

Drastic changes of the domain size in an ultrathin magnetic film

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A general framework for the domain size in any ultrathin film with perpendicular magnetic anisotropy is here discussed. The domain structure is analyzed by using the classical theory taking into consideration the demagnetization field contribution to the domain wall energy. A sinusoidal model is considered to describe the domain structure while approaching, in two different cases, the monodomain state with in-plane magnetization. The first case is realized applying a large enough in-plane magnetic field. The second one is obtained by decreasing the perpendicular magnetic anisotropy, which is connected in many ultrathin systems with the increase of film thickness. A change in the domain size of several orders of magnitude is obtained while approaching the magnetization reorientation region. The minimal stripe domain period $p = 8\pi\ell_{\text{ex}}^2/d$ is calculated from the sinusoidal model, where ℓ_{ex} is the exchange length and d is the thickness of the film. The range of possible domain size changes in ultrathin films is predicted. The domain size has been experimentally studied in a 1 nm Co film characterized by a square hysteresis loop. The investigations have been performed by polar Kerr based microscopy and magnetic force microscopy. The domain structure of two remnant states generated by applying an in-plane and a perpendicular magnetic field has been compared. Drastically, the smallest domain size has been observed for the former. © 2003 American Institute of Physics. [DOI: 10.1063/1.1556161]

Understanding the magnetic ordering of ultrathin films is of the utmost importance, not only for basic science but also for possible applications. A considerable number of experimental and theoretical works have been devoted to the analysis of domain structure (DS) properties in ultrathin magnets with different quality factors Q ($=K_1/2\pi M_S^2$ —the relation of the uniaxial anisotropy to the demagnetization energy) and different thickness, d . One can expect huge domain sizes in an ultrathin sample.¹ However, very small domains were observed when approaching the reorientation phase transition (RPT) where a thickness increase induces a change from vertical to in-plane magnetization.² The DS properties have been already studied in ultrathin cobalt films near the RPT induced by in-plane magnetic field, where very small domains, not available for visualization by optical microscopy, were expected.³

The present work is focused on both the theoretical and the experimental studies of equilibrium domain sizes range in an ultrathin magnetic film, characterized by thickness d , quality factor Q and the exchange length

$\ell_{\text{ex}} = [(A/(2\pi M_S^2))]^{0.5}$ where A is the exchange constant. The influence of an in-plane magnetic field H_{\parallel} is also here considered.

The DS has been studied in an ultrathin cobalt film prepared in a molecular beam epitaxy system. A sapphire single crystal wafer was covered by: (i) 20 nm Mo buffer layer grown at 1000 °C; (ii) 20 nm Au deposited at room temperature; (iii) 1 nm Co layer; (iv) 8 nm Au coverage. Magneto-optical magnetometry revealed the effective magnetic anisotropy constant $K_{1\text{eff}} = (0.473 \pm 0.003) \text{ MJ/m}^3$. The measured square hysteresis exhibited $H_c = 0.39 \text{ kOe}$. For ultrathin cobalt films the thickness dependence of $K_{1\text{eff}}(d)$ is described by the well known formula: $K_{1\text{eff}} = K_1 - 2\pi M_S^2 = K_{1V} - 2\pi M_S^2 + 2K_{1S}/d$ taking into consideration the volume and the surface contributions⁴ (K_{1V} and K_{1S} , respectively). Such parameters, K_{1V} and K_{1S} , were determined for a Au/Co wedge/Au sample deposited on mica⁵ and used for the DS period analysis at a wide thickness range. The thickness of the phase reorientation transition for such ultrathin layer is typically in the range 1.7–2.0 nm.

The DS has been visualized by an optical microscopy based on polar Kerr effect and magnetic force microscope (MFM).

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First, let us analyze the DS and its period in an uniaxial film with easy axis perpendicular to the plane submitted to H_{\parallel} field. The total sample energy, E , is described by the sum of the exchange, anisotropy, Zeeman and demagnetizing energies

$$E = L_x d \int_0^{p/2} \left(A \left(\frac{d\theta(y)}{dy} \right)^2 + K_1 \sin^2(\theta(y)) - M_S H_{\parallel} \sin(\theta(y)) \right) dy + E_D, \quad (1)$$

where L_x is the domain length along domain walls; $\theta(y)$ is the polar angle (a periodical function, with period p , determining the magnetization distribution in the film); E_D describes the demagnetizing energy. Usually the demagnetizing energy term is evaluated without considering the domain wall width. We focus our discussion on two approaches: (i) assuming the demagnetization effect in the domain walls according to Schlömann's theory,⁶ (ii) considering a sinusoidal domain structure as the limiting DS at the reorientation region between two states of multi-domains and in-plane mono domain.

The zero-field case is well described by the classical theory⁷⁻⁹ for large enough Q and negligible wall thickness. The equilibrium normalized period, p_0/ℓ_c , as a function of the normalized thickness, d/ℓ_c , can be described by a transcendental equation with the Lerch's functions,¹⁰ where ℓ_c is the characteristic length [$\ell_c = \sigma_w / (4\pi M_z^2)$ describes the ratio between the domain wall σ_w and demagnetizing energies, M_z being the z component of the magnetization vector].

In this section we use the classical description to calculate $p(d)$ —dependencies. The main problem is how to take into account the demagnetizing effect in domain wall energy for the ultrathin regime. Usually one considers, in the simplest approximation, that the wall energy is equal to $4(AK_{1\text{eff}})^{0.5}$. Under such assumption the domain period p_{eff} drastically decreases when approaching the RPT thickness d_1 ($K_{1\text{eff}}=0$). More carefully, the demagnetizing effect in the ultrathin regime when $d \ll \delta$ (δ is the domain wall width) can be considered using $\sigma_w = \sigma_{w0} - 2\pi M_S^2 \delta$. For very thin films, i.e., in the limit $d \rightarrow 0$, the wall width depends on the quality factor as⁵ $\delta = \delta_0(1 - 1/Q)^{-1/2}$ (where $\delta_0 = \pi[A/(K_{1\text{eff}} + 2\pi M_S^2)]^{0.5}$ is the wall width and $\sigma_{w0} = 4[A/(K_{1\text{eff}} + 2\pi M_S^2)]^{0.5}$). Then, from these expressions one can calculate $\sigma_w = \sigma_{w0}[1 - (1/4Q)\sqrt{1 - 1/Q}]$. The domain period p_{dw} , calculated using this more precise approximation, drastically decreases approaching d^* ($< d_1$) when σ_w goes to zero. Comparing p_{eff} and p_{dw} one can find a significant influence of the demagnetizing contribution on the domain size. Figure 1(b) shows $p_{dw}(d/\ell_{\text{ex}})$ dependencies calculated for films with thickness independent magnetic anisotropy. Such materials are, for instance, the tetragonal ordered alloys studied in Ref. 11.

Let us now consider a domain structure near the RPT in the simple sinusoidal approximation where $\Theta(y) = \Theta_0 \sin(2\pi y/p)$ ($\Theta = \pi/2 - \theta$), initially proposed for a semi-infinite magnetic space.¹² Using the expression for $\Theta(y)$ in Eq. (1), the normalized total energy density is given by

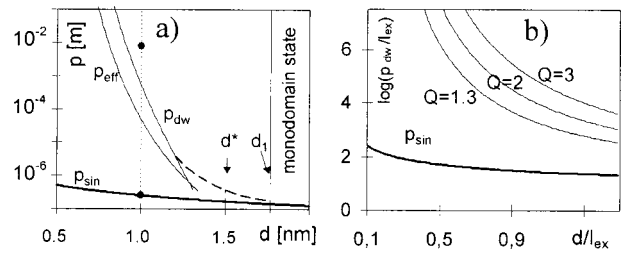


FIG. 1. Thickness dependence of the domain structure period. (a) Thin lines— $p_{\text{eff}}(d)$, $p_{dw}(d)$ calculated from the classical model using $K_{1V} = 0.85 \text{ MJ/m}^3$, $K_{1S} = 0.37 \text{ mJ/m}^2$, as experimentally determined for ultrathin cobalt wedge (see Ref. 5) ($M_S = 1420 \text{ Gs}$ and $\ell_{\text{ex}} = 3.2 \text{ nm}$ were assumed); d^* and d_1 are also determined for these parameters. The thick line describes $p_{\text{sin}}(d)$ calculated from Eq. (3) showing the in-plane magnetic field induced DS size. The dashed line connects the $p_{dw}(d)$ and the $p_{\text{sin}}(d_1)$ in the thickness region where the classical theory does not work. The dotted line represents the stripe domain period region available for the investigated 1-nm-thick Co sample. (b) Thin lines— $p_{dw}(d)$ calculated from the classical model for films with different thickness independent Q factor. The thick line describes $p_{\text{sin}}(d)$.

$$\frac{E_{\text{sin}}}{2\pi M_S^2 \ell_{\text{ex}}} = \frac{d}{\ell_{\text{ex}}} \left(\frac{2\ell_{\text{ex}}^2 \pi^2 \Theta_0^2}{p^2} + Q - \frac{\Theta_0^2}{2} Q - 2 \frac{H_{\parallel}}{4\pi M_S} \times \left(1 - \frac{\Theta_0^2}{4} \right) \right) + \frac{p\Theta_0^2}{4\pi\ell_{\text{ex}}} \left(1 - \text{Exp}\left(-\frac{2\pi d}{p} \right) \right). \quad (2)$$

Minimizing Eq. (2) with respect to p and assuming $d/p \ll 1$, one can find this simple formula for the equilibrium period

$$p_{\text{sin}} = \frac{8\pi\ell_{\text{ex}}^2}{d}. \quad (3)$$

It is worth noting that the p_{sin} period does not depend on the anisotropy constants and it is the minimal possible domain period, which can be achieved for any sample applying large enough H_{\parallel} .¹³ The period is much smaller (see Fig. 1) than the equilibrium one given by the classical model. The minimal period can be also reached approaching the RPT by the thickness change.

The question is: what is the equilibrium domain period in the thickness range $d < d_1$ for a given set of material parameters K_{1S} , K_{1V} , M_S and ℓ_{ex} ? There are two curves $p_{\text{eff}}(d)$, $p_{dw}(d)$ and the point for the minimal period p_{sin} available for the defined material parameters at thickness near d_1 , see Fig. 1(a). One can deduce that the classical model cannot be applied for a significant thickness region near the RPT where a more complicated magnetization distribution should be considered, see, e.g., the model given in Refs. 11 and 14. We have extrapolated the $p_{dw}(d)$ to the $p_{\text{sin}}(d_1)$ point by the dashed line.

It is possible to have different domain periods $p_{\text{sin}} \leq p < \infty$, in a sample with a given thickness, depending on the sample parameters (e.g., coercivity force) and its magnetic history. In order to give an experimental example, we have studied an ultrathin Co film (1 nm thick). We have showed in Fig. 1 the range of available periods for this sample. Using the classical and the sinusoidal models discussed above, one can find a difference of more than four orders of magnitude

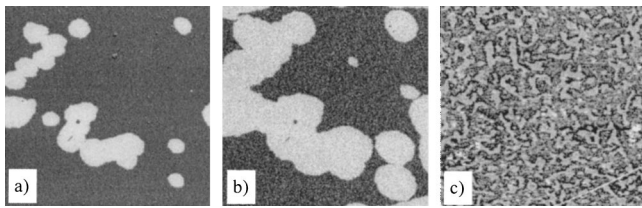


FIG. 2. Remnant domain structures visualized using: (a) and (b) magneto-optical microscope (image size 2 mm×2 mm); these images were obtained after the first and second magnetic field pulses (magnitude 382 Oe and time duration 1 s), respectively; (c) magnetic force microscope (image size 20 μm ×20 μm); the structure was produced by in-plane magnetic field.

in two equilibrium periods determined for: (i) the zero field state, $p_{dw} = 8.3$ nm; (ii) the state near the H_{\parallel} —induced RPT, $p_{\text{sin}} = 258$ nm, Fig. 1.

We have produced different domain structures by using two methods: (i) applying a perpendicular magnetic field along one direction (“white” in the image) in a sample previously saturated along the opposite (“black”) direction; (ii) switching off a large enough H_{\parallel} which previously saturated the sample. The results are shown in Figs. 2(a) and 2(b) (magneto-optical image) and Fig. 2(c) (MFM image), respectively.

The high coercivity prevents the system from reaching the equilibrium state. Let us consider the remagnetization process [shown in Figs. 2(a) and 2(b)], which has been started from saturated sample. Because of the small magnetostatic force in comparison to the coercivity, the increase of white domains goes through an almost isotropic expansion from the nucleation centers. This process is quite different from that observed in, e.g., bubble materials⁹ where such expansion proceeds by the increase of volume of curved stripes with rather well defined width determined by the magnetostatic and wall energies.

The domain pattern produced with an in-plane field is completely different than that obtained with a perpendicular

one. The pattern from Fig. 2(c) is similar to the DS observed for bubble materials, e.g., garnets.⁹ The formation of domains from the saturated state occurs by nucleation in many centers and by branching of curved stripes with about 0.6 μm width. The width is of the same order as p_{sin} . So, the fine DS was formed as the equilibrium one at the H_{\parallel} induced RPT. Due to the coercivity force, the structure is “frozen” after switching off the field.

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