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 and experimentally. 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. 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 for multi-domain structures with perpendicular orientation. However, this analysis did not allow for the existence of any flux closure domains.

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 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. The analysis of the data shows the presence of a uniaxial perpendicular magnetic anisotropy energy density, $K_u \sim 0.3 \times 10^6$ erg/cm$^3$, a factor of 5 times smaller than the demagnetization energy density, $2 \pi M^2_s$. 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. 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.](image)

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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

\[
E_{\text{total}}(D, L, \theta) = E_{\text{demag}} + E_{\text{wall}} + E_{\text{closure}},
\]

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

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

\[
E_{\text{closure}} = \frac{1}{2} (K_u L^2/D) \tan \beta \sin^2 \theta
\]

with \( \tan \beta = \sin \theta/(1 + \cos \theta) \).

\( E_{\text{wall}} \) consists of three contributions: the wall energy density \( \sigma_w \) associated with the 180° Bloch wall dividing the interior of the domains, \( \sigma_N (1 - \cos \theta) \) associated with the Néel wall as the magnetization rotates from the normal through an angle of \( \theta \) 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 \( \sigma_i \) 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.

Utilizing the \( K_u \) values shown in Fig. 2 for Ni(111) films, \( A = 1.0 \times 10^{-6} \text{ erg/cm}^2 \) and \( M_s = 485 \text{ emu/cm}^3 \), Eq. (1) was minimized with respect to the three variables: \( D, L, \) and \( \theta \). Although the \( L/D \) was found to be essentially 100% for all thicknesses, the calculations indicate that magnetization direction, \( \theta \), 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, \( D \) (solid line), to the experimental results in Fig. 4 shows remarkably good quantitative agreement, although the model breaks down for films with \( t \leq 50 \text{ nm} \) 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
uniaxial magnetic anisotropy is more accurately described by

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

where \( K_1 = 4.48 \times 10^6 \) erg/cm\(^3\) and \( K_2 = 1.50 \times 10^6 \) erg/cm\(^3\). Using \( M_s = 1435 \) emu/cm\(^3\), \( A = 3.01 \times 10^{-6} \) erg/cm, \(^13\) the minimization of Eq. (1) results in \( L/D \sim 1 \) and \( \theta \sim 60^\circ \) 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 consequently result in an \textit{in-plane} magnetization, which is in agreement with the experimentally observed magnetization for these films.

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