Magnetic domain structure in thin films with large perpendicular anisotropy

1992 J. Phys.: Condens. Matter 4 L191

(http://iopscience.iop.org/0953-8984/4/11/004)

J. Phys.: Condens. Matter 4 (1992) L191–L193. Printed in the UK

LETTER TO THE EDITOR

Magnetic domain structure in thin films with large perpendicular anisotropy

Zhu-Pei Shi

Department of Physics, New York University, 4 Washington Place, New York, NY 10003, USA

Received 13 January 1992

Abstract. The formation of magnetic domains in thin films with large perpendicular anisotropy is investigated. By using a simple model of flux closure strip domain patterns, we find the domain size in very thin films depends *linearly* on film thickness. This interesting result agrees well with the experimental observation of magnetic domains in thin epitaxial Co/Au(111) films (by Allenspach and co-workers).

Allenspach *et al* [1] found magnetic domains in thin epitaxial Co/Au(111) films—the first experimental support that domains should form in very thin films with large perpendicular anisotropy. They determined that the domain size Δ depends *linearly* on film thickness d below a crossover d_c ($\Delta \sim d$), which contradicts Kittel's earlier magnetic domain theory [2] about domain growth increasing with film thickness as $\Delta \sim \sqrt{d}$. Yafet and Gyorgy [3] predicted the existence of domains even in monolayer films, based on an elaborate calculation which included uniaxial surface anisotropy, K_s, and dipolar magnetic energy. They found that a threshold value $K_{s,min}$ exists, so that when $K_s > K_{s,min}$ a domain configuration has lower energy than a uniformly magnetized state. Here we present a simple model of flux closure strip domains for very thin films which is similar to Kittel's domain configuration [2] to demonstrate that the domain size is linearly related to film thickness.

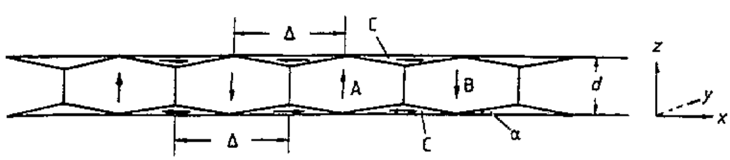

Figure 1. Flux closure strip domain structure. A and B represent domains of up and down magnetization which are perpendicular to the film. Edge C (with small angle α) completes the domain structure so that it satisfies flux closure. Coordinates x and y are in the film plane and z is perpendicular to the film; d is the thickness of the film and Δ is the width of a domain.

We consider a very thin film with large perpendicular anisotropy as shown in figure 1. The coordinate system is arranged so that coordinates x and y are in the film plane. Domains A (up) and B (down) represent perpendicular magnetization due to the large perpendicular anisotropy. We assume that the magnetic flux closure domain pattern is more favourable in this system [4], in which case the edge region C with small angle α adjusts to satisfy flux closure. The film thickness is d and the width of a domain is parametrized by Δ. The free energy of the system is written as

$$F = -\frac{1}{2}\int \boldsymbol{H}\cdot\boldsymbol{M}\,\mathrm{d}V + K_{\mathrm{eff}}V_{\mathrm{a}} + \sigma_{\mathrm{w}}S \qquad (1)$$

where the first term is magnetic energy F_{m}, the second term is anisotropy energy F_{a}, K_{eff} is an effective anisotropy energy density, and V_{a} is the total volume of domains. The third term is the energy F_{w} of the boundary surfaces between domains; σ_{w} represents surface energy density, and S is the total area of the domain boundaries. The energy F_{w} per unit area of the film is

$$F_{\mathrm{w}} = (2\sigma_{\mathrm{w1}}/\cos\alpha) + \sigma_{\mathrm{w2}}((d/\Delta) - \sin\alpha) \qquad (2)$$

where σ_{w1} is the 90° wall energy density between domains A and C or B and C, and σ_{w2} is an 180° wall energy density between domains A and B. According to the experimental data [1] we know that the domain size Δ is much larger than the film thickness d. We can then assume that the angle α (see figure 1) is very small and (2) reduces to

$$F_{\mathrm{w}} = 2\sigma_{\mathrm{w1}} + \sigma_{\mathrm{w2}}(d/\Delta). \qquad (3)$$

The anisotropy energy per unit film area is $F_{\mathrm{a}} = K_{\mathrm{eff}}\Delta$, and the symmetric flux closure domain structure suggests that the magnetic energy F_{m} is approximately zero. Total energy per unit film area is then

$$F = 2\sigma_{\mathrm{w1}} + \sigma_{\mathrm{w2}}(d/\Delta) + K_{\mathrm{eff}}\Delta. \qquad (4)$$

By minimizing with respect to the domain width Δ, we find

$$\Delta = (\sigma_{\mathrm{w2}}d/K_{\mathrm{eff}})^{1/2}. \qquad (5)$$

For thick films K_{eff} is just the volume anisotropy K_{v}, which gives domain size $\Delta \sim d^{1/2}$ corresponding to Kittel's result [2]. However, for very thin films where K_{eff} depends strongly on film thickness d, one may express the effective anisotropy as [1]

$$K_{\mathrm{eff}} = K_{\mathrm{v}} + 2K_{\mathrm{s}}/d \qquad (6)$$

where K_{s} is the surface anisotropy energy density. The magnitude of K_{v} is about 10^5 erg cm^{-3} and K_{s} is about 1 erg cm^{-2}, so that $2K_{\mathrm{s}}/d \sim 10^7$ erg cm^{-3} for film thicknesses of $d \cong 10$ Å, which is larger than K_{v}. Thus it is plausible to neglect the K_{v} term in (6) because of the very large surface anisotropy in very thin films, namely $2K_{\mathrm{s}}/d \gg K_{\mathrm{v}}$, and equation (6) reduces to

$$K_{\mathrm{eff}} = 2K_{\mathrm{s}}/d. \qquad (7)$$

By substituting (7) into (5) we obtain the domain width

$$\Delta = (\sigma_{\mathrm{w2}}/2K_{\mathrm{s}})^{1/2}d. \qquad (8)$$

The linear coefficient depends only on the ratio of the 180° wall energy density of domain boundaries to the surface anisotropy energy density. This interesting result agrees with the recent experimental observation [1]. By using the data in [1] we can estimate the surface energy density σ_w of domain boundaries. For K_s = 0.62 erg cm^{-2} and for a 3.5 monolayer Co film (~ 9 Å), the average domain size is $\Delta \sim 1\,\mu m$ and we obtain $\sigma_w \sim 10^6$ erg cm^{-2}. This surface energy density may be too large, and one should question whether the flux closure strip domain structure is the true 'ground state' of very thin films or rather a metastable state (i.e. there may exist a lower energy domain structure than this kind of flux closure strip domain pattern). It needs to be pointed out that the phenomenological quantity K_s cannot give any insight into the physical origin of the uniaxial anisotropy.

In conclusion, we have presented a simple model of flux closure strip domain structure in ultra-thin films with large perpendicular anisotropy to show that the domain size depends *linearly* on thin-film thickness. This result agrees well with the experimental observation of magnetic domains in thin epitaxial Co/Au(111) films with a thickness below the crossover value. This simple model is meaningful, but it still needs to be improved.

I would like to thank Professor Peter M Levy for introducing me to this problem and for very helpful discussions. This work was supported in part by New York University.

References

[1] Allenspach R, Stampanoni M and Bischof A 1990 *Phys. Rev. Lett.* **65** 3344
[2] Kittel C 1946 *Phys. Rev.* 70 965
[3] Yafet Y and Gyorgy E M 1988 *Phys. Rev.* B **38** 9145
[4] Slonczewski J C, Petek B and Argyle B E 1988 *IEEE Trans. Magn.* **MAG-24** 2045