1, 0.42 by 0.42 μm^2 element also shows single-domain behavior, as shown in Fig 2. So CPP-GMR element with SyAF shows single-domain switching behavior while the size diminishes to 0.18 μm^2, even with low aspect ratio 1, which means that CPP-GMR with SyAF structure has much higher tendency to form a single-domain than the conventional one. The single-domain switching behavior of the low aspect ratio CPP-GMR element with SyAF is probably because of the single-domain structure of low aspect ratio SyAF that we directly observed using magnetic force microscopy and magneto-optic kerr measurement [3]. We argued that SyAF allows an enclosed magnetic flux and creates less stray field, which reduces the magnetostatic coupling with adjacent ferromagnetic layers and facilitates to form single-domain structure even with the low aspect ratio of 1.

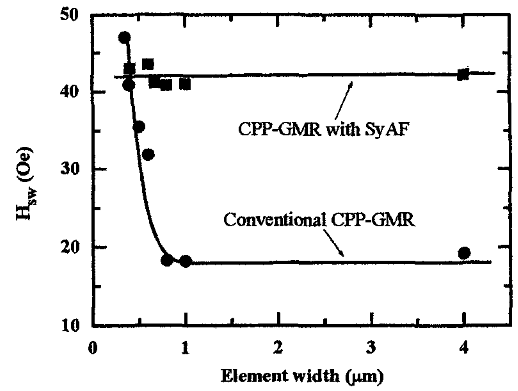

Fig.3. The magnetic switching field as a function of element width for conventional CPP-GMR and CPP-GMR with SyAF structures.

Figure 3 provides the element width dependence of magnetic switching field for conventional CPP-GMR and CPP-GMR with SyAF structures, in which aspect ratio is 1. For the element with conventional CPP-GMR structure, its switching field substantially increases when the element width decreases below 1 μm, which is because of large demagnetizing field arising from the poles at the edge of element bits. But switching field keeps nearly constant for CPP-GMR with SyAF element.

As reported [4], for single-domain, the switching field of SyAF can be described as:

$$H_{SW} = \frac{2K(t_1+t_2)}{M_1t_1-M_2t_2} + \frac{4\pi C(k)(M_1t_1-M_2t_2)}{w}, \qquad (2)$$

where *C(k)* and *w* are the demagnetizing factor depending on aspect ratio *k* and the width of element bit, respectively. When aspect ratio is 1, *C(k)* becomes zero and thus magnetic switching field has no relationship with *w*, leading to size-independent switching field. Thus the origin of size-independent switching field in CPP-GMR with SyAF element is its single-domain structure under low aspect ratio 1.

In conclusion, we studied the effects of SyAF on CPP-GMR, domain structure and magnetic switching behavior in single spin-valve films. SyAF as free layers greatly enhances CPP-GMR ratio from 0.83% to 3.56% at room temperature and also doubles RA in our system. Field sweep rate dependence of switching field demonstrates that CPP-GMR with SyAF exhibits single-domain behavior, while its size shrinks below 0.18μm^2 even with low aspect ratio 1. Single-domain under aspect ratio 1 brings CPP-GMR with SyAF structure a size-independent magnetic switching field. Higher CPP-GMR, single-domain structure and size-independent switching field justify the great potential for the structure of CPP-GMR with SyAF as free layers to be used in future ultra-high recording density storages.

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4. REFERENCES

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