Enhancement of Room Temperature-Exchange Biasing in Specular Spin Valves

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The exchange bias properties of the $Co_{1-x}Fe_x$ natural-oxidized nano-oxide layer (NOL) in the specular spin valve system are investigated. The exchange bias energy (J_{ex}) increased with the Fe content of the CoFe NOL. This result suggests that the enhancement of the pinning field/energy at room temperature was induced by the inserted NOL into the pinned layer. The enhancement of both the magnetoresistance ratio and the exchange bias field was realized by increasing the Fe content in the $Co_{1-x}Fe_x$ NOL.

Index Terms—**Exchange coupling, giant magnetoresistance (GMR), nano-oxide layer (NOL), specular reflection, spin valves.**

I. INTRODUCTION

HIGHER sensitivity with reduced giant magnetoresistance (GMR) element size is required in a higher density magnetic recording head. To realize the high sensitivity, the enhancement of the GMR effect needs to be investigated. The nano-oxide layer (NOL) in a specular spin valve (SPSV) is fairly effective at enhancing the MR ratio [1]–[4], leading to the advanced current in-plane (CIP) configuration devices. On the other hand, in addition to the enhancement of the MR ratio, strong pinning at the pinned layer is also required. Therefore, the exchange coupling through the NOL is a key factor when the NOL is inserted into the pinned layer. Recently, the enhancement of the exchange field below the Néel temperature (T_N) of the NOL after the magnetic field cooling was reported for a $Co_{0.9}Fe_{0.1}$ NOL inserted into a conventional spin valve [5]. In this paper, to confirm the origin of the exchange field from the NOL, the magnetization curve and the temperature dependence on magnetization for $Co_{1-x}Fe_x$ NOL-inserted samples were investigated. Room temperature NOL-exchange biasing superimposed on an antiferromagnetic (AFM) exchange bias in SPSV was also considered as a way to realize a CIP-GMR with higher sensitivity and a more stable pinned layer.

In this paper, we investigate the exchange bias properties of the NOL ($Co_{1-x}Fe_x$—natural oxidation) in the SPSV system by measuring the magnetization and by conversion electron Mössbauer spectroscopy (CEMS).

II. EXPERIMENTAL PROCEDURE

The sequential sputtering method was used for the sample preparation. The typical design of the SPSV sample was underlayer/Ta–Ru–PtMn(12 nm)–$Co_{0.90}Fe_{0.10}$(1.4 nm)–$Co_{1-x}Fe_x$(0.6 nm)–Cr(0.08 nm)–Nat.Ox–$Co_{0.90}Fe_{0.10}$(2 nm)–Cu(2.2 nm)– $Co_{0.90}Fe_{0.10}$(2 nm)–Cu(2 nm)–Ta(3 nm) on a Si substrate. For the reference, a nonspecular sample was also prepared (Ta–Ru–PtMn(12 nm)–$Co_{0.90}Fe_{0.10}$(3 nm)–Cu(2.2 nm)–$Co_{0.90}Fe_{0.10}$(2 nm)–Cu(2 nm)–Ta(3 nm)).

It should be mentioned that all the NOLs were fabricated on $Co_{0.90}Fe_{0.10}$ and that the thickness of the pinned layer was fixed around 3 nm, so the exchange coupling from the AFM PtMn was assumed to be the same for each sample. The conventional natural oxidation process was carried out in an extra chamber [3]. The $Co_{1-x}Fe_x$ thickness was 0.6 nm. All of the films were annealed at 270 °C for 10 h under a magnetic field of 7 kOe. Details of the sample preparation are given in [3] and [6]. A 0.08-nm Cr layer was deposited on the surface of the $Co_{1-x}Fe_x$ to improve the stability of the NOL layer, while the sample without oxidation was prepared without the Cr. The MR ratio was measured using conventional four-terminal methods. The MR ratio of the sample without an NOL was 8.8%. In comparison, samples with the NOL showed values around 10%. The increased MR ratio is caused by the specular effect of the NOL. The magnetization was measured by using a conventional vibrating sample magnetometer (VSM) with 10×10-mm samples. A conversion electron Mössbauer spectroscopy (CEMS) measurement was used to confirm the AFM component.

III. RESULTS AND DISCUSSION

Generally, it is very difficult to determine the structural and magnetic properties of the NOL itself because of its very small thickness and burial inside the spin valve film stack. Investigating the magnetization of the two CoFe layers in contact with the NOL is quite useful in understanding the NOL. Measuring the magnetic field cooling effect is especially effective at characterizing the magnetism of the very thin oxide layer.

First, the synthetic SPSV was investigated. Details of the sample preparation are given in [2] and [3]. The conventional natural oxidation process was carried out for the fabrication of the NOL. The field cooling effect was observed for Co-rich natural oxidation samples, which suggests the existence of an AFM component in the NOL [7].

To confirm whether this characteristic temperature corresponds to T_B (blocking temperature) of the CoO, a conventional SPSV with an IrMn AFM layer was prepared. The MR curve, after being field-cooled at ± 10 kOe, was measured and the H_{ex} at each temperature is plotted in Fig. 1. From this figure, the
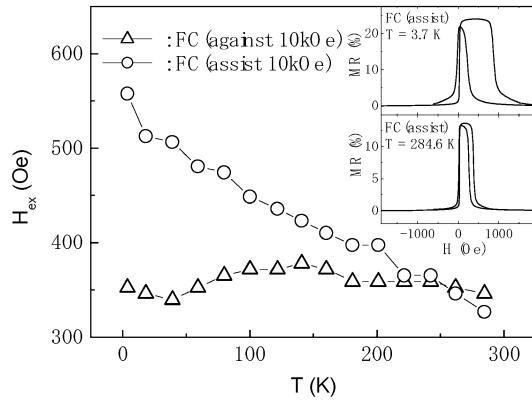
Fig. 1. Temperature dependence of exchange bias field after field cooling (FC) at ±10 kOe (against: FC at opposite to pinned direction; assist: FC at pinned direction).
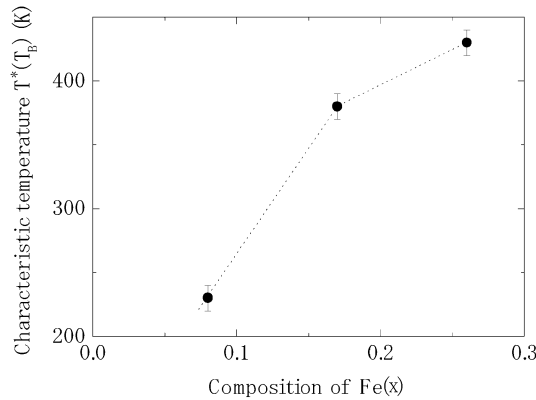

Fig. 2. Blocking temperature (T_B) versus Fe in $Co_{1-x}Fe_x$ NOL.

Fig. 3. Schematic illustration of the structure for CoFe NOL. (a) $C_{0.92}Fe_{0.08}$–Cr NOL. (b) $Co_{0.74}Fe_{0.26}$–Cr NOL.

Fig. 4. Exchange energy J_{ex} as a function of Fe content in $Co_{1-x}Fe_x$ NOL.

enhancement of the exchange coupling is confirmed below the T_B of CoO($\sim$250 K [8]). This result agrees with the report from Ventura *et al.* [5]. Below the T_B of CoO, the NOL exchange biasing is superimposed on the AFM exchange bias in the SPSV. Accordingly, the composition of the oxide compound for $Co_{0.92}Fe_{0.08}$–Cr NOL is likely to be CoO and Cr_2O_3 (with the bulk T_N of 290 and 307 K, respectively). The blocking temperature (T_B) for $Co_{0.92}Fe_{0.08}$–Cr shows a lower value than the T_N of the bulk. Even though the T_B does not have to agree with T_N, this difference is reasonable if we assume the T_N is decreased by the reduced thickness of the AFM-NOL component. The decrease of T_N as a function of thickness of CoO was reported in [8].

The blocking temperature increases with increasing Fe content as shown in Fig. 2. In $Co_{0.74}Fe_{0.26}$–Cr NOL, the blocking temperature is 450 K, which is high enough for a recording head [9]. This result suggests the presence of α–Fe_2O_3 or α–$(CrFe)_2O_3$, since the T_N for both are higher than room temperature. Fig. 3 shows a schematic illustration of the structure for CoFe NOL. The paramagnetic component above T_N and the AFM component weaken the exchange energy through the NOL (J_{NOL}) in the synthetic SPSV, which leads to the decreased stability of the antiparallel/parallel configuration between the free and pinned layers. For the direct observation of the exchange biasing superimposed by the NOL on the
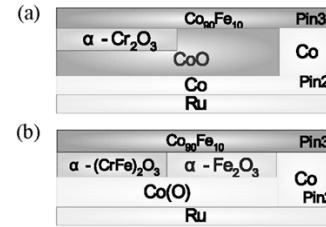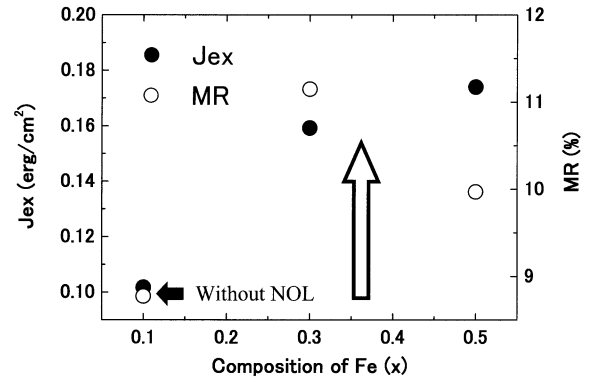
AFM exchange bias, the exchange energy (J_{ex}) of conventional SPSV(Ta–Ru–PtMn(12)–$Co_{0.90}Fe_{0.10}$(1.4)– $Co_{1x}Fe_x$ ($x = 0.3, 0.50$)(0.6)–Cr(0.08)–O_x– $Co_{0.90}Fe_{0.10}$(2)–Cu(2.2)– $Co_{0.90}Fe_{0.10}$(2)–Cu(2)–Ta(3)(nm)) was investigated. Fig. 4 shows J_{ex} as a function of Fe content, which was calculated from $J_{ex} = H_{ex}$ Mst. The H_{ex} of $Co_{0.90}Fe_{0.10}$ without NOL, $Co_{0.70}Fe_{0.30}$ NOL, and $Co_{0.50}Fe_{0.50}$ NOL are 226, 282, and 295 Oe, respectively. We succeeded in observing the enhancement of pinning field/energy in the conventional SPSV by inserting NOL into the pinned layer at room temperature and with more Fe in the $Co_{1-x}Fe_x$ NOL. It is believed that this enhancement originates from the exchange bias field from the antiferromagnetic component in the NOL with the higher T_B.

To confirm the presence of this AFM component with the high T_B, a Mössbauer spectroscopy measurement was performed. The hyperfine structures of the $Co_{0.74}Fe_{0.26}$ NOL were investigated by conversion electron Mössbauer spectroscopy. The sample for CEMS measurement was Si–Ta(5 nm)–Ru (2 nm)–[$Co_{0.90}Fe_{0.10}$(2 nm)–Ru(0.85 nm)–$Co_{0.70}Fe_{0.30}$ (0.6 nm)–Cr(0.08 nm)–Nat.Ox.–$Co_{0.90}Fe_{0.10}$ (2 nm)–Ru(2 nm)]$_{10}$– Ta(5 nm).

Fig. 5 shows the Mössbauer spectra and the result of the analysis. The dots in the figure show the experimental results, and the solid lines are the result of fitting by the least squares method. Though the signal/noise (S/N) of the spectrum is not good enough, this spectrum is explained by four components. There is a component of the high hyperfine field at around 410 kOe, which corresponds to α–Fe_2O_3 and the low hyperfine field of Fe(Co) at around 310 kOe. This spectrum includes one unknown magnetic phase which might correspond to another Fe^{3+} oxide such as an α–$(CrFe)_2O_3$ phase. This result agrees with expectations based on T_B and exchange bias energy [Fig. 3(b)].
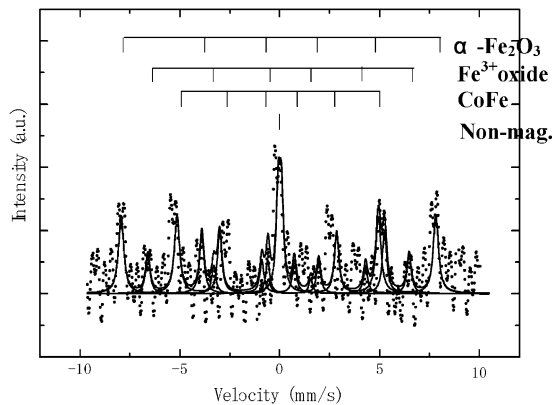
Fig. 5. Mössbauer spectra and result of analysis.

The best fit is obtained when we assume the direction of the magnetic moment for the oxidized component is randomly oriented in the plane. The estimated volume fraction of α–Fe_2O_3, α–$(CrFe)_2O_3$, $Fe(Co)$, and nonmagnetic component are 32%, 14%, 38%, and 16%, respectively. The nonmagnetic component might be a magnetic component with its T_N below room temperature. In comparison, the $Co_{0.92}Fe_{0.08}$–Cr NOL mainly consists of nonmagnetic components which correspond to the phases with T_N below room temperature. As a result, the room temperature NOL exchange biasing occurs through superimposing the AFM exchange bias by the Fe-rich NOL with the formation of α–Fe_2O_3 and α–$(CrFe)_2O_3$. The exchange bias effect of rather thick α–Fe_2O_3 was reported in [7]. It suggests that the stability of the pinned layer is improved by the AFM α–Fe_2O_3 and α–$(CrFe)_2O_3$ components, which agrees with our model of the NOL structure for the Fe-rich NOL. To improve the S/N of the spectrum and analyze more detail in the NOL, we are now carrying out the preparation of ^{57}Fe-enriched samples for CEMS measurements. Further, the higher content of Fe in the NOL for the conventional SPSV with AFM layer will also be studied.

IV. SUMMARY

Exchange coupling in SPSV strongly depends on the magnetism and the structure of the NOL. The field-cooling effect was observed, which suggests the existence of an antiferromagnetic component such as CoO for Co-rich NOL. The NOL exchange biasing superimposed on an AFM exchange bias in SPSV is believed to be present below the T_B of CoO. The blocking temperature of the NOL AFM component increases with increasing Fe content in the CoFe NOL. In $Co_{0.74}Fe_{0.26}$, the characteristic temperature of 450 K was produced. α–Fe_2O_3 and Fe^{3+} oxide α–$(CrFe)_2O_3$ phases were observed by Mössbauer spectroscopy. The enhancement of both the MR ratio and the exchange bias field was realized at room temperature by increasing the Fe content in the $Co_{1-x}Fe_x$ NOL.

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