Temperature dependence of domain-wall bias and coercivity

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Some models for exchange bias at the interface of a ferromagnet and antiferromagnet involve the formation of partial domain walls in the antiferromagnet layer. Numerical calculations of mean-field temperature dependence are used to examine thermally induced instabilities in the partial domain wall at ideal compensated and uncompensated antiferromagnet interfaces. At compensated interfaces, depinning of the partial wall results in a total loss of bias. At uncompensated interfaces, thermal effects at the interface cause the wall to move into the antiferromagnet. The critical fields for this partial depinning are different for the forward and reverse magnetization directions. This mechanism on uncompensated interfaces allows for simultaneous loop shift and coercivity, which is not found in the compensated case.
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I. INTRODUCTION

Several mechanisms of exchange bias have been proposed to explain the experimentally observed bias and coercive fields of exchange coupled ferromagnet/antiferromagnet systems since the original work by Meiklejohn and Bean.[1] Exchange bias can be described by a displacement of a hysteresis loop along the field axis by $H_E \propto J_I / M_f t_f$ where J_I is the interlayer exchange between the ferromagnet and antiferromagnet, M_f is the saturation magnetization of the ferromagnet, and t_f is the thickness of the ferromagnet. The bias field is measured by taking the midpoint of the two loop intercepts on the field axis. Likewise, the coercivity is measured as half the absolute width of the hysteresis loop at the field axis.

The earliest models tended to overestimate the bias field for reasonable values of J_I. Modified mechanisms have been proposed requiring partial domain wall formation near the interface. These models apply to ideal uncompensated[2] and compensated[3] interfaces, with differences appearing in the angular dependence of H_E and spin canting the compensated interface. Domain-wall bias emphasizes a balance between an applied field H_a and wall energy $\sigma = 2\sqrt{A_{af} K_u}$, where A_{af} and K_u are the exchange spring and uniaxial magnetocrystalline anisotropy energies, respectively. If the partial wall becomes unstable with respect to out-of-plane fluctuations, the domain wall is depinned from the interface and results in a loss of bias.[4] This happens at a critical rotation angle θ_c and also depends on an easy-plane anisotropy K_o tending to keep the spins in-plane.[5] Since the effective K_o is reduced by thermal fluctuations, θ_c is also sensitive to increased temperature.[6]

In a mean-field approach to temperature dependence, the effective K_o above plays a role akin to an energy barrier to thermal activation.[7–9] While dynamic processes are important when the system is close to a transition, mean-field theory[10] is very useful for studying the static features of the system away from this point. Equilibrium configurations calculated from a mean-field theory may not predict the exact critical temperatures and fields, but the approach captures the essential physics of the system before and after such a transition.

In this article, we examine the thermal stability of partial domain wall-mediated bias on compensated and uncompensated antiferromagnetic interfaces. Thermal fluctuations are shown to reduce the stabilizing effect of K_o, and induce a transition from reversible domain-wall mediated bias with no coercivity to coercive hysteresis loops having small or vanishing bias.

II. MEAN FIELD CALCULATIONS

The stability of partial domain walls in the antiferromagnet to thermally induced transitions is examined using an atomistic model. Landau–Lifshitz equations of motion for each spin S_i at position i are constructed and solved numerically:

$$\frac{\partial S_i}{\partial t} = -\gamma(S_i \times h_i) + \alpha(S_i \times S_i \times h_i). \tag{1}$$

The effective field h_i at each spin site contains contributions from the applied field H_a (in units of $M_f t_f/\sigma$), the exchange integral between nearest neighbors J_{ij} and also uniaxial anisotropy K_U in the antiferromagnet. The ferromagnetic layer is assumed to be isotropic. The equilibrium configuration found using this method probes the out-of-plane stability and thereby avoids some difficulties with metastable configurations.

The bulk antiferromagnetic exchange integral J_{af} is chosen such that the antiferromagnet has a Néel temperature (T_N) of 300 K and the bulk ferromagnetic exchange integral was set at $J_f = 10 J_{af}$. Demagnetizing fields in the ferromagnet are represented by an additional term in h_i of magnitude $4\pi S_z$, where S_z is the component of S_i along the film normal. The gyromagnetic ratio and damping factor are γ and α,

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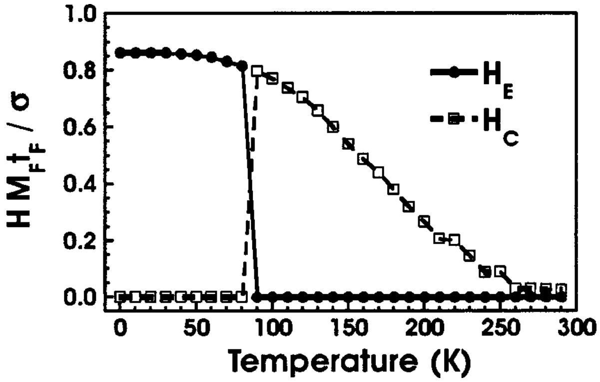

FIG. 1. Temperature dependence of bias field and coercive field for a compensated interface with $J_I=3J_{af}$. The critical temperature at which bias vanishes is 90 K. Note that biased loops and coercivity do not occur simultaneously.

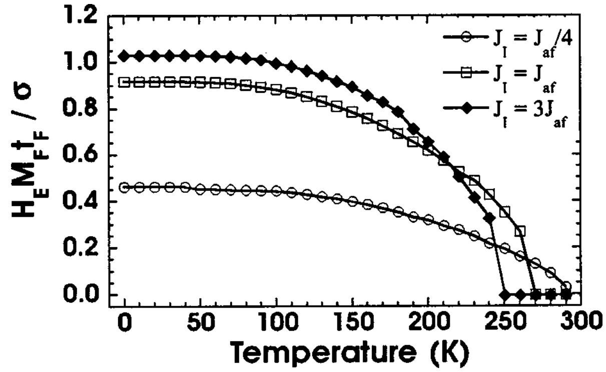

FIG. 2. Temperature dependence of the bias field for uncompensated interfaces with $J_I=J_{af}/4$, $J_I=J_{af}$ and $J_I=3J_{af}$. Note that T_{eb} increases for as J_I is decreased.

respectively. Spins are arranged in a simple cubic structure, with periodic boundary conditions in the [100] and [010] directions. The ratio J_{af}/K_u is chosen to give a characteristic domain wall width of about ten atomic planes and the antiferromagnet layer thickness was chosen to be large enough to accommodate the domain wall.

Temperature dependence is implemented by replacing h_i with its thermally averaged value $\langle h_i \rangle$, where the spin vectors $\mathbf{S}_i$ are reduced in size by the Brillouin function $\langle S_i \rangle = S_i \times B(T)$. Note that $B(T)$ is itself a function of h_i, so $\langle h_i \rangle$ requires iteration to self-consistency.[10]

III. RESULTS AND DISCUSSION

The results presented here were calculated using $K_o = K_u$, $t_f = 10\,\mathrm{ML}$ and $t_{af} = 20\,\mathrm{ML}$. Values of $\alpha = \gamma = 0.0002$ were used and these gave stable convergence in reasonable time. To avoid numerical problems with metastable configurations, the external field was applied at 80° and 10° to the antiferromagnet anisotropy axis for the compensated and uncompensated interface, respectively.

Equilibrium spin configurations between 0 and 290 K were calculated for $J_I = 3J_{af}$ with an ideal compensated interface. Calculations for an ideal uncompensated antiferromagnetic interface were carried out for $J_I = J_{af}/4$, J_{af} and $3J_{af}$.

A. Compensated interfaces

A minimum J_I/J_{af} ratio of at least 2 was required to obtain a stable partial domain wall at $T = 0$ K.[5] Bias and coercive fields as a function of temperature for $J_I = 3J_{af}$ on a compensated interface are shown in Fig. 1. Below $T = 90$ K, the antiferromagnet spin configuration supports a reversible domain wall. Above $T = 90$ K, the wall can exceed the critical angle θ_c so depinning of the wall can occur.

Just prior to becoming unstable, the spin structure in the antiferromagnet consists of a domain wall wound through an angle close to θ_c, with the spins away from the interface winding towards the positive anisotropy axis. When depinning occurs, the ferromagnet magnetization immediately falls to its negative saturation value as the antiferromagnet spins rotate out of the plane of the film. This allows the domain wall to escape, and causes the system to ''forget'' its initial configuration in the positive direction. The spin structure after depinning is identical to the initial condition at positive saturation, except now the spins further away from the interface rotate towards the negative anisotropy axis.

When the ferromagnet magnetization is restored to positive saturation, it is as if the system had its initial condition in the negative direction. A domain wall is again wound up to angle θ_c relative to the negative anisotropy axis, and depinning occurs as the ferromagnet is pulled into the field direction. The critical fields for depinning occur at the same magnitude in both directions. Since bias is measured as the midpoint between these critical fields, the bias field is zero.

If a J_I/J_{af} ratio of unity is used, the partial domain wall always depins from the interface during magnetization reversal. In a mean-field formulation, the temperature dependence of the coercive field has been shown to follow the Brillouin function.[11] The bias field is zero at all temperatures due to the perfect compensation at the antiferromagnet interface.

B. Uncompensated interfaces

Bias fields as a function of temperature for uncompensated interfaces with different J_I are given in Fig. 2. In the limit of $J_I \ll \sigma$, antiparallel alignment of spins in the antiferromagnet is only slightly perturbed. This is the case for $J_I = J_{af}/4$, where bias is fully reversible up to 290 K. The decrease in the bias field with temperature is due to reduction of the interface antiferromagnet $\langle S \rangle$ as the temperature approaches T_N. Exchange bias is lost at critical temperature T_{eb} near T_N.

When J_I is increased, the bias field vanishes at a temperature T_{eb} less than T_N. At low temperatures a domain wall forms in the antiferromagnet and remains pinned to the interface as the magnetization is reversed. Above T_{eb}, partial walls in the antiferromagnet are depinned during magnetization reversal and the bias disappears.

The coercive fields have interesting temperature dependence as shown in Fig. 3. For $J_I = J_{af}/4$ there is no coercivity, but for $J_I = J_{af}$ and $J_I = 3J_{af}$, there is coercivity below T_{eb}. The coercivity begins to appear before the bias field goes to zero, and maximum coercivity occurs at T_{eb} where the bias field becomes zero. The appearance of coercivity

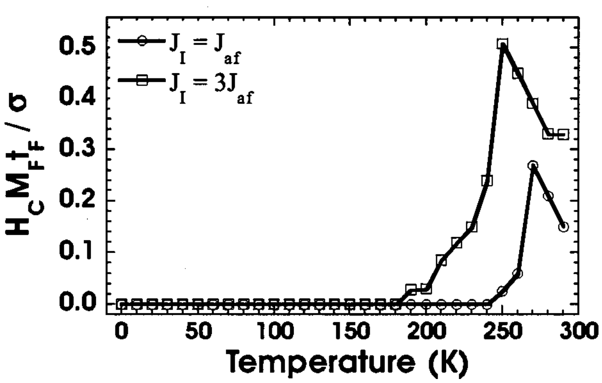

FIG. 3. Temperature dependence of the coercive field for uncompensated interfaces with $J_I=J_{af}/4$, $J_I=J_{af}$, and $J_I=3J_{af}$. The onset of coercivity occurs at lower temperatures as J_I is increased.

corresponds to differences in the thermal magnitudes of the interface antiferromagnet $\langle S\rangle$ for the forward and reverse magnetizations. This can be understood as follows: Near T_N, the thermal magnitudes of the antiferromagnet spins can vary greatly throughout the film. This has a large influence on the structure of the partial wall formed during magnetization reversal. In particular, just before the bias field vanishes at T_{eb}, the partial wall does not entirely depin from the interface at the coercive field, but penetrates into the antiferromagnet and is centered at a depth determined by a minima in $\langle S\rangle$ as a function of depth. This process occurs over a narrow window of temperatures just below T_{eb}.

IV. CONCLUSION

Results from a mean field theory for exchange bias at finite temperatures was presented for ideal compensated and uncompensated interfaces. Pinning of partial walls to the interface was found to be sensitive to the thermally averaged magnitudes of antiferromagnet spins near the interface. The bias field was found to vanish at a critical temperature T_{eb} less than the Néel temperature. For large values of interlayer exchange, coercivity appears as the bias field vanishes. In the case of an uncompensated interface, a maximum in the coercivity occurs at T_{eb} due to partial depinning of the domain wall in the antiferromagnet.

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