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Hysteresis from antiferromagnet domain-wall processes in exchange biased systems

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Abstract

The presence of magnetic impurities in the antiferromagnet can account for some ferromagnetic hysteresis behavior observed in exchange bias systems. We show theoretically that such impurities can modify domain-wall formation in the antiferromagnet, which under certain conditions can give rise to coercivity enhancement and asymmetric hysteresis. The linear dynamics of the ferromagnet/antiferromagnet structure in the presence of impurities is also presented.

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Keywords: Exchange bias; Domain-wall dynamics; Ferromagnetic resonance; Hysteresis

Exchange bias refers to the unidirectional anisotropy induced in a ferromagnetic film exchange coupled to an antiferromagnet [1]. This coupling can serve to pin the ferromagnet layer for a certain range of fields and is a mechanism that has found widespread use in magnetoelectronic devices [2]. An overview of exchange bias theory and experiment can be found in Ref. [3].

The induced anisotropy causes a shift in the ferromagnet hysteresis loop by an amount termed the exchange bias field (H_{eb}). Mauri et al. proposed a model for exchange bias based on the formation of a partial antiferromagnet wall to address discrepancies between experimental observations and early theoretical estimates of H_{eb} [4]. While it is successful in this respect, the theory, however, does not explain the coercivity enhancement observed in certain systems within the single-domain picture. Indeed, one can appeal to polycrystalline models, in which competing grains with varying anisotropy orientations and strengths give rise to reversible and irreversible behavior, to explain the simultaneous loop shift and increases in the coercive field [5]. In this paper, we present a microscopic theory of exchange bias for a

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single-domain material in which defects in the antiferromagnet layer govern the domain-wall processes that lead to ferromagnetic hysteresis. The impurities act to pin the domain-wall and can account for observed features such as asymmetric hysteresis. We also show how changes in the ferromagnetic spin-wave spectrum can provide signatures for such domain-wall processes.

Following the treatment of Braun et al. for ferromagnetic walls [6], we can obtain a simple physical picture of pinning in the antiferromagnet by considering an impurity of the form $K_u(x) = K_{u0}\{1 - \rho\delta[(x - x_d)/\lambda]\}$, which represents a small local pointlike reduction ρ in the uniaxial anisotropy energy K_u at a distance x_d from the interface. In addition to the interlayer coupling, the energy arising from deformations to the antiferromagnetic spin structure is given by

$$E_{af}[\varphi(x)] = \int_0^\infty \mathrm{d}x \left[A\left(\frac{\partial\varphi}{\partial x}\right)^2 + K_u(x)\sin^2\varphi \right], \tag{1}$$

where A is the exchange stiffness and $\varphi(x)$ represents the angle of the antiferromagnet staggered magnetization relative to the easy axis. If ρ is sufficiently small, the solution to the usual variational problem $\delta E/\delta\varphi = 0$ for the domain-wall profile is valid to first order. Substituting this solution $\varphi^*(x)$ into Eq. (1) gives a modified form for the twist energy $E_{af}(\varphi_0)/\sigma_w = (1 - \cos\varphi_0)/2 - E_\rho$, where

$$E_\rho = \frac{\rho \sin^2\varphi_0}{4}\left[\cosh\left(\frac{x_d}{\lambda}\right) + \cos\varphi_0 \sinh\left(\frac{x_d}{\lambda}\right)\right]^{-2}, \tag{2}$$

φ_0 is the interface antiferromagnet spin angle, $\lambda \equiv \sqrt{A/K_{u0}}$ is a characteristic length, and $\sigma_w \equiv 4\sqrt{AK_{u0}}$ is the energy of a 180° Bloch wall.

Depending on the position and density of the defects, a local minimum in the antiferromagnet energy can appear, as shown in Fig. 1. This minimum corresponds to the point at which the partial wall center coincides with the position of the defect, whereby the anisotropy energy cost is reduced by positioning a large spatial magnetization gradient in a region of reduced K_u. As the partial wall is wound during magnetization reversal, it can become "trapped" in the (pinning) potential well from which an energy barrier must then be surmounted in order for the wall to unwind. Such processes can therefore lead to irreversible behavior.

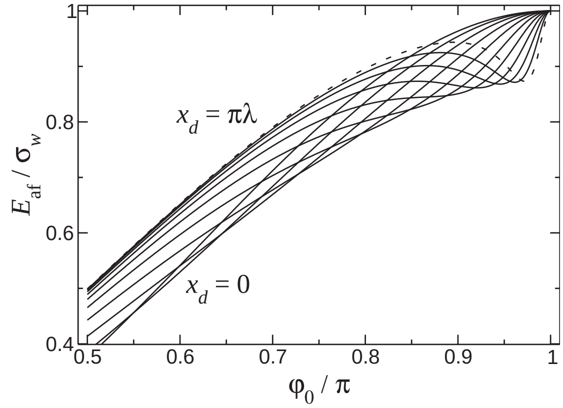

Fig. 1. Normalized antiferromagnet energy E_{af}/σ_w as a function of interface twist angle φ_0, where σ_w is the energy for a 180° antiferromagnet Bloch wall. The curves are shown for a series of defect distances, from $x_d = 0$ to π in steps of 0.1π, for $\rho = -0.5$.

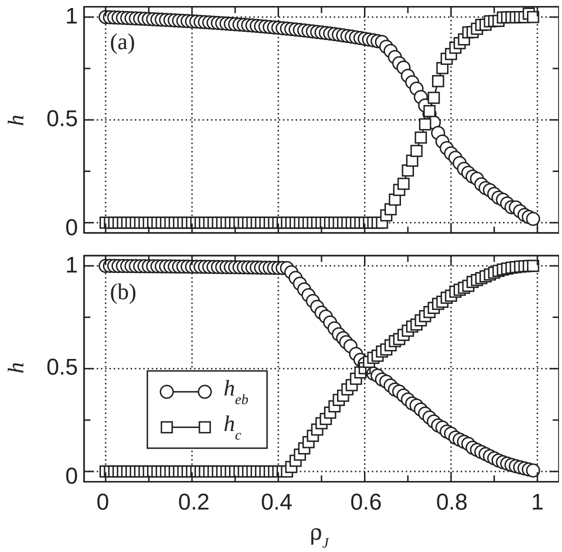

Fig. 2. Defect-modified exchange bias. Bias field h_{eb} and coercivity h_c are shown as functions of the exchange defect density ρ_J, for (a) $x_d = 2$ ML and (b) $x_d = 4$ ML. All fields are expressed in reduced units of $h = 2H\,M_s t_F/\sigma_w$.

An example of defect-modified exchange bias is given in Fig. 2, where variations in the bias field and coercivity due to a defect in the antiferromagnet are shown. The impurity considered here is taken to modify the local exchange bonds locally. In our notation, a defect position denoted by x_d represents a change in the exchange coupling between layers $x_\mathrm{d}-1$ and x_d in the antiferromagnet, where $x_\mathrm{d}=0$ represents the interfacial layer. For these calculations, we have employed numerical simulations of an atomistic spin model to determine the equilibrium configuration of the ferromagnet/antiferromagnet structure [7], since large defect concentrations cause significant deformations to the domain-wall profile and the Bloch-wall approximation is no longer valid. One observes a monotonic decrease in the bias field with the defect density that is accompanied by a significant coercivity at moderate to high defect densities. There are two mechanisms for this bias field reduction. The first involves the overall reduction in the antiferromagnet wall energy due to the defect and induces no irreversible behavior; this mechanism is dominant at low defect densities. The second involves pinning the antiferromagnet wall as it is formed during reversal, which arises from the appearance of a local energy minimum in which the wall can become "trapped" as argued previously. This mechanism is important at moderate to high defect densities and leads to irreversible behavior, which can be seen in the corresponding increase in the coercive field in Fig. 2.

The hysteresis that follows from the wall-pinning processes in the antiferromagnet is asymmetric. Some examples for an $x_\mathrm{d}=4$ ML exchange defect are shown in Fig. 3. The behavior of the magnetization reversal is qualitatively different depending on the strength of the wall pinning. At low defect densities ($\rho_\mathrm{J}=0.15$) the wall is largely unaffected by the impurity, where one observes a reversible magnetization curve that resembles largely the zero-defect curve. At moderate defect densities ($\rho_\mathrm{J}=0.45$), the wall in the antiferromagnet becomes pinned at the defect during reversal and persists in this configuration for a large range of negative fields during remagnetization. Close to zero field, the wall is released from the pinning center and a sharp reversal of the magnetization is observed. Note that the pinning and depinning of the wall in this example is executed with opposite senses of rotation, as indicated by the transverse component of the magnetization shown in Fig. 3. This is in stark contrast to the behavior in the strong pinning regime ($\rho_\mathrm{J}=0.75$), where the wall is observed to wind around with the same sense of rotation at reversal and remagnetization. Here, a partial wall is formed during reversal and becomes strongly pinned at the defect. The antiferromagnet spins continue to wind with the same rotation sense during remagnetization to form a second twist wall with the same chirality. The large twist structure becomes unstable in positive field and a depinning transition drives the abrupt rotation of the ferromagnet into the positive direction. A more detailed study of defect-modified exchange bias can be found elsewhere [7].

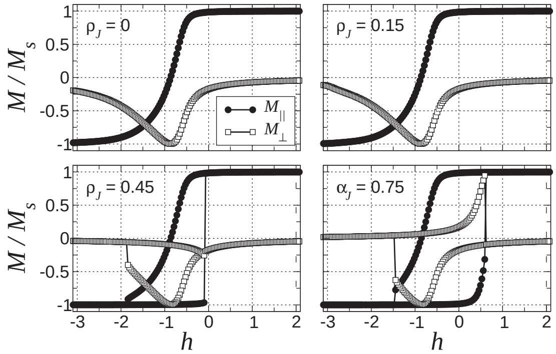

Fig. 3. Hysteresis loops calculated from numerical simulations for three different exchange defect strengths with $x_\mathrm{d}=4$ ML: (a) $\rho_\mathrm{J}=-0.15$, (b) $\rho_\mathrm{J}=-0.45$ and (c) $\rho_\mathrm{J}=-0.75$. Variations of the transverse component of the magnetization, $M_\perp$, are also shown.

The domain-wall processes leading to such asymmetric hysteresis should also be detectable as changes to the excitation spectrum of the bilayer. Following the method described in Refs. [8,9], we study the small-amplitude excitations $\vec{m}_i(t)$ in the ferromagnet/antiferromagnet structure by solving the linearized equations of motion,

$$-\frac{1}{\gamma}\frac{\partial\vec{m}_i(t)}{\partial t}=\vec{m}_i(t)\times\vec{H}_i^{\mathrm{eff}}+\vec{M}_i\times\vec{h}_i^{\mathrm{eff}}(t), \tag{3}$$

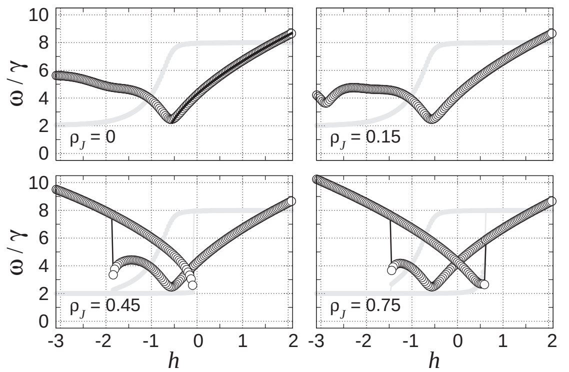

Fig. 4. Ferromagnetic resonance frequency as a function of applied field through a hysteresis loop sweep for a series of defect strengths ρ_J with $x_d = 4$ ML. Shown in gray are the corresponding hysteresis loops. The solid line for $\rho_J = 0$ represents a fit based on Eq. (4).

about the non-uniform ground state $\vec{M}_i$, which is obtained numerically as described above. Here, i denotes the layer number and $\vec{H}_i^{\rm eff}(t)$ is the (time-dependent) effective field experienced by layer i. This set of coupled equations describing the linear dynamics constitutes a large eigenvalue problem that may be solved numerically.

In this discussion, we shall only concern ourselves with the long-wavelength excitations that are accessible in resonance experiments in the GHz range. The variation of the ferromagnetic resonance frequency is shown in Fig. 4 as a function of applied field for a series of defect parameters. It is immediately apparent that the resonance curves do not possess a mirror symmetry about the bias field axis, which reinforces the point that the loop shift cannot be considered as the result of a fictitious internal field. The variation of the resonance frequency with field is well-described by the Kittel equation

$$(\omega/\gamma)^2 = (H + H_b)(H + H_b + 4\pi M_s), \qquad (4)$$

before the magnetization reverses, but a more complicated behavior is observed at negative fields at which the antiferromagnet wall is formed. Here H_b is a shift field that may not necessarily correspond to the exchange bias field. At low defect concentrations ($\rho_J = 0.15$) the magnetization curve is reversible, but features in the resonance spectrum appear at large negative fields that correspond to excitations of the antiferromagnetic domain-wall, as indicated by the second dip in the resonance frequency close to $h = -3$ in Fig. 3. For defects that result in a complete depinning of the wall from the interface ($\rho_J = 0.45$ and $\rho_J = 0.75$), one observes large jumps in the resonance frequencies that correspond to the pinning/depinning transitions. In this strong-pinning regime, one observes that the resonance frequencies are not modified by the presence of the domain-wall, which can be seen by a frequency variation that is consistent with Eq. (4) and indicates that the interfacial antiferromagnet spins are largely collinear with the ferromagnet outside the region of wall formation. Similar features have been observed in experiment [10].

In summary, we have presented a microscopic theory of coercivity enhancement and asymmetric hysteresis in exchange bias systems based on the partial domain-wall model. Irreversible behavior is controlled by domain-wall pinning processes that are driven by magnetic impurities in the antiferromagnet layer. We argue that such wall processes should be detectable in the ferromagnetic resonance spectrum.

Acknowledgements

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References

[1] W.H. Meiklejohn, C.P. Bean, Phys. Rev. 102 (1956) 1413; W.H. Meiklejohn, C.P. Bean, Phys. Rev. 105 (1957) 904.
[2] G.A. Prinz, Science 282 (1998) 1660.
[3] J. Nogués, Ivan, K. Schuller, J. Magn. Magn. Mater. 192 (1999) 203;
A.E. Berkowitz, Kentaro Takano, ibid. 200 (1999) 552;
R.L. Stamps, J. Phys. D: Appl. Phys. 33 (2000) R247;
M. Kiwi, J. Magn. Magn. Mater. 234 (2001) 584.
[4] D. Mauri, H.C. Siegmann, P.S. Bagus, E. Kay, J. Appl. Phys. 62 (1987) 3047.
[5] M.D. Stiles, R.D. McMichael, Phys. Rev. B 59 (1999) 3722;

M.D. Stiles, R.D. McMichael, Phys. Rev. B 60 (1999) 12950;
M.D. Stiles, R.D. McMichael, Phys. Rev. B 63 (2001) 064405.
[6] H.B. Braun, J. Kyriakidis, D. Loss, Phys. Rev. B 56 (1997) 8129.
[7] Joo-Von Kim, R.L. Stamps (unpublished).
[8] F.C. Nörtemann, R.L. Stamps, R.E. Camley, Phys. Rev. B 47 (1993) 11910.
[9] Joo-Von Kim, R.L. Stamps, J. Appl. Phys. 89 (2001) 7651.
[10] D. Spenato, J. Ben Youssef, H. Le Gall, J. Magn. Magn. Mater. 240 (2002) 254;
D. Spenato, J. Ben Youssef, H. Le Gall, J. Appl. Phys. 93 (2003) 7711.