Strong effects of magnetic anisotropy on exchange coupling and magnetotransport properties of ferromagnetic/NiO/ferromagnetic trilayers

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Strong effects of the magnetic anisotropy on the exchange coupling are observed in $FM_1/NiO(6\ nm)/FM_2$ trilayers with ferromagnetic (FM) layers Co or Fe. Different magnetic properties are found for Co/NiO/Fe and Fe/NiO/Co trilayers with Ag sublayer and cover layer. The Ag sublayer strongly affects the magnetic anisotropy of FM/antiferromagnetic (FM/AF) bilayers and further influences the exchange coupling in $FM_1/NiO/FM_2$ trilayers. In particular, the sign of the magnetoresistance changes from negative after zero-field cooling to positive after field cooling, which is due to a reversal of the Co spin polarization. Furthermore, the interfacial coupling between FM and NiO enhances the blocking temperature of NiO. © *2010 American Institute of Physics*. [doi:10.1063/1.3480418]

The interlayer coupling in ferromagnetic/nonmagnetic metallic (FM/NM) systems has been studied because of the underlying physics and potential technological applications.[1,2] Many exotic physical phenomena have been observed in conventional FM/NM systems.[3,4] The oscillation of the coupling strength with spacer thickness is attributed to the topology of the Fermi surface of the spacer metals.[5,6] Especially, attention has been focused on the exchange coupling in FM/antiferromagnetic/FM (FM/AF/FM) trilayers.[7,8] A strong competition between two kinds of coupling, i.e., the interfacial coupling between two interfaces and the interlayer coupling between two FM layers across the AF layer, has been observed in FM/AF/FM trilayers with AF a metallic or insulating spacer.[9] It was reported that the FM properties are greatly affected by the underlayer in $[Pt/Co]_3/NiO/[Pt/Co]_3$ multilayers,[10] and a similar phenomenon was observed also in other systems.[11] However, most previous work has been focused on trilayers with the same FM layers and it has been seldom reported that the exchange coupling is influenced by the order of different FM layers. In this letter, we report the different magnetic properties of Fe/NiO/Co and Co/NiO/Fe trilayers and magnetotransport properties of the two trilayers.

Trilayers Co (3 nm)/NiO (6 nm)/Fe (10 nm) (A), Fe (10 nm)/NiO (6 nm)/Co (3 nm) (B), and bilayers Co (3 nm)/NiO (6 nm) (C), NiO (6 nm)/Fe (10 nm) (D), Fe (10 nm)/NiO (6 nm) (E), and NiO (6 nm)/Co (3 nm) (F) were prepared by dc and rf magnetron sputtering at room temperature on a Si (100) substrate with Ag (10 nm) sublayer and Ag (5 nm) cover layer. The substrate, sublayer and cover layer in all these trilayers and bilayers are the same so that we do not mention Si (100)/Ag (10 nm)/…/Ag (5 nm) in the further text. The films were grown in a high-vacuum chamber equipped with multisputtering guns. The base pressure of the chamber was better than 2×10^{-7} Torr and Ar gas was kept at a pressure of 4×10^{-3} Torr during sputtering. Commercial Ag, Co, Fe, and NiO targets with 99.99% purity were used. The crystal structure was investigated by means of x-ray diffraction with Cu K_α radiation. The magnetic properties were measured at different temperatures in a superconducting quantum interference device, and the resistance and magnetotransport properties were measured using the standard four-probe dc method. All measurements were measured with the field parallel to the film plane.

The hysteresis loops at 10 K of trilayer A, after field-cooling (FC) in 2 kOe and zero-FC (ZFC) and of trilayer B, after FC in 2 kOe, are shown in Fig. 1. It is clear that after FC a step in the third quadrant is found for each trilayer. Moreover, a larger step in the magnetization (M_P) is observed for trilayer A (as the arrow indicates). The difference between the two M_P values is defined as ΔM_P. The inset in Fig. 1 presents the negative-field part of the *M-H* loops recorded at 100 K after FC for the trilayers A and B. No clear step is found for B at 100 K.

The *M-H* loops of the bilayers C, D, E, and F have been recorded at 10 K after FC (Fig. 2). It is found that the coercivity (H_C) and the exchange-bias field (H_E) are different for all of them,[12] which indicates that the sublayer strongly affects the magnetic anisotropy and further influences the in-

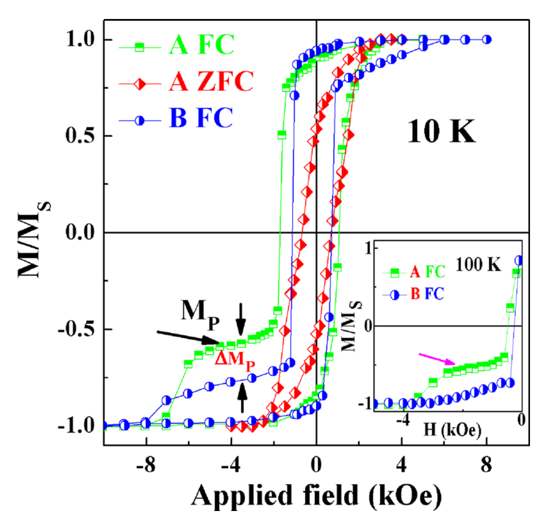

FIG. 1. (Color online) Hysteresis loops at 10 K of the trilayers Co (3 nm)/NiO (6 nm)/Fe (10 nm) (a) after FC in 2 kOe and ZFC and Fe (10 nm)/NiO (6 nm)/Co (3 nm) (b) after FC in 2 kOe. Inset: *M-H* loops in negative field of A and B after FC at 100 K.

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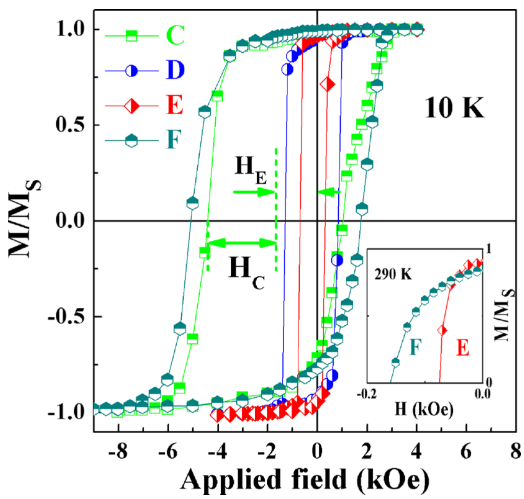

FIG. 2. (Color online) *M-H* loops at 10 K of the bilayers Co (3 nm)/NiO (6 nm) (c), NiO (6 nm)/Fe (10 nm) (d), Fe (10 nm)/NiO (6 nm) (e), and NiO (6 nm)/Co (3 nm) (f) after FC. Inset: *M-H* loops at 290 K in negative field of the bilayers E and F.

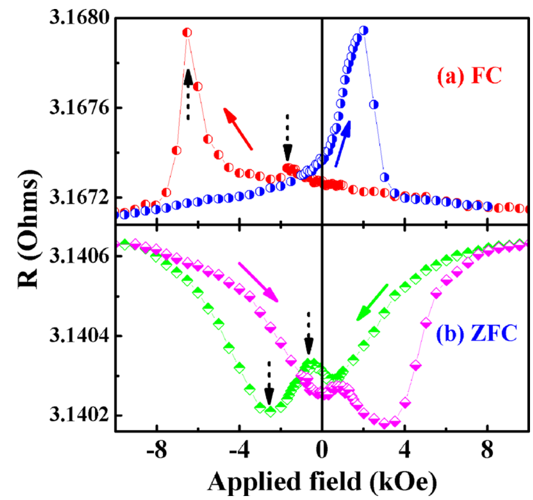

FIG. 4. (Color online) *R-H* curves at 10 K for trilayer A after FC (a) and ZFC (b).

terfacial coupling of the bilayers.[13] At high temperatures, the *M-H* loops of trilayers A and B exhibit good coupling, both when the H_C values of two FM/AF of the trilayers are equal to each other, or when the FM interlayer coupling between two FM layers dominates. To make this clear, the negative-field parts of the *M-H* loops at 290 K of the bilayers E and F are shown in the inset of Fig. 2. The H_C of 0.075 kOe for the former and 0.16 kOe for the latter confirms the domination of interlayer coupling at high temperatures.

To study the temperature dependence of the magnetic properties of the trilayers, the saturation magnetization (M_S) of the trilayers A and B after ZFC are presented in Fig. 3. All M_S values are normalized to the 200 K value for each sample. It is noticed that the variation in M_S with temperature is similar for the two trilayers and that M_S increases from 10 to 200 K and then decreases with further increasing temperature. The inset of the figure shows clearly that ΔM_P increases with increasing temperature from 0.19 at 10 K to 0.42 at 200 K.

To further clarify the relationship between the magnetization orientation of the FM layers and the magnetoresistance (MR), the *R-H* curves of trilayer A recorded after FC and ZFC at 10 K are presented in Figs. 4(a) and 4(b). It is interesting to notice that MR is negative for ZFC but positive for FC, which has been seldom reported previously.[9,10] It indicates that the applied field changes the sign of the FM spin polarization (P) in the trilayers. In Figs. 4(a) and 4(b), the fields corresponding to maximum or minimum R values (indicated by the dashed arrows) are consistent with the moment reversals of Fe and Co in Fig. 1.

The temperature dependence of the magnetotransport properties of bilayer E after ZFC and FC, and trilayers A and B after ZFC is presented in Fig. 5. For convenience, all values of R have been normalized to the value at 295 K. The inset of the figure presents the *R-T* curves of trilayer A after ZFC and FC in fields of 2 and 10 kOe. As can be seen in Fig. 5, the temperature corresponding to the minimum R (T_m) has nearly the same value of about 245 K for the ZFC trilayers A and B, whereas T_m is about 175 K for the ZFC and FC of bilayer E. Furthermore, T_m shifts to lower temperatures in an applied field, as shown in the inset of Fig. 5.

The change in the total energy with changing temperature arises mainly from the interfacial and interlayer ex-

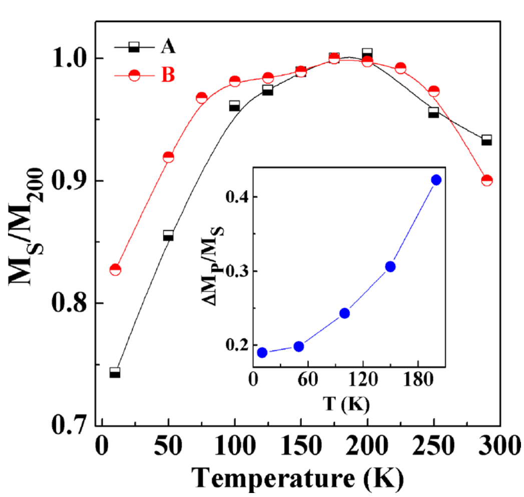

FIG. 3. (Color online) The saturation magnetization M_S normalized to the value at 200 K of the trilayers A and B after ZFC. Inset: The $\Delta M_P/M_S$ vs temperature.

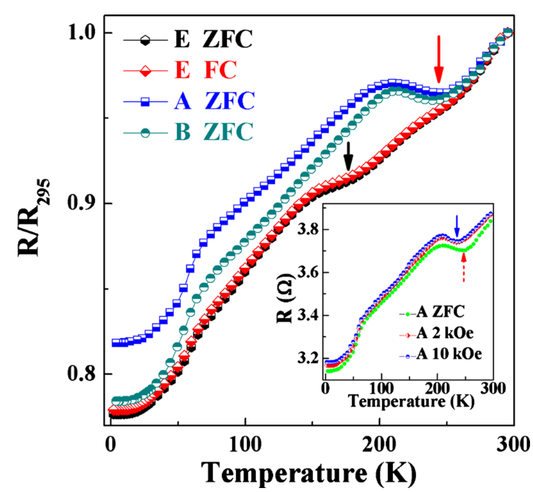

FIG. 5. (Color online) *R-T* curves for the bilayer E after ZFC and FC, and the trilayers A and B after ZFC. Inset: *R-T* curves for trilayer A after ZFC and FC in zero field, and at 2 and 10 kOe.

change coupling in the FM/NiO/FM trilayers.[7] Because they have the same FM and AF layers, the interlayer coupling between the FM layers can be considered to be the same in the trilayers A and B. We now focus on the interfacial coupling in FM and AF layers with changing temperature. The interfacial-coupling energy decreases with increasing temperature.[14,15] The interlayer-coupling strength is given by $J(T) \propto (T/T_0/\sinh(T/T_0))$,[5] and increases with increasing temperature.[9]

At low temperatures, the interfacial coupling is quite strong and the interfacial coupling in the bilayers in Fig. 2 is consistent with that in the trilayers in Fig. 1. The value of M_P of about 0.6 for trilayer A in Fig. 1 indicates antiparallel moments of Fe and Co.[16] However, the larger M_P value for trilayer B in Fig. 1 may be due to a divided Co layer, in which some moments of Co will reverse with reversal of Fe layer at first, while the reversal of the other moments' occurs at a larger field. Furthermore, with increasing temperature, the increase in ΔM_P results from weaker interfacial coupling in B than in A. As the interfacial coupling decreases and the interlayer coupling increases with increasing temperature, the temperature of the maximum of M_S in Fig. 3 corresponds to the balance temperature of the two types couplings.[7]

The experimental results at low bias are generally interpreted in terms of Jullière's expression, $\Delta R/R=(R_{AP}-R_P)/R_{AP}=2P_1P_2/(1+P_1P_2)$, where R_{AP} and R_P are the resistances in the antiparallel and parallel states, respectively, and P_1 and P_2 are spin polarizations of the two electrodes.[17] The change in sign of MR in Fig. 4 after FC is due to the reversal of P in an applied field. Figures 4(a) and 4(b) confirm that P of Co reverses with increasing applied field. Moreover, T_m in Fig. 5 is the T_B of NiO due to the disappearance of exchange bias in trilayers around T_m. The decrease in T_m and nearly no difference of R after ZFC and FC in bilayer E originate from enhancement of T_B of AF by interfacial coupling and from weak interfacial coupling in Fe/NiO, respectively.[16] In addition, the T_B of AF can be greatly affected by an applied field, to shift to low temperature in larger field,[18] and this is why T_m shifts to lower temperature as seen in the inset of Fig. 5. The low-temperature behavior of R can be expressed as $R=R_0+\alpha T^\gamma$, where γ is the exponent parameter[19] and the $R \propto T^3$ may be due to the large amount of disorder in our system.[20]

In summary, different magnetic properties are found for Co/NiO/Fe and Fe/NiO/Co trilayers. The sublayer greatly affects the magnetic anisotropy of bilayers. Furthermore, the change in sign for MR from negative after ZFC to positive after FC is due to the reversal of the Co spin polarization, and the interfacial coupling will enhance T_B of AF material.

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