APPLIED PHYSICS LETTERS **95**, 222506 (2009)

Inverted magnetoresistance in dual spin valve structures with a synthetic antiferromagnetic free layer

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(Received 14 September 2009; accepted 29 October 2009; published online 3 December 2009)

We report an oscillation of the giant magnetoresistance (GMR) ratio as a function of Ru layer thickness in the CoFe/Cu/[CoFe/Ru/CoFe]SAF/Cu/CoFe/IrMn dual spin valve (SV) structure. A normal GMR with a positive sign is observed for the thickness of Ru providing a ferromagnetic interlayer exchange coupling (IEC). The inverted GMR is observed for the thickness of Ru providing an antiferromagnetic IEC, which is consistent with IEC period across the Ru spacer as well as the electrical separation of the overall structure into two SVs connected in parallel. © *2009 American Institute of Physics*. [doi:10.1063/1.3266522]

Following the discovery of giant magnetoresistance (GMR),[1,2] extensive experimental and theoretical investigations were performed on spin valve (SV) systems. In a typical SV two ferromagnetic (FM) layers are separated by a nonmagnetic spacer, in which one FM layer is pinned by exchange anisotropy by using an antiferromagnetic (AF) layer, while the other FM layer (free layer) can be switched with a small external magnetic field. However in a SV with submicrometer scale, the interlayer magnetostatic field arising from the pinned layer on the free layer becomes larger. In order to eliminate this effect, a synthetic antiferromagnetic (SAF) structure has been used to replace the pinned or the free layer. Since in the SAF structure, the magnetizations of the two FM layers separated by nonmagnetic spacer have strong AF interlayer exchange coupling (IEC) resulting in a closed flux loop between the two layers of the SAF and a effective reduction in the dipolar field on the free layer.

The MR ratio is defined as $(R_{ap}-R_p)/R_p$, where R_p and R_{ap} is the resistance when the magnetizations of the two FM layers are aligned in parallel and antiparallel, respectively. Generally, when the magnetizations of the two FM layers are parallel the resistance is lower and higher when they are antiparallel configuration. This negative MR is termed the normal GMR (the resistance is higher for an antiparallel alignment). In some cases, however, a positive MR (inverted GMR) response is seen (the resistance is lower for an antiparallel alignment). The inverted GMR effect was first reported by George *et al.*[3] The MR, which was positive at low field and negative at high field, resulted from a magnetic spin-flop transition. Recently, several experimental and theoretical studies have shown an inverted GMR effect in different systems.[4–9] In the rare-earth transition metal multilayers, inverted GMR is due to the direct AF coupling across a Co/Dy interface.[4] Due to the increase of the density of states at the Fermi level for majority spin electrons in the $Fe_{1-x}V_x/Au/Co$ system[5] and doping effect in the Co/Ru/CoRu system,[6] the spin polarization of the conduction band having opposite sign in alternate FM layers results in inverted GMR. Inverted GMR in the SAF pinned layer structure was observed by Marrows *et al.*[9] and they explain the observed inverted GMR by the pinning field direction being opposite to the growth field direction due to the thickness difference between FM layers.

In this letter, we demonstrate the dependence of GMR on Ru thickness in a SAF free-layered dual SV (DSV) structure. Using this method, a GMR of 7.2% is observed in the structure without the Ru spacer layer. With increasing the Ru thickness, the GMR ratio decreases to −3.8% but becomes positive value again at the Ru thickness of 1.2 nm. Our systematic experiments show that the inverted GMR in the SAF free layer structure is related to the magnetic exchange coupling between FM layers across Ru spacer as well as the electrical separation of the overall structure into two SVs connected in parallel.

Samples were of the following: Ta 5/CoFe 1.5/Cu 2.8/[CoFe 1.3/Ru t/CoFe 1.3]/Cu 2.8/CoFe 2.5/IrMn 10/Ta 5 (in nm), where Ru thickness was varied from 0–1.5 nm in the SAF layer [CoFe 1.3/Ru t/CoFe 1.3]. The samples were prepared using a six-target dc magnetron sputtering system under a typical base pressure of less than 2×10^{-7} Torr. The magnetic easy axes were defined by applying a 10 mT magnetic field during deposition. The SV microstructure and magnetic properties were characterized using High Resolution Transmission Electron Microscopy (HRTEM) and Superconducting Quantum Interference Device (SQUID), respectively. A probe station and a Quantum Design Physical Property Measurement System (PPMS) were used to measure the magnetotransport properties of the SV structure at low field and high field, respectively.

Figure 1 shows the room temperature low field response of the SAF free-layered DSV structure as a function of Ru thickness. Two different GMR characteristics can be distinguished from the magnetotransport curves. As shown in Fig. 1(a), GMR of 7.2% is observed in the structure without the Ru spacer. Inserting of a 0.4 nm thick Ru layer in the SAF layer surprisingly gives an inverted GMR with a ratio of −1.9%. The arrows are indicative of the magnetization directions for each layer in the structure shows inverted GMR (A detailed description of magnetization switching process is shown in Fig. 4). Further increasing the Ru thickness to 1.2 nm, the GMR ratio becomes positive again. In order to clearly see the effect of Ru thickness on the GMR ratio, we

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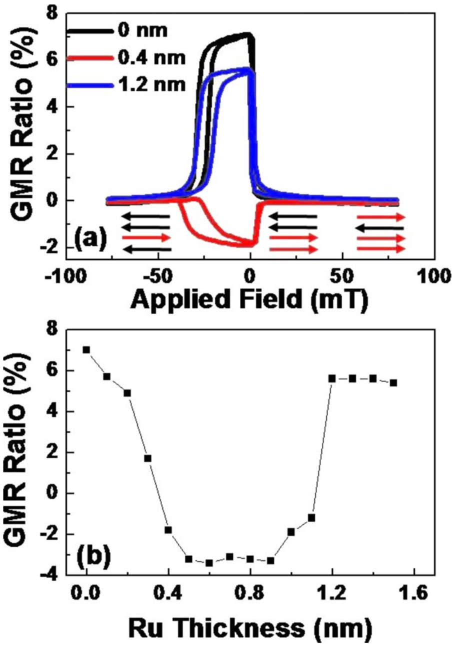

FIG. 1. (Color online) [(a) and (b)] Ru thickness dependence of the GMR ratio in the dual SV structure.

plotted the GMR ratios as a function of Ru layer thickness in Fig. 1(b). An oscillation of GMR ratio is clearly observed. When the Ru thickness is thinner than 0.4 nm or thicker than 1.1 nm, a positive GMR ratio is observed, however when the Ru thickness is between 0.4 and 1.1 nm, the GMR ratio is negative. Moreover, the GMR ratio changes abruptly at those two critical Ru thicknesses which indicate the spin dependent transport mechanism may have been changed.

To find the correlation between the GMR and the IEC, we have made the same DSV structures without the top IrMn AF layer. Figure 2 shows the magnetization curves for the Ru $t=0$ and 0.4 nm in the SAF layer. A well-defined anisotropy and antiparallel alignment during the magnetization reversal occurrs upon insertion of a 0.4 nm Ru layer. A SAF structure can reduce the magnetostatic energy in the free layer separated by nonmagnetic spacer therefore it shows lower saturation magnetization value than Ru $t=0$ nm sample. The Ru $t=0.4$ nm has larger coercivity (H_c) value than Ru $t=0$ nm sample. Lower net moments of the SAF result in lower torques under a magnetic fields, leading to larger H_c. The magnetization curve of the Ru $t=0.4$ nm sample shows two-step switching with a small remanent magnetization, which is the typical of AF IEC.

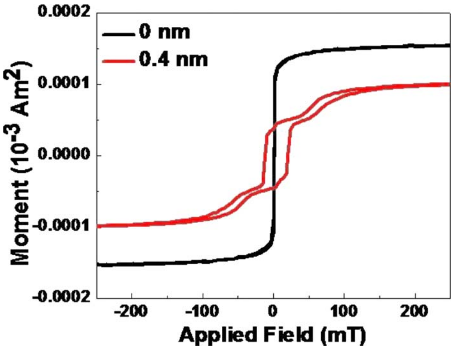

FIG. 2. (Color online) (a) Magnetization curves for a CoFe 2.6 (nm) and CoFe 1.3/Ru 0.4/CoFe 1.3 (nm) free-layered dual SV structures without an AF IrMn exchange bias layer.

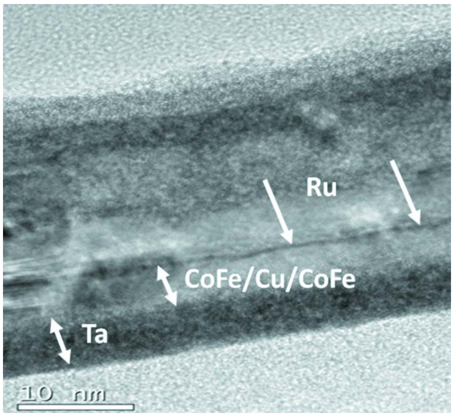

FIG. 3. (Color online) HRTEM image of the dual SV structure consisting of CoFe 1.3/Ru 0.6/CoFe 1.3 (nm) SAF free layer.

This AF IEC is observed in the structure for the thickness of Ru providing an inverted GMR ratio (range of 0.4–1.1 nm) and this IEC becomes FM once again at a Ru thickness of 1.2 to 1.5 nm which provides a normal GMR ratio. It is well-established that when the Ru layer thickness increases, the Ruderman-Kittel-Kasuya-Yosida (RKKY) coupling of the CoFe layers in the SAF layer will oscillate from FM to AF and back again. The oscillation period of the IEC is in good agreement with the previously reported IEC of the Co/Ru/Co system.[10] Our experiments demonstrate that the inverted GMR in a SAF free-layered DSV structure is not originating from difference between the pinning field and the growth field direction.[9]

Furthermore, from Fig. 1(a), we also observe a different shift in the magnetotransport curve for different Ru spacer thickness. In order to make a close examination of the morphology of the SAF free-layered DSV, the samples were examined by HRTEM with special attention paid to the SAF layer. Figure 3 shows a HRTEM image of the SAF free-layered DSV structure for Ru thicknesses of 0.6 nm. The Ru is clearly distinguished by Z-contrast which indicates the high quality of the Ru layer with smooth interface. Based on the HRTEM image with magnetotransport curves, therefore, it indicates that the inverted GMR is related to the IEC between the two FM layers across the Ru spacer.

Figure 4 shows the (a) magnetotransport and (b) magnetization curve for a 0.4 nm Ru layer in the SAF, over a large field range (up to 5 T) measured by PPMS and SQUID, respectively. Our DSV structure, as shown in Fig. 4(a) inset, can be treated as two SVs (SV-1 with an IrMn layer and SV-2 without the IrMn layer) separated by the Ru layer and these are electrically connected in parallel. In order to paint a clearer picture of the magnetic moment configuration in high applied field, we show the magnetization direction of each magnetic layer for five different field positions. In the field position (1), the magnetization of all the layers are aligned parallel to the field direction. As the field is reduced [position (2)], the resistance increases gradually, because the magnetization direction of SAF layer 1 rotates toward an antiparallel orientation with respect to that of SAF layer 2 due to the strong AF IEC across the Ru layer. However, the magnetizations of FM1 and FM2 stay aligned to the applied field until zero field. In this case, SV-1 is in parallel configuration but SV-2 in antiparallel configuration. In field position (3), the

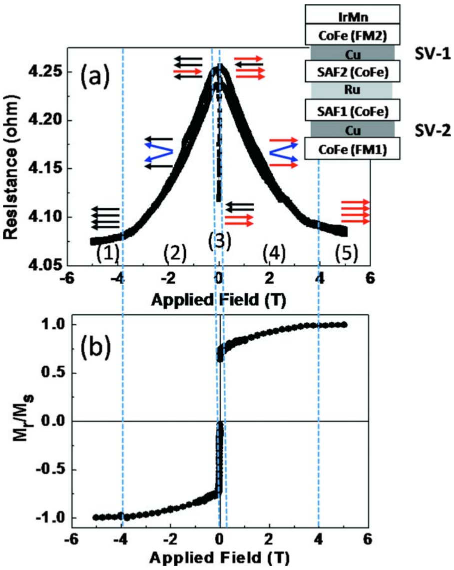

FIG. 4. (Color online) High field (a) magnetotransport and (b) magnetization curves for a CoFe 1.3/Ru 0.4/CoFe 1.3 (nm) free-layered dual SV structures.

magnetization of FM1 switches (since it is not pinned), which creates a state where both the SV-1 and SV-2 are in parallel configuration. Since the CoFe layers adjacent to both Cu spacers are parallel, this means effectively two low-resistance SVs in parallel, which gives an overall low electrical resistance even though the magnetizations of FM1 and FM2 are antiparallel. The saturation magnetization of a single CoFe layer (1.3 nm) in the SAF layer was found to be 0.714 MA/m which gives an IEC of $-1.21\ \mathrm{mJ/m^2}$ across the Ru layer.[11] For such high exchange coupling, further increasing the field to position (4), the magnetization of FM2 switches to the field direction. In this state, the SV-1 is in the antiparallel state while the SV-2 is in the parallel state. As the applied field is increased further (position (5)) to positive saturation the exchange coupling across the SAF is overcome and all layers are aligned parallel.

In summary, we clearly observe an oscillation of GMR ratios as a function of Ru thickness from positive to negative and back again in SAF free-layered DSV structure. The inverted GMR in the SAF-DSV is related to the electrical separation of the overall structure into two GMR SVs connected in parallel, where the resistance state of one SV dominating over the resistance state of another SV. In addition the AF configuration in the SAF layer related to an inverted GMR. An inverted GMR is observed with a thickness of Ru providing an AF IEC. Moreover, the oscillation period of the GMR ratio is consistent with IEC period across the Ru spacer.

We are grateful to M. Venkatessan for the SQUID measurements. This work was supported by Science Foundation Ireland as part of the MANSE project. C. Fowley and B. S. Chun had the same contribution to experiment, analysis, and write up for this paper.

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