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Comparative study of stripe magnetic domains in epitaxial Ni(111) and Co(0001) films

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The evolution of stripe magnetic domain structures observed by magnetic force microscopy on epitaxial Ni(111) and Co(0001) films as a function of film thickness is successfully explained by a periodic one-dimensional model with tilted partial flux closure domains. The model predicts a sizable fraction of the magnetization not being parallel to the film's normal, which consequentially results in an *in-plane* magnetization in agreement with the experimentally observed magnetization for these films. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1450842]

Stripe magnetic domain structures in ferromagnetic thin film and bulk materials have been studied both theoretically[1–5] and experimentally.[6–9] A stripe domain configuration in thin films results from a competition between magnetostatic, exchange, magneto-crystalline, and any other growth-induced anisotropy energies with the domain size depending not only on the sample thickness but also on the sample magnetic history. In a recent study, Hehn *et al.*[8] have analyzed the stripe domain structures observed by magnetic force microscopy (MFM) in epitaxial Co(0001) films using a model developed by Kooy and Enz[3] for multi-domain structures with perpendicular orientation. However, this analysis did not allow for the existence of any flux closure domains. Indeed, subsequent micromagnetic calculations by Rudiger *et al.*[9] have shown that flux closure caps are present in epitaxial Co(0001) films. In the present study, we have reanalyzed the thickness-dependent domain structure data on the epitaxial Co(0001) films[8] as well as similar MFM data on epitaxial Ni(111) films prepared in our laboratory by molecular beam epitaxy (MBE) using a one-dimensional periodic model with tilted partial flux closure domains.[10] Any tilt of the moments in the flux closure domains would correspondingly give rise to an *in-plane* magnetization in agreement with experimental observations for these films.

Epitaxial Ni(111) films with thicknesses in the range of 15–500 nm were grown by seeded epitaxy on Ag(111)/Si(111) substrates using MBE deposition[11,12] and covered with a 2-nm-thick Au cap layer to prevent oxidation. Both *in situ* reflection high energy electron diffraction and x-ray diffraction studies confirm the epitaxial growth. Magnetic hysteresis (M-H) loop measurements on these Ni(111) films indicate an in-plane magnetization, i.e., it is easier to magnetize the films along the film plane compared to the film normal. For example, Fig. 1 shows the hysteresis curves for a 200-nm-thick Ni(111) film obtained with the applied magnetic field H oriented parallel and perpendicular to the film plane. The effective anisotropy energy density was calculated using the area between the M-H curves for parallel and perpendicular geometry.[12] The analysis of the data shows the presence of a uniaxial perpendicular magnetic anisotropy energy density, $K_u \sim 0.3\times10^6$ erg/cm^3, a factor of 5 times smaller than the demagnetization energy density, $2\pi M_s{}^2$. It was also found that K_u was roughly independent of the film thickness as shown in Fig. 2. These features, K_u being independent of film thickness and $K_u < 2\pi M_s{}^2$, have also been found for the Co(0001) films.[8] The origin of K_u in Ni(111) films could be due to a growth induced residual stress in the films. Ni being magnetostrictive, a strain induced anisotropy could contribute to K_u, in addition to the fourth order magneto-crystalline anisotropy contribution along the ⟨111⟩ film normal.

Magnetic domain structures in the as-grown samples of Ni(111) were imaged using a Digital Instruments Multi-Mode™ atomic force microscope in the tapping mode configuration with all measurements being performed at room temperature in air and with zero applied magnetic field. All films [except a 15-nm-thick Ni(111) film] exhibit disordered stripe domain patterns as shown in Fig. 3(a) for a 200-nm-thick Ni(111) film. The distinct bright and dark regions in these MFM images have a greater length scale than the corresponding atomic force morphology images as displayed in Fig. 3(b). In fact, these MFM images look very similar to

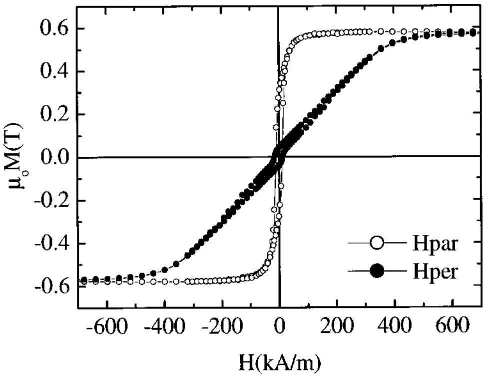

FIG. 1. Magnetic hysteresis loops for a 200-nm-thick Ni(111) with the applied magnetic field H oriented parallel and perpendicular to the film plane.

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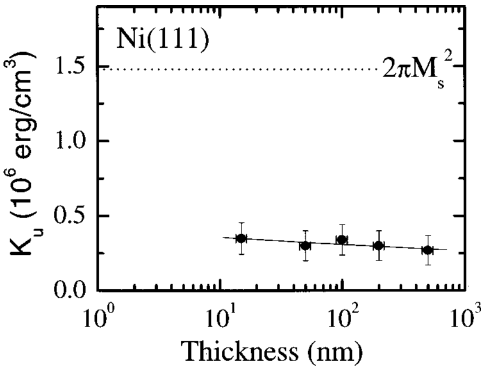

FIG. 2. Perpendicular uniaxial anisotropy energy density, K_u, vs film thickness t for epitaxial Ni(111) films. The solid line represents a least-squares-fit to a linear fit for Ni(111) films.

MFM scans performed on epitaxial Co(0001) films of Ref. 8. The average domain size D is determined by measuring the distance between successive bright to dark regions using line scans across the MFM image and is displayed as a function of film thickness for the Ni(111) films in Fig. 4 and for Co(0001) films[8] in Fig. 5.

Using a one-dimensional periodic stripe domain model with tilted partial flux closure domains,[10] the evolution of the domain structure with film thickness can be determined. Referring to Fig. 6, the total energy per unit area of the surface can be written as

$$E_{\text{total}}(D,L,\theta)=E_{\text{demag}}+E_{\text{wall}}+E_{\text{closure}}, \tag{1}$$

$$E_{\text{demag}}=\frac{16M_s^2D}{\pi^2}\sum_n^{\text{odd}}\frac{1}{n^3}\left\{(1-\cos\theta)\left(\cos\frac{n\pi L}{2D}\right)+\cos\theta\right\}^2 \times[1-\exp(-n\pi t/D)], \tag{2}$$

$$E_{\text{wall}}=\sigma_w(t-L\tan\beta)/D+\sigma_N\left(\frac{1}{2}\right)(1-\cos\theta)(2L/\cos\beta)/D + \sigma_c\cos\theta(L\tan\beta)/D, \tag{3}$$

$$E_{\text{closure}}=\frac{1}{2}(K_uL^2/D)\tan\beta\sin^2\theta \quad \text{with} \quad \tan\beta=\sin\theta/(1+\cos\theta). \tag{4}$$

E_{wall} consists of three contributions: the wall energy density σ_w associated with the 180° Bloch wall dividing the interior of the domains, $\sigma_N\frac{1}{2}(1-\cos\theta)$ associated with the Néel wall as the magnetization rotates from the normal through an angle of θ into the closure domain, and $\sigma_c\cos\theta$ associated with the wall formed by the magnetization rotation in the center of the closure domain. Although each specific wall energy σ_i is expected to be different, we will assume as a first approximation that each is identically equal to $\sigma_w=4(AK_u)^{1/2}$, where A is the exchange stiffness constant.

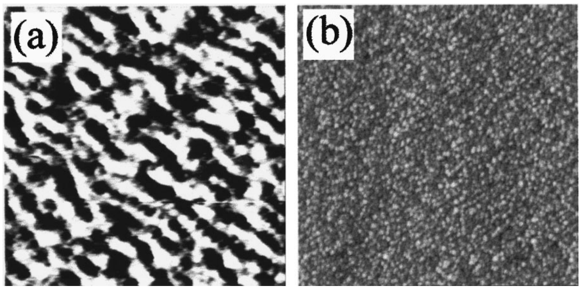

FIG. 3. (a) MFM and (b) atomic force microscope images from the same 5 μm×5 μm region on a 200-nm-thick Ni(111) film.

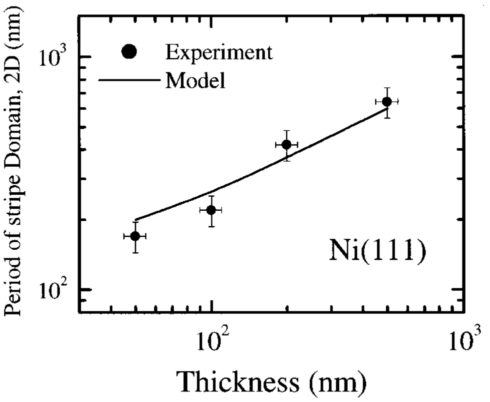

FIG. 4. Thickness dependence of the stripe domain period for Ni(111) films. The solid line represents a calculation based on the tilted partial flux closure domain model.

Utilizing the K_u values shown in Fig. 2 for Ni(111) films, $A=1.0\times10^{-6}$ erg/cm,[7] and $M_s=485$ emu/cm^3, Eq. (1) was minimized with respect to the three variables: D, L, and θ. Although the L/D was found to be essentially 100% for all thicknesses, the calculations indicate that magnetization direction, θ, increases from 73° to 82° with increasing film thickness from 100 to 500 nm and that the closure domains occupy a significant volume fraction (45%–24%). A direct comparison of the resulting calculated domain periods, 2D (solid line), to the experimental results in Fig. 4 shows remarkably good quantitative agreement, although the model breaks down for films with $t\leqslant50$ nm as a single domain structure with a complete *in-plane* magnetization is predicted. Further detailed information on the domain wall structures in these films would require more complex models and a full micromagnetic calculation.

For the Co(0001) films studied by Hehn *et al.*,[8] the

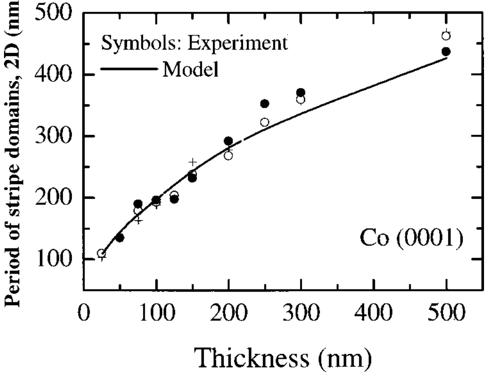

FIG. 5. Thickness dependence of the stripe domain period for Co(0001) films from Ref. 8. The solid line represents a calculation based on the tilted partial flux closure domain model.

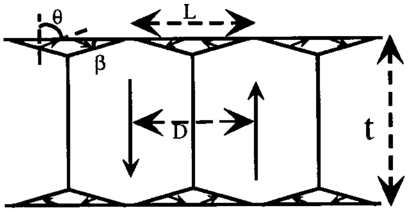

FIG. 6. A schematic of the domain configuration with tilted partial flux closure domains.

uniaxial magnetic anisotropy is more accurately described by[1]

$$K_u = K_1 \sin^2 \theta + K_2 \sin^4 \theta, \tag{5}$$

where $K_1 = 4.48 \times 10^6$ erg/cm^3 and $K_2 = 1.50 \times 10^6$ erg/cm^3.[4] Using $M_s = 1435$ emu/cm^3,[4] and $A = 3.01 \times 10^{-6}$ erg/cm,[13] the minimization of Eq. (1) results in $L/D \sim 1$ and $\theta \sim 60°$ for all Co(0001) films with thickness $t > 25$ nm and domain periods comparable to the measured values as shown in Fig. 5. Similar to the Ni(111) films, the closure domains occupy a significant volume fraction of the Co(0001) films as a 50-nm-thick film shows ~45% which decreases to ~12% in a 500-nm-thick film.

In summary, a rather simplistic periodic domain model with tilted partial flux closure domains successfully explains the observed disordered stripe domain structures observed in MFM data of Ni(111) and Co(0001) films and predicts a sizable fraction of the magnetization not being parallel to the film's normal. These tilted partial flux closure domains consequentially result in an *in-plane* magnetization, which is in agreement with the experimentally observed magnetization for these films.

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