Magnetic remanent states in antiferromagnetically coupled multilayers

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In antiferromagnetically coupled multilayers with perpendicular anisotropy unusual multidomain textures can be stabilized due to a close competition between long-range demagnetization fields and short-range interlayer exchange coupling. In particular, the formation and evolution of specific topologically stable planar defects within the antiferromagnetic ground state, i.e. wall-like structures with a magnetic configuration extended over a finite width, explain configurational hysteresis phenomena recently observed in [Co/Pt]/Ru and [Co/Pt]/NiO multilayers. Within a phenomenological theory, we have analytically derived the equilibrium sizes of these “ferroband” defects as functions of the antiferromagnetic exchange, a bias magnetic field, and geometrical parameters of the multilayers. In the magnetic phase diagram, the existence region of the ferrobands mediates between the regions of patterns with sharp antiferromagnetic domain walls and regular arrays of ferromagnetic stripes. The theoretical results are supported by magnetic force microscopy images of the remanent states observed in [Co/Pt]/Ru.

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I. INTRODUCTION

Recently synthesized antiferromagnetically coupled multilayers with strong perpendicular magnetic anisotropy, such as [Co/Pt]/Ru, [Co/Pt]/NiO, Co/Ir, Fe/Au, behave as synthetic metamagnets. Such perpendicular media are currently investigated as promising materials for thermally stable high-density recording technologies and for the emerging spin electronics. These effectively antiferromagnetic structures display a rich variety of magnetization reversal processes accompanied by various reorientation effects and the formation of complex multidomain structures [1]. In addition to the equilibrium multidomain phases different systems of irregular networks of domain walls and bands have been reported to exist in the antiferromagnetic phase of [Co/Pt]/Ru [1, 2, 3], [Co/Pt]/NiO [4, 5] and [Co/Pd]/Ru [6] multilayers. These topologically stable planar magnetic defects strongly depend on the magnetic and temperature history [1, 3, 6, 7]. Micromagnetic analysis shows that, depending on the material parameters and the magnetic history, the antiferromagnetic remanant states may display sharp domain walls, “trapped” ferromagnetic strips which we call ferrobands, antiferromagnetic strips in a metastable ferrostripe matrix, and various metastable isolated magnetic layers of thickness $h$ separated by nonmagnetic spacers of thickness $s$ (Fig. 1 Insets (A) and (B)). The theoretical approach creates a consistent and quantitative micromagnetic model for the domain patterns responsible for configurational hysteresis effects in this class of materials.

II. FERROBANDS VERSUS SHARP DOMAIN WALLS

According to the experimental observations and theoretical analysis, the antiferromagnetic multilayers with strong perpendicular anisotropy may have antiferromagnetic single-domain structure as zero-field ground-state in certain ranges of geometry and materials parameters $h/2$. Planar defects separating antiferromagnetic domains in remanent states of these multilayers may arise either as sharp domain walls or as ferrobands (“shifted antiferromagnetic walls”) (Fig. 1 Insets (A) and (B)). Sharp walls are similar to 180° domain walls in bulk antiferromagnets. Ferrobands arise in antiferromagnetically coupled multilayers due to a subtle interplay between magnetodipole and interlayer exchange interactions. To investigate this phenomenon we consider an isolated ferroband of width $a$ in a multilayer consisting of $N$ identical magnetic layers of thickness $h$ separated by nonmagnetic spacers of thickness $s$ (Fig. 1 Inset (B)). The magnetic energy of this system (per unity band length) can be written in the following form [9]

$$E = 4\pi M^2 h^2 N \left[ F(u) + \eta u \right],$$

where $u = a/h$ is the reduced band width, the magnetostatic energy $F(u)$ is derived by solving the corresponding...
magnetostatic problem for a “charged” band

\[ F(u) = \frac{1}{4\pi} \sum_{k=1}^{N-1} \left( 1 - \frac{k}{N} \right) \Xi(u, \tau k) \]

where \( \tau = 1 + s/h \), and

\[ \Xi(u, \tau k) = 2f(u, \tau k) - f(u, \tau k + 1) - f(u, \tau k - 1), \]

\[ f(u, \omega) = (\omega^2 - u^2) \ln(\omega^2 + u^2) - \omega^2 \ln(\omega^2) - 4\omega u \arctan(u/\omega). \]

Here we introduce an effective magnetic coupling parameter

\[ \eta = \left( 1 - \frac{1}{N} \right) \frac{\delta}{h} - \frac{H}{4\pi M}. \]

\( H \) is an applied magnetic field perpendicular to the multilayer. The exchange length \( \delta \) is given by the ratio of the antiferromagnetic coupling \( J > 0 \) and the stray-field energy, \( \delta = J/(2\pi M^2) \). Note that \( \eta \) includes all material parameters of the systems, while the reduced magnetostatic energy \( F(u) \) depends only on geometrical parameters of the multilayer, namely, the ratio \( s/h \). The condition \( dE/du = 0 \) yields the equation for equilibrium ferroband widths:

\[ \eta = G(u) \equiv \frac{1}{8\pi} \sum_{k=1}^{N-1} \left( 1 - \frac{k}{N} \right) \Xi_u(u, \tau k), \]

where

\[ \Xi_u(u, \tau k) = 2g_u(u, \tau k) - g_u(u, \tau k + 1) - g_u(u, \tau k - 1), \]

\[ g_u(u, \omega) = 2 \left[ u \ln(\omega^2 + u^2) + u + 2\omega \arctan(u/\omega) \right]. \]

Typical solutions of Eq. (5) are plotted in Fig. 1 for thickness ratios \( s/h \) corresponding to geometrical parameters in different experimentally investigated systems: \( s/h = 0.36 \) [6], 0.19 [1] and 0.06 [5]. Note that a sharp domain wall can be treated as the limiting case of a ferroband with zero width.

The stability condition, \( d^2E/du^2 = 0 \), gives the equation

\[ \sum_{k=1}^{N-1} \left( 1 - \frac{k}{N} \right) \ln \left[ 1 + \frac{1 + 2u^2 - 2\tau^2 k^2}{(\tau^2 k^2 + u^2)^2} \right] = 0 \]

which, combined with Eq. (5), determines critical values of the ferroband width \( u_c \) and \( \eta_c \). Because Eq. (7) does not include the material parameters, the solutions for \( u_c \) are functions of the ratio \( s/h \) alone. In particular, for bilayers

\[ a_c = \sqrt{s^2 + 2sh + h^2/2}. \]

By substituting \( u_c \) into Eq. (5) we find \( \eta_c = G_{c} \equiv G(u_c) \). The analysis shows that solutions of Eq. (5) exist in the range \( 0 < \eta < \eta_c(s/h) \). The equations \( \eta = 0 \) and \( \eta = 2\pi \)
The critical field $H$ is larger than that of the sharp domain wall. Finally at $H^3$, and for $H < H^2$, the energies of both defect types become equal (profile 2). In decreasing bias field the ferroband energy gradually increases. At a certain value of the bias field $H^* (h)$ the energies of both defect types become equal (profile 3), and for $H^* (h) > H > H_2 (h)$ the ferroband energy is larger than that of the sharp domain wall. Finally at the critical field $H_2 (h)$ the ferrobands collapse (profile 4), and for $H < H_2 (h)$ only sharp wall solutions can exist (profile 5).

Because the variation of the ferroband width does not change the domain wall energy the equilibrium ferroband sizes do not depend on the characteristic length. They are formed only under competing influence of the antiferromagnetic exchange and the combined external bias and dipolar stray fields.

III. REORIENTATION EFFECTS AND REMANENT STATES

Topological defects can not arise spontaneously. However, they can be induced by magnetization processes. Thus, the formation and evolution of topological defects strongly depends on the sequence of magnetic-field-driven states and the transitions between them. Usually antiferromagnetic domain walls and ferrobands arise in the remanent state after demagnetization. This follows from the fact that antiferromagnetic domain walls and ferrobands are remnants of the ferromagnetic phases within the antiferromagnetic matrix. These wall defects also arise after in-plane demagnetization however, the defects antiferromagnetic state, i.e. the domain pattern may own different sizes and morphologies after different field histories. But, the structure of the topological wall defects should be the same in either case. Depending on the magnetic layer thickness remanent states consist of multidomain patterns with sharp domain walls ($h < h_b$), ferrobands ($h_b < h < h_f$), or the regular ferrostripe phase ($h > h_f$) (Fig. 3). In multilayers with thicker magnetic layers the antiferromagnetic and ferromagnetic phases are separated by the region of transitional domain structures (metamagnetic domains) (Fig. 4). In this case the antiferromagnetic phase may include remnants of metamagnetic domains. Such textures have been observed in [Co/Pt]Ru multilayers after out-of-plane saturation. Experimental data on the variation of the ferroband size under influence of the applied field have been reported in Ref. [5]. In the experimental investigation a ferroband in a $[\text{Pt}(5\,\text{Å})/\text{Co}(4\,\text{Å})]_4/\text{NiO}(11\,\text{Å})/[\text{Co}(4\,\text{Å})/\text{Pt}(5\,\text{Å})]_4$ bilayer was squeezed by an opposing magnetic field. By fitting the experimental data of Ref. [5] we calculate from Eq. (5) the exchange constant $J = 0.002$ erg/cm² ($\delta = 0.065$ nm) and the optimal ferroband width as a function of the bias field, $a(H)$ (Fig. 2 Inset). This value of $J$ is in reasonable agreement with those for [Co/Pt]NiO multilayers investigated in Ref. [4].

According to experimental observations ferrobands can exist either in a single domain state or split into a system of domains creating, so called “tiger-tail” patterns. The “tiger-tail” multidomain states of these defects clearly are due to dipolar depolarization. In principle, these effects can be considered by additional stray field terms for the modulated magnetization along a ferroband in the model energy. Further experimental investigations of “tiger-tail” patterns together with a micromagnetic analysis of these multidomain patterns should give deeper insight into the formation and evolution of topological defects in this class of magnetic nanostructures.

In conclusion, we present an exhaustive analysis of specific topological defects (ferrobands) arising in perpendicular antiferromagnetically coupled multilayers. Our analytical solutions generalize and complete numerical studies of these defects in Refs. [2, 4, 5]. Magnetic-field-driven evolution and transformation of ferrobands explain the formation of defected remanent states recently observed in [Co/Pt]Ru and [Co/Pt]NiO antiferromagnetic multilayers.
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[1] O. Hellwig, A. Berger, J. B. Kortright, E. E. Fullerton, J. Magn. Magn. Mater. 319 13 (2007).
[2] O. Hellwig, A. Berger, E. E. Fullerton, Phys. Rev. Lett. 91, 197203 (2003).
[3] T. Hauet et al. Appl. Phys. Lett. 93, 042505 (2008).
[4] A. Baruth et al. Appl. Phys. Lett. 89, 202505 (2006).
[5] Z.Y. Liu et al., Appl. Phys. Lett. 93, 032502 (2008).
[6] Y. Fu et al., Appl. Phys. Lett. 91, 152505 (2007).
[7] J. E. Davies et al., Phys. Rev. B 77, 014421 (2008).
[8] N. S. Kiselev, U. K. Rößler, A. N. Bogdanov, O. Hellwig, cond-mat/0806.2170 (2008).
[9] N. S. Kiselev et al. Appl. Phys. Lett. 91, 132507 (2007).
[10] A. Hubert, R. Schäfer, Magnetic Domains (Springer-Verlag, Berlin, 1998).