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 \( t_{\text{AF}} \) from 5 to 500 Å has been made. For large CoO thicknesses \( (t_{\text{AF}}>100 \text{ Å}) \), the exchange field varies as \( 1/t_{\text{AF}} \), whereas for small CoO thicknesses \( (t_{\text{AF}}<100 \text{ Å}) \), finite-size scaling of the Néel temperature \( T_N \) and also the blocking temperature \( T_B \) dominate.

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 \( t_{\text{AF}} \). For \( t_{\text{AF}}>100 \text{ Å} \), where \( T_N \) remains unchanged, \( H_E \) is found to vary as \( 1/t_{\text{AF}} \). For \( t_{\text{AF}}<100 \text{ Å} \), 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/SiO₂ multilayers.

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 \( T_N=292 \text{ K} \) and permalloy (Ni₈₁Fe₁₉) 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.

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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 \( t_{\text{AF}}>100 \text{ Å} \) 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 \( 1/t_{\text{AF}} \) 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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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 $t_{\text{AF}}$ in the thickness range of $t_{\text{AF}} > 100$ 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 Meiklejohn and Bean,\textsuperscript{1} where the exchange coupling between neighboring spins at the FM/AF interface produces an exchange field of the form

$$H_E = \frac{nJS_{\text{AF}}S_{\text{FM}}}{M_{\text{FM}}t_{\text{FM}}}.$$

where $S_{\text{FM}}$ and $S_{\text{AF}}$ are the spins of the magnetic moments in the FM and AF layers at the interface, $M_{\text{FM}}$ and $t_{\text{FM}}$ are the magnetization and layer thickness of the FM, respectively, $J$ is the spin-spin interaction strength between $S_{\text{FM}}$ and $S_{\text{AF}}$ 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 $1/t_{\text{AF}}$ 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,\textsuperscript{13} Mauri,\textsuperscript{14} and Koon.\textsuperscript{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 $t_{\text{AF}} > 100$ Å remains at the bulk value, $T_B$ of the thinner samples progressively decreases with $t_{\text{AF}}$. As the layer thickness is reduced below 100 Å, one observes finite-size effects of $T_N$.\textsuperscript{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\textsubscript{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\textsubscript{2} multilayers.\textsuperscript{11} Both sets of data are in excellent agreement. At each thickness, the blocking temperature $T_B$ is slightly
below \( T_N \). This comparison also shows that the dependence of exchange bias in the thickness range of \( t_{AF} < 100 \, \text{Å} \) 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 \( t_{AF} \), 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 \( t_{AF} \), 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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