

## Temperature dependence of exchange biased thin films

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A thin ferromagnet exchange coupled to an antiferromagnet often results in an enhanced width and a shift in the center position for the hysteresis curve. Recent calculations have shown how these features could occur in for both compensated and uncompensated antiferromagnet interfaces. These calculations were performed at zero temperature. We explore a model which allows for imperfectly compensated interfaces due to interface roughness and which calculates the spin configurations and hysteresis curves as a function of temperature. We find that the Koon results—ferromagnet spins directed perpendicular to the antiferromagnet spins—is appropriate for low temperature and nearly compensated interfaces. Increasing temperature and noncompensation favors a configuration where the ferromagnetic spins line up closer to the easy axis of the antiferromagnet. A particularly interesting result is that the coercive field decreases much more rapidly than the bias field as temperature is increased. This is in agreement with some recent experimental results, and we speculate that the exchange bias is substantially due to the surface structure of the antiferromagnet while the coercive field depends on the behavior of the spins in the bulk of the antiferromagnet.

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When a thin ferromagnet is exchange coupled to an antiferromagnet, the bilayer can have a hysteresis curve characterized by an increased coercivity, and a shift in the hysteresis curve, known as exchange biasing. The phenomenon has been of interest, partly because of the possible technological applications. Although this effect was first observed over 40 years ago, modeling the effect has proven to be problematic.<sup>1-8</sup> Most of the research has focused on the unidirectional bias field, with less attention paid to the coercivity. While one recent model<sup>4</sup> has found that a spin flop coupling scheme<sup>4,9</sup> could be responsible for the exchange biasing even with a compensated antiferromagnetic surface, other works indicate that some interfacial magnetization is needed for biasing.<sup>5,6,8</sup> The origin of enhanced coercivity has also been discussed recently in the literature.<sup>5-7</sup>

In this paper we investigate theoretically the temperature dependence of exchange biasing. We find, that the bias and coercive fields have qualitatively different thermal behaviors, suggesting separate mechanisms.<sup>5-8</sup> We also show that the orientation of the sample in the hysteresis field is important in determining the characteristics of the hysteresis curve. Both of these results are in good qualitative agreement with recent experiments.<sup>10,11</sup>

We use dynamic calculations<sup>6</sup> to calculate the behavior of a thin film ferromagnet/antiferromagnet bilayer in an external field. Our geometry is the body-centered structure used by Koon.<sup>4</sup> Interface roughness is simulated by introducing some uncompensation in terms of the interface bonds. At the interface, a spin in the ferromagnet, an **a** spin, is assigned an effective number of neighbors of antiferromagnet spins, types **b** and **c**, that it sees. For our geometry this is two **b**

spins and two **c** spins. In order to effect roughness, an asymmetry is introduced into the number of neighbors of a representative spin in the ferromagnet. This effectively weakens or strengthens one of the sublattice types, introducing a net magnetic moment to the top layer of the antiferromagnet.

The temperature dependence is calculated by using the Brillouin function to find the thermally averaged magnetic moments:

$$\frac{m}{m_0} = B\left(\frac{\vec{m}_0 \cdot \vec{H}_{\text{eff}}}{kT}\right),$$

where  $H_{\text{eff}}$  is the local effective field at a particular site, found using the thermalized magnetic moments of the neighboring spins,  $m_0$  is the zero temperature magnetic moment, and  $m$  is the thermally averaged size of the magnetic moment.

Our parameters are the same as those in Ref 6. We take a system with 20 ferromagnetic layers, 30 antiferromagnetic layers and the exchange coupling in the ferromagnet is about 14 times stronger than that of the antiferromagnet. The interface exchange coupling is equal to the exchange coupling in the antiferromagnet. The degree of noncompensation is 2 percent, and the angle of the applied field with respect to the easy axis is 80°. With our parameters, the Néel temperature of the bulk antiferromagnet is about 230 K.

We first examine the magnetic structure as a function of temperature. For a perfectly compensated antiferromagnetic surface, the magnetization in the ferromagnet (at zero field) will point perpendicular to the easy axis in the antiferromagnet. If the coupling between the ferromagnet and the antiferromagnet is antiferromagnetic in sign, the structure corresponds to a surface spin flop in the antiferromagnet, with the ferromagnet pointing opposite to the net moment produced

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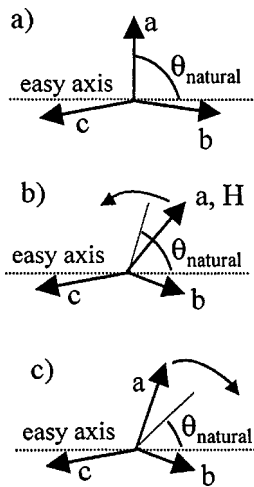


FIG. 1. Schematic structure of the interface spins as seen from above. The natural angle (zero applied field) is shown for three cases. (a) shows the perfectly compensated case. (b) and (c) have some interface roughness reducing the effective **b** spin and causing a change in the natural angle. The direction of rotation is determined by the positioning of the applied field, as seen in (b) and (c).

in the antiferromagnet. This is illustrated in Fig. 1(a). The ‘‘natural angle’’ in this case, the angle of the ferromagnetic magnetization at zero field, is  $90^\circ$ . If an asymmetry in the balance of **b** spins and **c** spins at the surface of the antiferromagnet is introduced, this natural angle is skewed in the direction of the weaker spin as shown in Fig. 1(b).

The spin configurations obviously will change throughout the hysteresis loop. The relative orientation of the external field and the natural angle determines the direction in which the ferromagnetic spins rotate as the magnetic field is reversed. There are two cases to consider, shown in Figs. 1(b) and 1(c). In the first, the external field is above the natural angle, and the spins move away from the easy axis, rotating through their natural angle on the way to the negative direction. As the ferromagnetic moment rotates, there is first a build-up of twist in the antiferromagnet and then a discontinuous jump to a new configuration at a lower energy state, the second spin flop state described earlier. As the external field is increased, the ferromagnetic moment then continues to rotate in the same direction to complete the hysteresis loop.

In Fig. 1(c), the natural angle is between the external field angle and the anisotropy axis. Now the ferromagnetic moment will head towards the easy axis, and there is again a build-up of a twist in the antiferromagnet with a jump to a new configuration. However, in this case the moment reverses its direction of rotation as it completes the hysteresis loop. Nonetheless the ferromagnet magnetization does not simply retrace its motion, as the spins have jumped into the lower energy state, creating an irreversible curve.

In this context the exchange biasing is seen to result directly from the interface roughness. In both cases the **c** sublattice of the antiferromagnet is the stronger of the two, causing a resistance to the rotation of the ferromagnetic moment as the external field moves into negative values. The return trip, on the other hand, is facilitated by the presence of the stronger **c** spins close to the ferromagnet. The **a** spins are

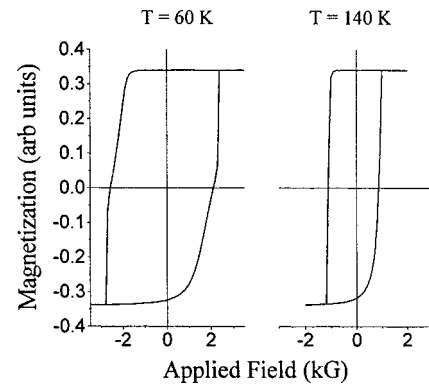


FIG. 2. Hysteresis curves at two different temperatures with two different directions of rotation. In (a) the natural angle is above the applied field [as in Fig. 1(b)]. In (b), the curve is more asymmetric, as the natural angle has dropped below that of the applied field as in Fig. 1(c).

effectively ‘‘pushed’’ by the **c** spins, returning more readily to their original quadrant. Hence, the coercivity at negative field values is larger than at positive values, i.e., the system is exchange biased. Further evidence for this is seen in the fact that positioning the external field initially in the same quadrant as the stronger **c** spins results in a positive exchange bias.

We now consider how the natural angle and temperature influence the hysteresis curves, illustrated in Fig. 2. As we will see, the natural angle decreases as the temperature increases. At  $T = 60\text{ K}$  the natural angle is at  $\theta = 82.05^\circ$ , above that of the external field at  $\theta_H = 80^\circ$ , as in Fig. 1(b). The resulting curves are large and blocky as seen in Fig. 2(a). The field is close to the natural angle, reinforcing the tendency of the spins to remain in the original configuration, resulting in a larger coercivity. The blockiness comes from the abruptness of the drop to the lower energy state.

In the second case, illustrated in Fig. 2(b), the temperature has been increased and the natural angle is now  $\theta = 78.85^\circ$ . The hysteresis loop is now much more asymmetric. In this case, the ferromagnet spins cross over the easy axis on the way down during the hysteresis loop as in Fig. 1(c), and then the system jumps to the lower energy state. On the return trip the spins see a qualitatively different environment, resulting in the asymmetry seen in the hysteresis loop.

The above shows that the natural angle of the system is an important indicator of the behavior of the system. If there is any amount of uncompensation at the surface, this natural angle drops as the temperature increases, approaching the easy axis, as shown in Fig. 3. This can result in a switch from case 1(b) to case 1(c). As a result we expect that low temperature hysteresis loops performed on smooth interfaces should show a qualitatively different form than those performed at higher temperatures or on samples with large amounts of interface roughness.

The reason for the reduction of the natural angle as a function of temperature is simple. At low temperatures the degree of noncompensation is small. Still, the ferromagnet is oriented closer to the ‘‘weaker’’ spins of the **b** sublattice. With antiferromagnetic interfacial coupling, this means that the total effective field on the **b** sublattice is smaller than the effective field on the **c** sublattice. This reduced effective field

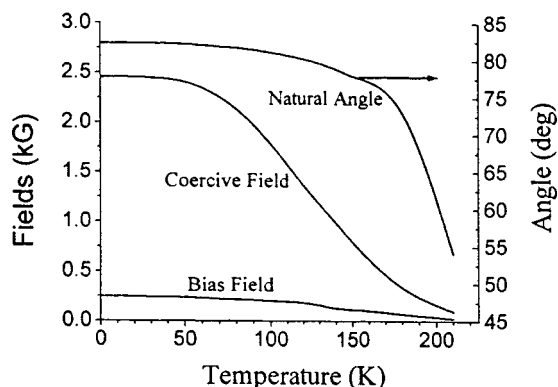


FIG. 3. The natural angle, coercive field and exchange bias field as functions of temperature. Note that the coercive field changes much more rapidly with temperature than the bias field.

means that the **b** sublattice spins at the interface are less stable against thermal fluctuations. Thus as temperature increases the thermal magnitudes of the **b** sublattice spins decrease faster than those for the **c** sublattice, effectively increasing the degree of noncompensation, and the natural angle is reduced.

We also plot the coercive field and bias field as a function of temperature in Fig. 3. These parameters are extracted from a series of hysteresis curves at different temperatures. It is apparent that the coercive field and the biasing field have substantially different temperature dependences. Furthermore, this result is surprisingly indifferent to parameters such as the interface coupling, or coupling within the antiferromagnet. This reinforces the idea that the coercivity and the bias are distinct phenomena.<sup>5-7</sup>

The calculations above are all done for a one-dimensional model where roughness is simulated as described above. We have also considered a two-dimensional system<sup>12</sup> where interface roughness is achieved by putting an actual step into the interface. Both models agree on the qualitative features of the results. The two-dimensional case, however, has an additional feature not seen in the simpler model, which is worth noting here. The natural angle of the ferromagnet, a critical parameter for the system, depends strongly on the size of the exchange coupling within the ferromagnet.

Strong ferromagnetic coupling reduces the natural angle, with the same results discussed earlier.

We comment now, briefly, on some consequences of our assumptions. Since we use a mean-field calculation, fluctuations are neglected. One might expect that these fluctuations would lead to the instability at lower magnetic fields thus reducing the coercivity. In addition we use a coherent rotation model to describe the spin reversal. Other mechanisms, such as domain wall motion and nucleation sites, are likely to be important in some systems,<sup>13</sup> but are not included here. Again one might expect that these mechanisms might reduce the coercivity from the values found here. Nonetheless, the general features found in our calculations do seem to match with the results of some recent experiments.<sup>14</sup>

In summary, we have studied the temperature dependence of exchange biasing in thin film ferromagnet/antiferromagnet bilayers. Our results support the recent speculations that the spin flop coupling is responsible for the heightened coercivity in the bilayer, while it is interface roughness that brings about the unidirectional bias.

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