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High interfacial exchange energy in TbFeCo exchange-bias films

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The exchange-bias films of ferrimagnetic/ferrimagnetic, ferromagnetic/ferromagnetic, and ferromagnetic/antiferromagnetic bilayers were fabricated to investigate their interfacial exchange energy $\Delta\sigma$. $\Delta\sigma$ of TbFeCo bilayers is larger than 5 erg/cm^2 at room temperature. By varying the composition of TbFeCo layers, both positive and negative exchange bias have been observed. A highly uncompensated-spin interface model was proposed to explain the strong exchange interaction in TbFeCo bilayers. Due to the characteristics of highly uncompensated-spin interface at TbFeCo bilayers, the exchange coupling field in TbFeCo bilayers exhibited less dependence on interfacial roughness than that in IrMn/NiFe bilayers. In addition, by adjusting the composition of TbFeCo, the anisotropy of pinning layer can be manipulated and exhibits strong effects on exchange bias of TbFeCo bilayers. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1556932]

Exchange bias (EB) between an antiferromagnet (AFM) and a ferromagnet (FM) was discovered more than 40 yr ago by Meiklejohn and Bean.[1] The simplest model,[1–2] assuming an ideal uncompensated plane at the FM/AFM interface, predicts bias field orders of magnitude larger than those observed. Mauri *et al.*[3] provided an explanation for the reduced bias field by introducing formation of domain walls parallel to the interface. Malozemoff interpreted EB in terms of a random field at the interface which causes the AFM to break up into domains.[4] The experimental correlation between the interfacial uncompensated CoO spins and the exchange field in CoO/NiFe bilayer was demonstrated by Takano.[5]

Except for FM/AFM systems, exchange bias also exists in ferrimagnet (FI)/FI[6] and ferromagnet (FM)/FM bilayer. Amorphous rare earth-transition metal (RE-TM) multilayers, possessing perpendicular anisotropy (K_u), exhibited strong exchange coupling.[7] A micromagnetic analysis,[8] conducting the concept of a Block wall existing at the interface between magnetic layers, has been performed to interpret the strong EB. In this study, we studied the difference of exchange-coupling strength among FI/FI, FM/FM, and FM/AFM bilayers, based on the view of spin–spin coupling at the interface. By exploring the EB dependence on interface roughness, on spin–spin coupling states, and on the K_u of pinning layers, a highly uncompensated spin interface model is proposed to explain the ultrahigh interfacial coupling between perpendicular TbFeCo layers.

Films were deposited by using magnetron sputtering at backing pressure of 3×10^{-7} Torr onto Si or Si/SiO_x substrates. The TbFeCo layers were sandwiched by SiN_x protective layers to prevent oxidation. The composition of TbFeCo films was calibrated by Rutherford backscattering spectrometry. To induced exchange-bias fields, IrMn/NiFe films, were postannealed at 200 °C for 10 min at a field of 1000 Oe. The crystal structure was characterized by x-ray diffraction. To explore the effects of interface roughness on exchange bias, we deposited films on substrates with different roughness. To prepare these substrates, we grew SiO_x of 300 nm on Si wafers by furnace oxidation and then dipped the wafers in the HF solution with distinct concentrations. The roughness of substrates and films was identified with an AFM. The rms roughness of substrates varied from 0.3 to 1.5 nm, and the wavelength changed from 18 to 39 nm. A vibrating sample magnetometer (VSM) and Kerr-effect tracer were used for measuring the magnetic properties. In addition, the K_u of single-layer TbFeCo was derived from the measurement of Hall effect with in-plane external field.[9]

Ultrastrong exchange coupling was found in amorphous TbFeCo bilayers with perpendicular K_u. Figures 1(a) and 1(b) show the minor hysteresis loops of TbFeCo bilayers with different compositions of pinning layer by applying the field in the out-of-plane direction. The layer with the composition of $Tb_{16.2}(Fe_{80}Co_{20})_{83.8}$ can be considered to be a pinned layer because of its lower coercivity than the other. The interfacial exchange energy ($\Delta\sigma$) of the TbFeCo bilayers is derived from $\Delta\sigma = H_b M_s t$, where H_b, M_s, and t are the biasing field, saturation magnetization, and thickness of pinned layer $Tb_{16.2}(Fe_{80}Co_{20})_{83.8}$. The $\Delta\sigma$ is typically calculated by the slope of H_b versus $(1/t_F)$ in FM/AFM bilayers; however, the saturation magnetization and the anisotropy constant of TbFeCo vary with film thickness,[10] so $\Delta\sigma$ of TbFeCo bilayers can only be estimated at the specific thickness. $\Delta\sigma$ of the TbFeCo bilayer estimated from Fig. 1(a), is about 5.3 erg/cm^2, which is 1 or 2 orders of magnitude higher than that in the FM/AFM systems. In addition, the EB field of TbFeCo bilayers shifted from the negative to the positive as the Tb content of the pinning layer varied from 22.1% to 27.5%, as shown in Fig. 1(b). Because of the antiferromagnetic coupling of spins between Tb and Fe(Co), the

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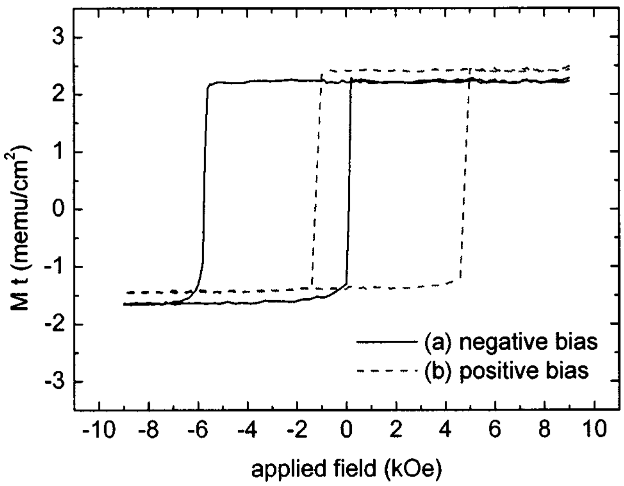

FIG. 1. Minor loops of the TbFeCo bilayers with a pinning layer $Tb_x(Fe_{80}Co_{20})_{100-x}$ (200 nm)/a pinned layer $Tb_{16.2}(Fe_{80}Co_{20})_{83.8}$ (100 nm): (a) $x=22.1$, negative bias and (b) $x=27.5$, positive bias.

net magnetization of TbFeCo is the difference of the two sublattices. As the TM (RE) magnetization is dominant, called TM rich (RE rich), the direction of TM (RE) magnetization determines the direction of the net magnetization. The double-layer films are of the antiparallel type (*A* type)[10] if one layer is TM rich and the other is RE rich. On the other hand, the parallel type (*P* type) bilayer is composed of two layers of the same dominated sublattices. The bilayer in Fig. 1(a) belongs to the *P* type because the two layers are both TM rich. For *P* type bilayers, the magnetization at the interface is parallel, which gives a negative bias. As Tb content increases to 27.5%, the pinning layer changes into RE rich, leading to an *A* type configuration. Figure 2 depicts the magnetization states of the *A*-type TbFeCo bilayers at positive saturation field. A Block wall was formed at the interface of the *A*-type bilayers at the positive saturation field, resulting from the opposite direction of RE–RE and TM–TM spins between two layers. It leads to a positive hysteresis-loop shift of the pinned layer, seldom observed in FM/AFM systems.

A highly uncompensated spin interface is proposed to explain the strong EB in TbFeCo bilayer systems. At the interface of TbFeCo bilayers, the adjacent spins of the same atoms, Tb–Tb and Fe(Co)–Fe(Co), are ferromagnetically

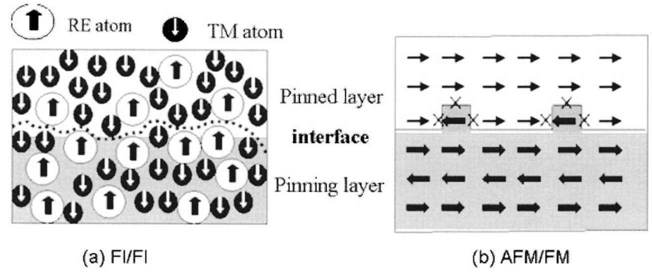

FIG. 3. Schematic diagrams of spin–spin coupling states at the interface of: (a) FI/FI and (b) AFM/FM bilayers.

coupled, and AF coupling only occurs between heterogeneous atoms, as shown in Fig. 3(a). Importantly, no spin compensation occurs between magnetic atoms, leading to high $\Delta\sigma$. In FM/AFM systems such as IrMn/NiFe, adjacent Mn–Mn spins in the IrMn layer prefer AF coupling, resulting in compensated spins at the interface due to roughness or defects, as shown in Fig. 3(b), and low $\Delta\sigma$. To explore the importance of uncompensated spin interface on EB strength, we studied the (111) texture IrMn/NiFe and SmCo/NiFe (FM/FM) exchange-bias films, with in-plane anisotropy, for comparison. The $\Delta\sigma$ values of the bilayer films were derived from VSM measurement by applying the in-plane field. The maximum $\Delta\sigma$ of the NiFe/IrMn bilayer in our experiments is 0.10 erg/cm^2 by varying interface roughness and enhancing the (111) texture. Generally, a single hysteresis loop was observed in the bilayers of hard FM/soft FM. As shown in Fig. 4, double loops were observed in SmCo 100 nm/NiFe 200 nm because of the satisfaction of $\Delta\sigma(1/M_h t_h + 1/M_s t_s) > Hc_h - Hc_s$, where *h* and *s* denote the hard and soft FM layers. Unlike the antiferromagnetic coupling in IrMn, the coupling between spins of Sm–Sm, Co–Co, and Sm–Co in SmCo prefers the ferromagnetic one, leading to an uncompensated spin interface in SmCo/NiFe systems. Thus, the strong exchange interaction exists between SmCo and NiFe layers, and $\Delta\sigma$ of 0.44 erg/cm^2 was obtained, several factors of magnitude higher than that in IrMn/NiFe. Since SmCo possess low in-plane K_u and the moments do not strictly lie in the film plane, the spin–spin coupling is reduced at the interface, which causes lower $\Delta\sigma$ than that in TbFeCo bilayers.

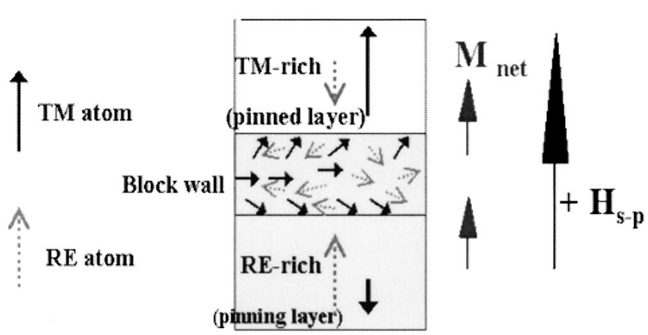

FIG. 2. Magnetization states of the *A*-type TbFeCo bilayers under a saturation field of the pinning layers.

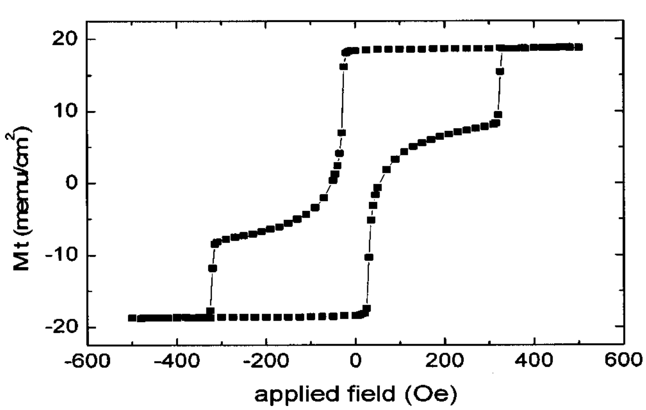

FIG. 4. Hysteresis loop of SmCo 100 nm/NiFe 200 nm in easy axis.

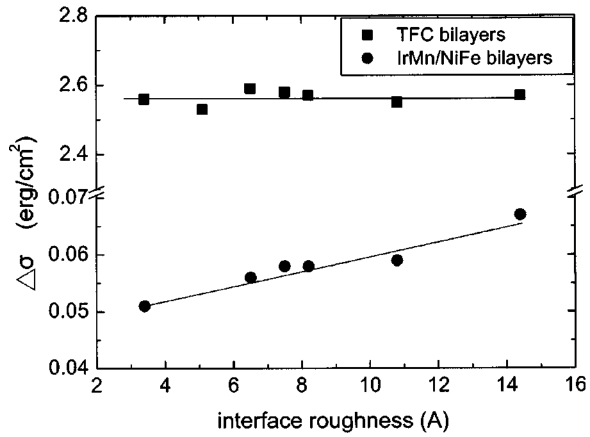

FIG. 5. Roughness dependence on $\Delta\sigma$ of the bilayers of $Tb_{26.1}(Fe_{80}Co_{20})_{73.9}$ (20 nm)/$Tb_{16.2}(Fe_{80}Co_{20})_{83.7}$ (20 nm) and IrMn (9 nm)/NiFe (20 nm). Notice that the wavelength of the roughness also varies from 18 to 39 nm with increasing rms roughness.

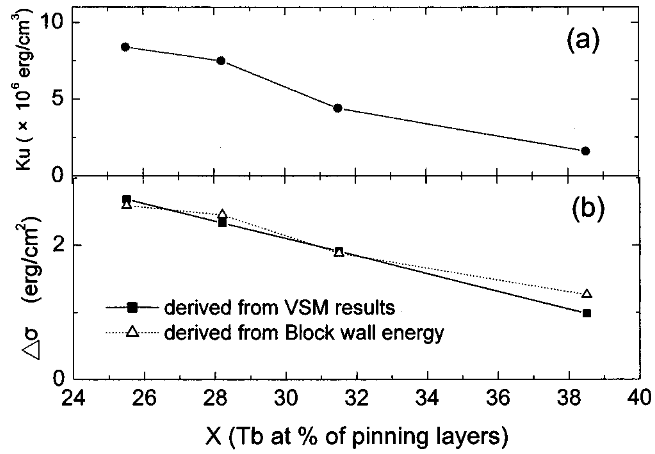

FIG. 6. (a) Variation of K_u of TbFeCo single layer with Tb content and (b) dependence of $\Delta\sigma$ and the Block wall energy E_b on Tb content of pinning layer in TbFeCo bilayers.

To further illustrate the difference of spin compensation between TbFeCo bilayers and IrMn/NiFe, we investigate the roughness dependence on EB. TbFeCo bilayers and IrMn/NiFe films were deposited on the substrates with varied rms roughness. Figure 5 shows EB dependence of TbFeCo bilayers and IrMn/NiFe films upon rms roughness. Notice that the wavelength of the roughness also varies from 18 to 39 nm with increasing rms roughness. Even though the rms roughness varies from 0.34 to 1.55 nm, $\Delta\sigma$ in TbFeCo bilayers almost remains constant. However, $\Delta\sigma$ of IrMn/NiFe exhibits a strong function of rms roughness and wavelength, that is, the $\Delta\sigma$ depends on the interfacial morphology. As mentioned above, the adjacent spins of the same atoms are ferromagnetically coupled and AF coupling occurs between heterogonous atoms in TbFeCo bilayers. The magnetic interface, which is associated with spin–spin coupling of the TbFeCo bilayer, is continuous and homogeneous no matter how the interface morphology or roughness changes. In contrast, the amount of uncompensated spin pairs in FM/AFM systems changes with interface morphology, implying that exchange coupling depends strongly upon the rms roughness and the wavelength. Based on these experiment results, we suggest that the enhancement of EB in FM/AFM may be attributed to increasing the amount of uncompensated spins at the interface of FM/AFM by adjusting the interfacial roughness and wavelength.

In addition to spin compensation, the anisotropy of the pinning layer plays an important role for EB. Unfortunately, in typical FM/AFM systems, the anisotropy K_u of AFM is hard to measure and manipulate. In the TbFeCo system, the K_u can be easily varied by composition, which enables us to study the effects of K_u on EB. We adjusted the composition of TbFeCo layers, and investigated the K_u dependence of pinning layers on EB. We fabricated the EB bilayers with the structure of the pinning layer $Tb_x(Fe_{80}Co_{20})_{(100-x)}$ 20 nm/pinned layer $Tb_{16.2}(Fe_{80}Co_{20})_{83.8}$ 20 nm, where x varied from 25.5 to 38.5. Figure 6(a) shows the K_u of the single TbFeCo layer with different composition. The pinned layer of $Tb_{16.2}(Fe_{80}Co_{20})_{83.8}$ possesses higher K_u than pinning layers. $\Delta\sigma$ of TbFeCo bilayers decreases with increasing Tb content of pinning layers, as indicated in Fig. 6(b). Based on the concept of Block-wall formation in FI/FI bilayer, the theoretical values of $\Delta\sigma$ can be expressed by[11,12] $\Delta\sigma = H_b M t = \sigma_w/2 = 2(A\times K_u)^{1/2}$, where A and σ_w denote exchange stiffness and Block-wall energy, respectively. By assuming a typical value of $A(2.0\times10^{-7}$ erg/cm) and substituting the K_u value into the above equation, we can derive the theoretical $\Delta\sigma$, which agrees approximately with the experimental value. This consistency implies that the Block wall was formed, similar to the AF domain wall model of Mauri *et al.*, in FM/AFM systems.[3]

In summary, we have demonstrated high interfacial exchange energy (>5 erg/cm^2) in TbFeCo bilayers. A highly uncompensated spin interface is proposed to explain the strong EB in TbFeCo bilayer systems. IrMn/NiFe exhibited weaker EB than SmCo/NiFe due to the AF coupling between the adjacent Mn–Mn atoms, verifying the importance of an uncompensated spin interface to EB. By adjusting the composition of TbFeCo films, we further demonstrated that the high K_u of the pinning layer significantly enhances the $\Delta\sigma$.

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