Dependence of exchange coupling on antiferromagnetic layer thickness in NiFe/CoO bilayers

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A systematic study of the dependence of exchange coupling in NiFe/CoO bilayers on CoO layer thickness t_{AF} from 5 to 500 Å has been made. For large CoO thicknesses ($t_{AF}>100$ Å), the exchange field varies as $1/t_{AF}$, whereas for small CoO thicknesses ($t_{AF}<100$ Å), finite-size scaling of the Néel temperature T_N and also the blocking temperature T_B dominate. [S0021-8979(98)52811-3]

The exchange coupling between a ferromagnet (FM) and an antiferromagnet (AF) displays a rich variety of phenomena.[1] When a FM/AF bilayer thin film is field cooled across the AF Néel temperature (T_N), the hysteresis loop of the FM is now shifted or biased away from the origin. This shift, known as the exchange field (H_E), can be several hundreds Oe in size. The AF must possess sufficient anisotropy to withstand switching of the FM magnetization. The exchange field decreases with temperature and vanishes a temperature termed the blocking temperature T_B, which is less than T_N of the AF layer. The anisotropy of the AF must decrease to zero at T_N. Near and below T_N, the anisotropy of the AF eventually becomes too weak to maintain its spin structure during the hysteresis cycle resulting in no exchange field.

Exchange biasing is important for applications in the spin-valve devices,[2] although the origin of this coupling remains unclear. Some of the important questions concerning exchange biasing include the relative spin orientation of the FM and AF layers, and the interaction between them. It has been well established that H_E varies inversely with the FM layer thickness.[3,4] This demonstrates that the exchange coupling is transmitted across the FM/AF interface. It has been widely assumed that this exchange coupling is a short-range interaction occurring only at the interface, although some new results suggest otherwise.[5] In this work, we address the dependence of exchange bias on the AF layer thickness.

There have been previous studies on the effect of the AF layer thickness on the exchange coupling strength in NiFe/FeMn[6,7] in NiFe/NiO[8] and in CoO/NiFe[9] bilayers. In these works, both the exchange fields and blocking temperatures were observed to correlate with the AF layer thickness in some manner. Unfortunately, most of these measurements were not made at sufficiently low temperature to conclusively determine the dependence on the AF layer thickness. Recently, a study of the AF layer thickness dependence on H_E was made in Fe_3O_4/CoO bilayers,[10] where the exchange field was measured to low temperatures. With the few samples, the values of H_E and the blocking temperature were observed to scale with the CoO thickness, but a clear relationship between the exchange field and the AF layer thickness was not determined.

In this work, we have determined the relationship between the AF layer thickness and the exchange bias using NiFe/CoO bilayers with a fixed NiFe layer and various CoO thicknesses from 5 to 500 Å. There are two qualitatively different behaviors of the dependence on the AF layer thickness t_{AF}. For $t_{AF}>100$ Å, where T_N remains unchanged, H_E is found to vary as $1/t_{AF}$. For $t_{AF}<100$ Å, the effect is due to finite-size scaling of T_N of very thin layers, and the results are in good agreement with the susceptibility measurements using CoO/SiO_2 multilayers.[11]

To examine the AF layer thickness dependence on the exchange field, the NiFe/CoO system was chosen, involving a well-known AF insulator CoO with $T_N=292$ K and permalloy ($NiFe=Ni_{81}Fe_{19}$) useful for many device applications. To carefully examine the AF layer thickness dependence, the bilayers in this study were taken from one large sample of a 300 Å film of NiFe grown on a wedge layer (5–500 Å) of CoO, which was grown on 300 Å Cu. The CoO wedge film allows many samples that were fabricated at the same time and under the same deposition conditions with CoO thickness being the only parameter. The NiFe was deposited in a magnetic field to induce an uniaxial anisotropy. We used the geometry of FM layer grown on top of the AF layer, so that the exchange field would saturate at low temperatures to reveal its dependence on the AF layer thickness.[12]

In Fig. 1(a), the temperature dependence of the exchange field of some representative samples with varying CoO layer thickness from 75 to 457 Å are shown. As expected, a plateau in the exchange field is observed at low temperatures whose value is intrinsic, for this bilayer geometry, to a specific AF layer thickness. The results for $t_{AF}>100$ Å clearly show an increase in the exchange field as the CoO thickness is reduced. The values of H_E vanish essentially at 291 K, the Néel temperature of bulk CoO. As shown in Fig. 1(b), the coercivity (H_C) has a quasilinear temperature dependence, decreasing to the intrinsic H_C of permalloy at approximately 291 K. The exchange fields at low temperatures, represented by the values at 80 K are shown as a function of the CoO layer thickness in Fig. 2. The results can be best described by $1/t_{AF}$ shown as the dashed curve. It should be noted that this relation holds only at low temperature where H_E is not temperature dependent. At a high temperature, where H_E has a strong temperature dependence, the H_E values do not give

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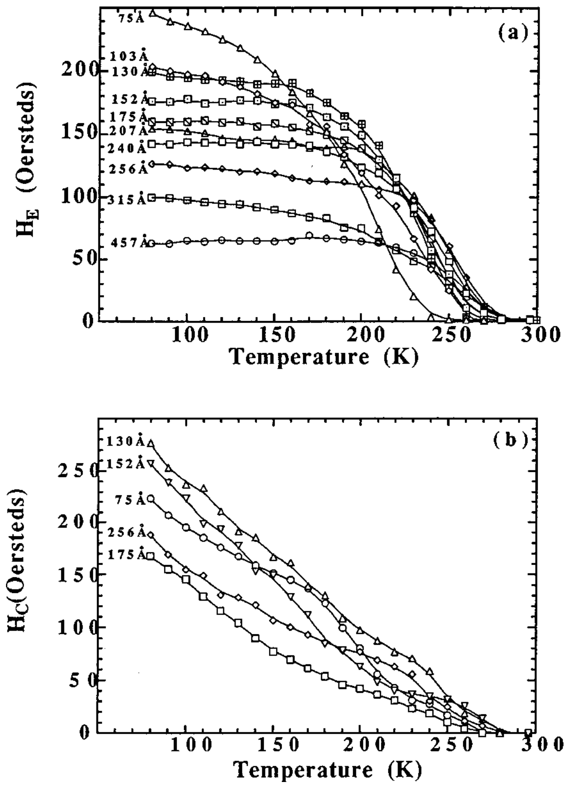

FIG. 1. Temperature dependence of (a) exchange field H_E and (b) coercivity H_c of representative samples of 300 Å NiFe/x Å CoO/300 Å Cu with CoO thickness from 75 to 457 Å.

meaningful thickness dependence. For example, if one uses the exchange field values at 250 K, one would give a totally different thickness dependence from that at 80 K, as shown in Fig. 2. These results clearly demonstrate the dependence of exchange coupling on t_{AF} in the thickness range of $t_{AF} > 100$ Å, where T_N remains unchanged.

The results in Fig. 2 are rather unexpected and significant because it illustrates that the exchange coupling in a FM/AF bilayer involves more than just the interfacial spins in the FM and AF layers. To elaborate the argument, consider the ideal interface model as originally suggested by

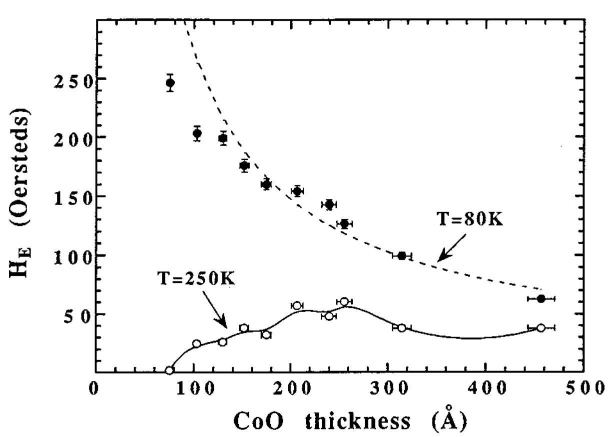

FIG. 2. The values of exchange field H_E measured at 80 and 250 K for 300 Å NiFe/x Å CoO/300 Å Cu as a function of the CoO layer thickness. The dashed line for the data at 80 K is $1/t_{AF}$.

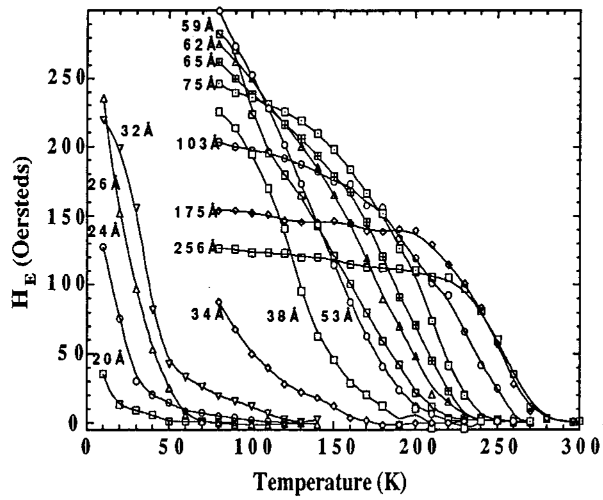

FIG. 3. Temperature dependence of exchange field H_E of 300 Å NiFe/x Å CoO/300 Å Cu with CoO thickness from 20 to 256 Å.

Meiklejohn and Bean,[1] where the exchange coupling between neighboring spins at the FM/AF interface produces an exchange field of the form

$$H_E = \frac{nJS_{AF} \cdot S_{FM}}{M_{FM} t_{FM}}, \quad (1)$$

where S_{FM} and S_{AF} are the spins of the magnetic moments in the FM and AF layers at the interface, M_{FM} and t_{FM} are the magnetization and layer thickness of the FM, respectively, J is the spin-spin interaction strength between S_{FM} and S_{AF} and n is the number of interactions per unit area with strength J. Since only the interfacial FM and AF spins are assumed to be involved, the thickness of the AF layer does not appear at all. The very fact that H_E has a $1/t_{AF}$ dependence indicates that this simple model and Eq. (1) require modifications. The spin structure and the domain walls of the AF layer ultimately influence the exchange field as suggested by the recent micromagnetics calculations by Malozemoff,[13] Mauri,[14] and Koon.[15]

In Fig. 2, the values of H_E for AF layers smaller than 100 Å have not been included because these results are qualitatively different from those of the thicker layers, and also that their H_E values do not saturate at 80 K. These features are illustrated in Fig. 3 for CoO thicknesses spanning from 10 to 256 Å. While the blocking temperature T_B of samples with $t_{AF} > 100$ Å remains at the bulk value, T_B of the thinner samples progressively decreases with t_{AF}. As the layer thickness is reduced below 100 Å, one observes finite-size effects of T_N,[10,11] which is followed by T_B. It is interesting to compare the finite-size effects of T_B measured from exchange bias in NiFe/CoO bilayers, and the finite-size effects of T_N measured from dc susceptibility measurements using CoO/SiO_2 multilayers. In Fig. 4 the blocking temperatures T_B (solid squares) obtained from the exchange field temperature dependence in Fig. 3 are compared with the Néel temperatures T_N measured by susceptibility in CoO/SiO_2 multilayers.[11] Both sets of data are in excellent agreement. At each thickness, the blocking temperature T_B is slightly

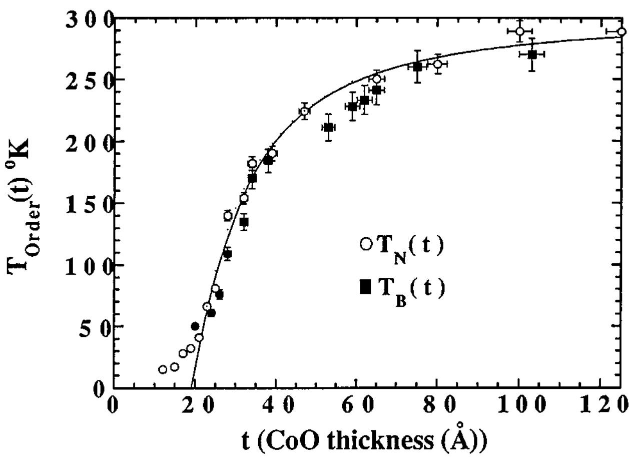

FIG. 4. Blocking temperature T_B (solid squares) of 300 Å NiFe/*x* Å CoO/300 Å Cu and Néel temperature T_N (open circles) of CoO/SiO_2 multilayers, as a function of the CoO layer thickness. The solid line is the finite-size scaling relation taken from Ref. 11.

below T_N. This comparison also shows that the dependence of exchange bias in the thickness range of $t_{AF}<100$ Å is largely effected by finite-size scaling of the AF Néel temperature.

To summarize, we have observed dependence of exchange bias on the antiferromagnetic layer thickness t_{AF}. For small values of t_{AF} (<100 Å), this is mainly caused by the finite-size scaling of T_N, whose value always lies slightly higher than that of the blocking temperature T_B. For larger values of t_{AF} (>100 Å), the exchange field has been shown to scale inversely with t_{AF}. This suggests that the simple picture of interfacial coupling between the FM and AF spins be modified to include the spin structure and the domain structure within the AF layer.

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