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Anisotropy transition of Co in IrMn/Co/FeO$_x$/Co by field cooling

Chih-Ta Shen, Chih-Huang Lai,[a] and Po-Hsiang Huang
Department of Materials Science and Engineering, National Tsing Hua University, Hsinchu, Taiwan 30013, Republic of China

S. Y. Hsu and Ting Yi Chung
Department of Electrophysics, National Chiao-Tung University, Hsinchu, Taiwan 300, Republic of China

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The temperature dependence of Co anisotropy on a nano-FeO$_x$ layer was studied in the structure of IrMn/Co (FM1)/FeO$_x$/Co (FM2). An anisotropy transition of the FM2 was observed from a combination of uniaxial and unidirectional anisotropies at room temperature (RT) to unidirectional anisotropy at temperature below 80 K through field cooling process. Various ferromagnetic (FM) and antiferromagnetic (AFM) components existing in the FeO$_x$ layer were attributable to the observed anisotropy of FM2. AFM domains with T_N higher than room temperature were responsible for the observed uniaxial anisotropy at RT and AFM domains with T_N of 80 K were accountable for the anisotropy transition, below which the unidirectional anisotropy became dominant. In addition, the direction of the shifted loop could be determined by the cooling field direction. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2172897]

INTRODUCTION

Spin valves are composed of two ferromagnetic (FM) layers separated by a spacer (Cu). A great attention has been drawn due to their applications for read heads in the past years. Inserting the nano-oxide layer (NOL) into the free or pinned layers could further enhance magnetoresistance (MR) ratio due to specular reflection and could also change the coupling mechanism.[1,2] Twist or biquadratic coupling was observed by inserting the nano-oxidized $Co_{50}Fe_{50}O_x$ (Ref. 1) or NiFeO$_x$ (Ref. 2) into the pinned layer. A pseudo-spin-valve-like MR loop with a high MR ratio was observed at 90°, direction perpendicular to the field annealing for antiferromagnets, which verified the existence of an induced uniaxial anisotropy at 90° by inserting NOLs.[2] The biquadratic coupling originating from the interaction between highly frustrated or compensated antiferromagnetic (AFM) and FM planes was reported.[3,4] Furthermore, temperature effects on the magnetic coupling through NOLs were reported in the previous works,[5–7] which discovered the anomalous loops at low temperature because of the different temperature dependences on the J_{NOL} and J_{exch}, where J_{NOL} indicated the interlayer coupling between the top and bottom FM layers and J_{exch} was the exchange coupling of AFM/FM.[5] The paramagnetic-antiferromagnetic transition of NOLs below room temperature was reported and different magnetic characteristics were observed due to the magnetic transition of NOLs.[6] The Néel temperature T_N of the $Co_{1-x}Fe_xO$ NOLs increased as the Fe contents increased.[7] When the FeO$_x$ was inserted in the pinned layer [IrMn/Co (FM1)/FeO$_x$/Co (FM2)], coexistence of the unidirectional and biquadratic coupling on the top pinned layer (FM2) was observed.[8] In this work, we reported the controllable coupling between FM1 and FM2 through FeO$_x$ by using field cooling. The transition of MR curves measured at 90° was observed from uniaxial pseudo-spin-valve-like loops at RT to unidirectional spin-valve loops at 10 K under a cooling field of 5000 Oe. Controllable coupling between FM layers through NOLs by field cooling process was investigated.

EXPERIMENTAL PROCEDURE

Spin valves with the structure of Ta 3 nm/Cu 1.2 nm/IrMn 8 nm/Co (FM1) 2 nm/FeO$_x$ 2.2 nm/Co (FM2) 2 nm/Cu 2.3 nm/Co (Free layer) 4 nm/Ta 3 nm were deposited on Si (100) wafers by using a sputtering system at a base pressure of 5×10^{-7} Torr. FeO$_x$ layers were formed by exposing 1.5 nm Fe films to oxygen plasma for 10 s at an oxygen partial pressure of 3 mTorr. To set the exchange biasing direction (0°) between IrMn and Co (FM1), all the films were postannealed in vacuum at 200 °C for 15 min at a presence of 1 kOe. An exchange field between IrMn and Co exceeds 1000 Oe and obtained after postannealing.[8] *R-H* and *M-H* curves were measured at different temperatures by using a physical property measurement system (PPMS) and superconducting quantum interference device (SQUID) under different cooling fields. The field cooling process was performed by applying a field at room temperature and by cooling down the samples to 10 K. The measured MR and *M-H* loops were then taken at different elevated temperatures. An x-ray photoelectron spectrometer (XPS) was employed to determine the oxidation state of the FeO$_x$ layer.

RESULTS AND DISCUSSION

In the previous work, we reported the coexistence of the unidirectional and biquadratic coupling on the FM2 as inserting the FeO$_x$ layer into the pinned layer.[8] At room temperature, a pseudo-spin-valve-like MR loop at 90° and a shifted

[a]Author to whom correspondence should be addressed; electronic mail: chlai@mx.nthu.edu.tw

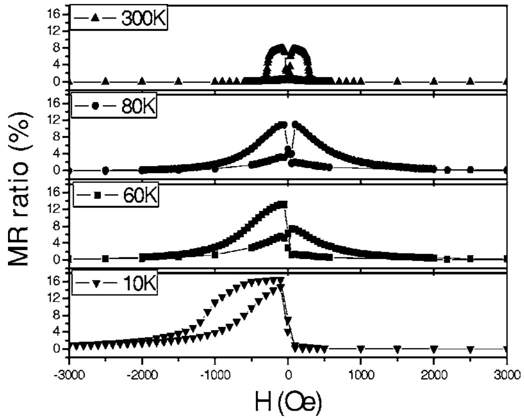

FIG. 1. MR curves measured at 90° at 10, 60, 80, and 300 K. The samples were first field cooled to 10 K at a field of +5000 Oe along 90°.

complicated MR loop at 0° were observed.[8] The uniaxial anisotropy at 90° of the FM2 layer may come from the spin-compensated AFM domains of the FeO_x layer and the unidirectional anisotropy at 0° may result from the unoxidized Fe, providing ferromagnetic channels.[8]

To further investigate the coupling mechanism of the system, the temperature effects on anisotropy were studied. Since the MR measurement is quite sensitive to the relative magnetization orientations between free and top pinned layers (FM2), the MR curves were used as indicators to study the magnetization orientations and anisotropy of the FM2 layer. The MR curves of the spin valves with the FeO_x nano-oxide layer measured at 90°, direction perpendicular to the biasing field of IrMn/Co (FM1), at different temperatures were presented in Fig. 1. During the cooling process, a field of +5000 Oe was applied at 90°. A shifted loop at 10 K measured at 90° indicated that dominated unidirectional anisotropy at 90° was present on the FM2; but as the measuring temperature increased, the strength of unidirectional anisotropy on the FM2 was suppressed and uniaxial anisotropy was enhanced. The anisotropy of the FM2 became pure uniaxial at 90° and symmetric MR loops were observed when the measuring temperature was above 80 K. These results suggested that the anisotropy of the FM2 could be controlled through the field cooling process.

To further demonstrate the controllable anisotropy of FM2 by a cooling field, we changed the field cooling direction from +5000 to −5000 Oe, that is, the cooling field of 5000 Oe was applied at 270°. The MR loops were shifted to the opposite direction accordingly as shown in Fig. 2(a), which suggested that the direction of the cooling field determined the direction of the FM2 anisotropy. Furthermore, we performed the field cooling process along 0°, parallel to the direction of exchange bias of IrMn/Co (FM1). A clear shifted MR loop at 10 K with an exchange bias field H_{ex} of 1200 Oe was observed by field cooling at +5000 Oe, as shown in Fig. 2(b). When the *R-H* loops were measured at 0° at RT, the unusual loop was observed and was explained by the coexistence of the unidirectional and biquadratic anisotropies on the FM2.[8] However, after the field cooling process, the biquadratic anisotropy was eliminated but the unidirectional anisotropy was enhanced.

The hysteresis loops of the structure Ta 3 nm/Cu 1.2 nm/IrMn 8 nm/Co (FM1) 2 nm/FeO_x 2.2 nm/Co (FM2) 2 nm/Ta 3 nm were measured to further confirm the anisotropy of FM2 at various temperatures. Figure 3(a) showed that the uniaxial anisotropy was dominated at 150 K, same as at RT, but the unidirectional anisotropy became dominated at 10 K when the samples were measured at 90°. Figure 3(b) showed that the biquadratic anisotropy was completely eliminated and only the unidirectional anisotropy existed at 10 K, measured at 0°. These *M-H* curves were consistent with the MR loops and verified the controllable anisotropy of FM2 by the field cooling process.

To understand the temperature-dependent coupling and anisotropy, the identification of kinds of FeO_x was essential. The XPS results revealed that mixed valance states of Fe, Fe^{2+}, and Fe^{3+} coexisted in the FeO_x layer, as shown in Fig. 5 of the Ref. 8. The unoxidized Fe mainly provided the ferromagnetic components and FeO, α–Fe_2O_3, γ-Fe_2O_3, or Fe_3O_4 might exist in the FeO_x layer, which possessed antiferromagnetic or ferrimagnetic properties. Based on the XPS results, AFM and FM components may coexist in FeO_x, which resulted in various effects of field cooling on the anisotropy of FM2. Since the unidirectional anisotropy of Co (FM1) at 0° was established through the field annealing process at 200 °C, this unidirectional anisotropy may couple to FM2 through the FM channels (unoxidized Fe) in the NOL layer. On the other hand, the AFM component with T_N higher than RT in the FeO_x might possess compensated anitiferromagnetic domains, which resulted in the uniaxial anisotropy at 90° on FM2.[9] This scenario could explain the observed anisotropy at RT well; however, a transition temperature seemed to exist at around 80 K, below which the spin configuration of FeO_x was strongly determined by the cooling

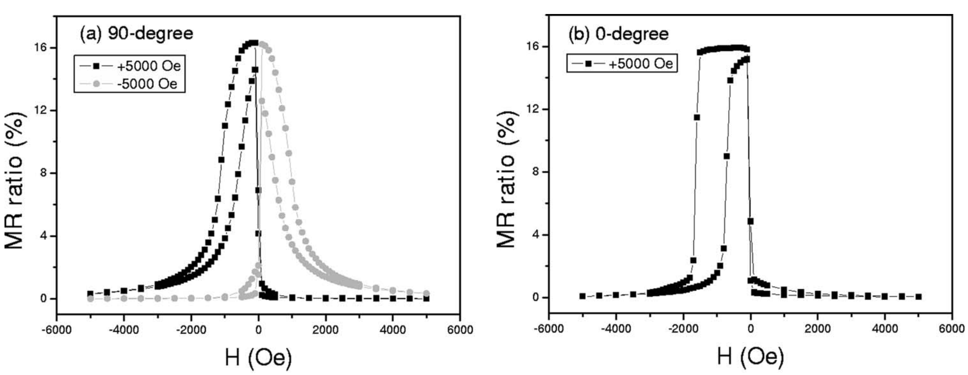

FIG. 2. MR curves measured at 10 K by field cooling at (a) 90° and (b) 0°.

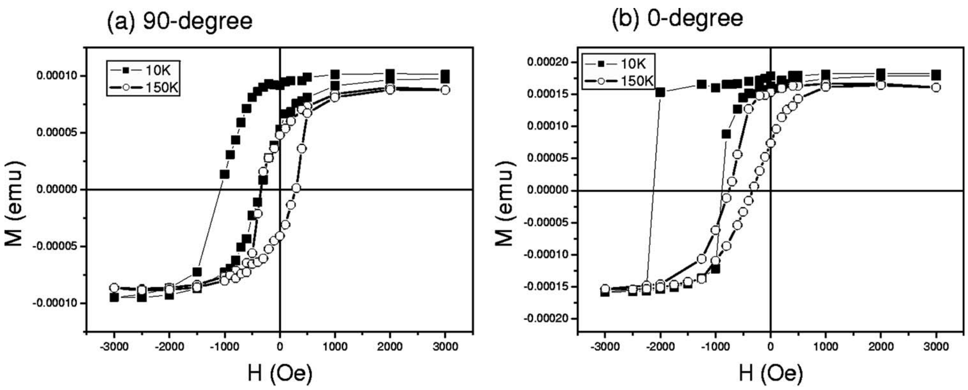

FIG. 3. Hysteresis loops measured at (a) 90° and (b) 0° at temperatures of 150 and 10 K. The samples were first field cooled to 10 K at a field of +5000 Oe along 90° in (a) and 0° in (b).

field. This transition might be related to the magnetic transition between paramagnetic and antiferromagnetic phases as reported before.[7] The Néel temperature T_N of the $Co_{1-x}Fe_xO$ NOLs increased as the Fe contents increased. As the x exceeded 0.17, the T_N was above room temperature.[7] In our system, some AFM components may possess T_N higher than RT (AFM1), consistent with the previous report,[7] resulting in an uniaxial anisotropy at 90° at RT; however, since the valance state of FeO_x was quite complicated, some of AFM components may have T_N around 80 K (AFM2), which led to an observed transition and dominated unidirectional anisotropy by the cooling field.

Due to the presence of different AFM domains, the anisotropy of the FM2 could be manipulated by the cooling field. During the field cooling at 90°, when temperature was cooled below 80 K, the spins of the AFM2 component were aligned by the cooling field, which induced an uncompensated moment toward to the cooling field direction and resulted in the shifted loop (Fig. 1). However, AFM2 became paramagnetic as the temperature was higher than 80 K and the AFM1 domains returned to their stable compensated state after the cooling field was removed. The spin-compensated configuration in AFM1 led to the observed uniaxial anisotropy at 90° at temperatures above 80 K. Since the spin configuration of the AFM2 domains was varied by the cooling field and temperature, the anisotropy of the FM2 was changed, and hence the shifted direction and the symmetric or asymmetric behavior of the MR loops were controlled accordingly. When the cooling field was applied along 0°, the uncompensated AFM2 components and FM component of FeO_x were all aligned in the same direction as the magnetization of bottom Co (FM1), resulting in an enhanced exchange field. Furthermore, the exchange field in 0° was larger than that in 90° and the observed loop in 0° was much square, suggesting that the easy axis of the FeO_x AFM component is along 0°.

CONCLUSION

Various FM and AFM components existing in FeO_x were proposed to explain the observed anisotropy change of the Co (FM2) layer on the nano-FeO_x layer in the structure of IrMn/Co (FM1)/FeO_x/Co (FM2). The MR curves and hysteresis loops indicated an anisotropy transition of FM2 from a combination of uniaxial (90°) and unidirectional (0°) anisotropies at room temperature to unidirectional anisotropy at temperature below 80 K through the field cooling process. The AFM component with T_N higher than RT possessing spin-compensated domains contributed to the uniaxial anisotropy along 90° at RT. The AFM component with T_N of 80 K was responsible for the anisotropy transition, below which the cooling field induced an extra unidirectional anisotropy; therefore, the direction of the exchange bias field is determined by the cooling field direction. The FM2 anisotropy could be controlled through the field cooling process.

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