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Dendritic domain structures in ultrathin cobalt films

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We report on the study of dendritic domain structures in gold-enveloped cobalt ultrathin films of thicknesses slightly below the thickness at which the reorientation from a perpendicular magnetization state to the in-plane state takes place. In these films, magnetization reversal proceeds through the dendritic growth of domains. A magnetic after-effect was observed. We reveal the mechanism and key parameters controlling the dendritic growth of magnetic domains.

Key words: *magnetic domains; ultrathin film; cobalt*

1. Introduction

Dendrite growth is a phenomenon well known in the physics of crystals. Up to now, however, this phenomenon has puzzled in many aspects. The main question of the general dendrite growth problem is how the nanoscale short-ranged interatomic interaction can drive structure growth on mesoscopic length scales. Previously, dendritic domain structures were observed in Co/Pt multilayers (0.4 nm Co/1.1 nm $Pt)_{10}$ [1, 2]. In these works, dendritic domain growth was explained by the difference in the activation volumes of the domain wall-motion and nucleation processes. Here, we report on the studies of dendrite domains in Co-monolayer ultrathin films (Au/Co/Au) and put forward another possible explanation of the phenomenon observed in our samples.

Cobalt ultrathin films of nominal thickness, d = 1.5–1.6 nm were studied. The thicknesses of our samples were slightly below the critical thickness d_1 = 1.79 nm [3] defining the reorientation phase transition (RPT) from the perpendicular to in-plane magnetization state.

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2. Experimental

Samples of the structure Al_2O_3\Mo (20 nm)\Au (20 nm)\Co(1.5 nm)\Au (8nm) were grown in a molecular beam epitaxy system under the pressure of 10^{-10} Torr. In samples with thicknesses inferior to d_1, perpendicular anisotropy favours the out-of-plane magnetization orientation and domain formation. Domain structure visualization was performed by an optical polarization microscope. A magnetic field H perpendicular to the sample plane was applied and the magnetization changes were recorded. A special software was developed to extract the domain parameters. Remnant dendritic domain structure (DDS) images were recorded during magnetization reversal induced by magnetic field pulses with (i) increasing numbers of pulses or (ii) increasing pulse amplitude.

3. Results and discussion

The studied samples are characterized by square-like magnetic hysteresis loops as shown in Fig. 1a. To study the dynamics of magnetization reversal, we measured the normal component of film magnetization as a function of time after applying $H > 0$ to a sample initially saturated by $H < 0$ (Fig. 1b). As is seen in Fig. 1b, a magnetic after-effect takes place. From this figure, one can see that in relatively low applied magnetic fields (H<100 Oe) the magnetization reversal rate is rather low and film magnetization does not reach saturation ($M/M_S = 1$) during the observation time.

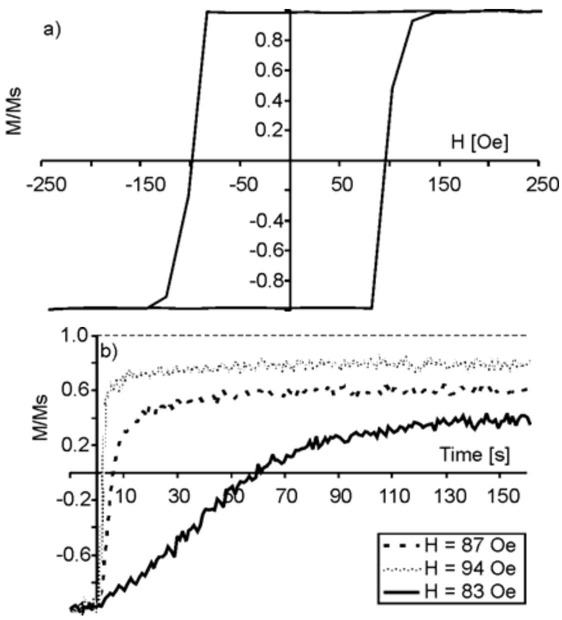

Fig. 1. Magnetic hysteresis loop for a cobalt film with a thickness of $d = 1.5$ nm (a) and time dependences of film magnetization for different strengths of the applied magnetic field (b)

Domain structure images were recorded for a remnant state after magnetic field pulses. Starting from the saturated state ($H < 0$, “black” field), we applied a sequence of reverse field pulses ($H > 0$, “white” field) of different durations and amplitudes.

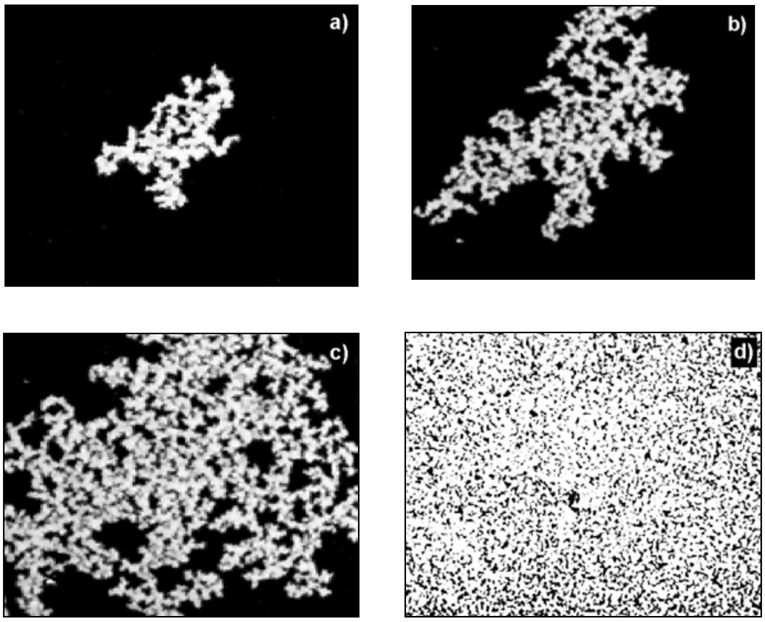

Fig. 2. Evolution of the dendritic domain structure in a cobalt film with a thickness of 1.5 nm. The sample was initially saturated by a field $H < 0$ favouring “black” domains. Images after: a) $H = 87$ Oe, $\Delta t = 1$ s, b) $H = 87$ Oe, $\Delta t = 2$ s, c) $H = 87$ Oe, $\Delta t = 3$ s, d) $H = 87$ Oe, $\Delta t = 200$ s. The image sizes are 0.11×0.10 mm^2

Figure 2a–d shows a typical dendrite domain growth during magnetization reversal. Initially, the reversal domain nuclei appear in the selected films and they subsequently grow by domain wall propagation in different directions. Such directions are “easy roads” for the motion of domain walls constituting many branches (fingers) to a dendrite. The total dendrite area significantly increases with time (or with the number of field pulses), while dendrite branch width practically does not change. We have found that dendrite branch width w is typically about 6 μm. Note that dendrite-like domain geometry differs from the so-called “swiss cheese” domain structure observed in Au/Co(d)/Au ultrathin films with $d = 0.8$ nm [4]. The latter has irregularities in its spatial hole distribution and their sizes, while in the DDS “black holes” are regularly distributed and have a characteristic size of about 1 μm. The dendritic character of magnetic flux penetration was recently observed in superconducting films [5, 6]. The final stage of DDS evolution is a barely saturated magnetization state, in which “hard” non-reversed magnetic domains (small black regions in Fig. 2d) still exist up to higher magnetic fields, $H \approx H_{\mathrm{col}} = 140$ Oe. Such an unexpected phenomenon – an incompletely saturated state – is related to the contributions of the spatial distribution of local coercive fields, H_c, and domain magnetostatic forces that keep isolated domains metastable.

Making use of an elaborated image processing software, we found the time dependences of the total area fraction of dendritic domains (Fig. 3a). The plots indicate that avalanches – jumps of the derivative of dendrite surface area (Fig. 3b) – are present in the evolution of dendritic domain structure. Such avalanches are the result of domain structure instabilities with respect to small variations in the applied field.

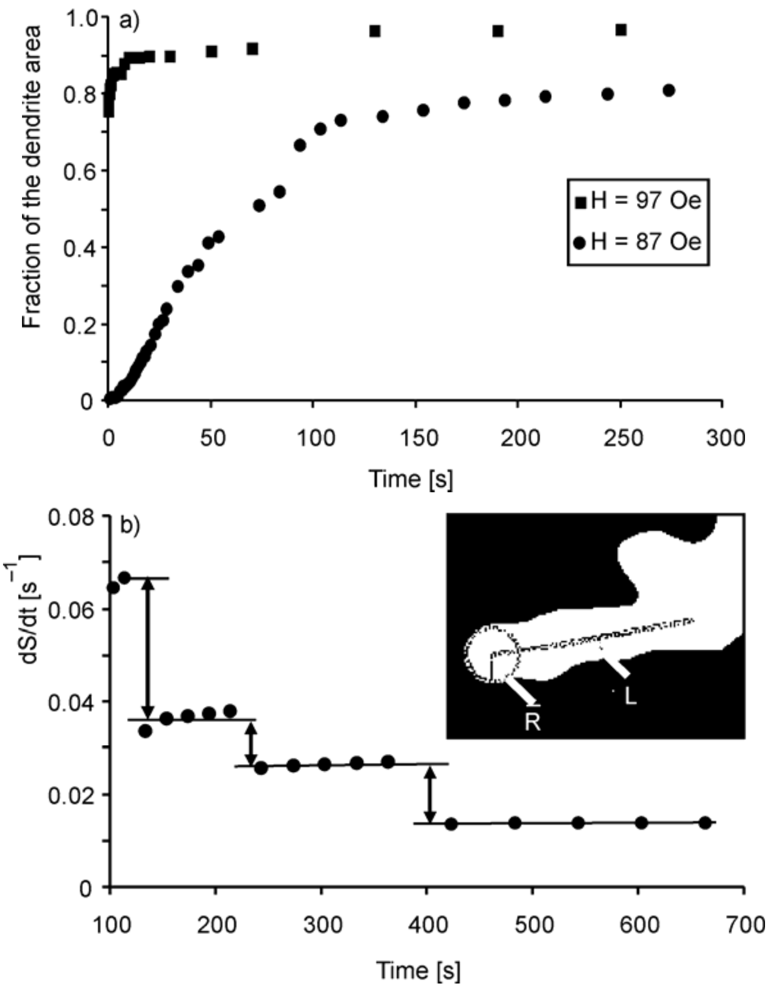

Fig. 3. Time dependence of the total reversed area fraction of domains for two amplitudes of the magnetic field (a) and time derivative of dendrite area (b), H = 87 Oe. The inset shows the geometry of a dendrite finger

Now we describe the dendrite growth mechanism in ultrathin Co films. Initially, some domain nucleation centres (stripe-like domains with magnetization parallel to the applied field) appear in areas where the film morphology favours nucleation processes. It could be possible, for example, that areas with a locally lowered anisotropy constant are caused by variations in film composition or thickness.

Further, nucleation centres grow through fingers. Finger geometry is described by: width w, length L and finger tip radius R (see the inset in Fig. 3). This growth is determined by a balance between magnetic (Zeeman) and magnetostatic forces for transversal and longitudinal directions, respectively,

$$F_{MS}^{t} = -\frac{\partial E_{MS}}{\partial w} \quad \text{and} \quad F_{MS}^{l} = -\frac{\partial E_{MS}}{\partial L}$$

which tend to increase both domain length and width, and the coercive force and domain wall tension preventing it. Local equilibrium requires a balance of all these forces per unit length of the finger contour. A force per unit contour length represents a 2D-pressure acting on the finger walls. Let us denote the 2D-pressures on the lateral finger wall and tip wall as $f_L = F^t/L$ and $f_{\text{tip}} = F^l/\pi R$, respectively. In these terms, the coercive pressure is $f_c = 2M_S H_c d$ and it is the same for transversal and longitudinal directions. The domain wall pressure is given by the Laplace formula $f_w = \sigma d/R$ (σ is the surface density the domain wall energy).

The curvature radius of a lateral finger surface is infinite, and the wall tension there is zero. Therefore, the condition for transversal domain growth is $f^{t}_{MS} + f_H \geq f_c$. In the case of $L >> w$, one can neglect the lateral magnetostatic force and rewrite the transversal growth condition as

$$2M_S Hd \geq f_c \tag{1}$$

Due to domain wall tension at the domain tip, however, the longitudinal growth is determined by the condition

$$\frac{1}{\pi R}\left[\left|\frac{\partial E_{MS}}{\partial L}\right| - \pi\sigma d\right] + 2M_S Hd \geq f_c \tag{2}$$

There is an inequivalence between the growth conditions in the longitudinal and transversal directions. Equation 2 shows that the possibility of longitudinal domain growth is strongly determined by the tip radius and domain wall energy density, σ. Comparing the longitudinal growth condition (Eq. (2)) with the transversal condition (Eq. (1)), one can conclude that the former one is softer, especially in the case of small values of R and σ. The wall tension is small near the RPT, because here the effective anisotropy constant tends to zero ($K_{\text{eff}}(d_1) = 0$), hence $\sigma \propto K_{\text{eff}}^{1/2}$ is low enough. In this case, the first term in Eq. (2) is positive, which promotes the longitudinal growth. This explains the fact that longitudinal growth dominates during dendrite formation in films with d close to the RPT thickness. The mechanism of dendritic domain growth can be explained with the help of Eqs. (1) and (2) as follows. From the nucleation area, the domains initially grow in both directions, transversal and longitudinal. During their growth, however, the domain tip radius increases and it causes the longitudinal growth of a given finger to stop, because of a decreasing driving force according to Eq. (2). After that, the second finger nucleates somewhere on the finger's side surface and the process repeats again until reaching $R \approx w/2$. In the next step, a new nucleation starts and a new finger appears, and so forth. Therefore, domains can only grow in directions where the tip curvature is high enough. As is known, a typical feature of any dendritic growth is a fast decay of tip velocity with time (see Ref. [7] and the references therein). In our case, this phenomenon has a natural explanation – lateral finger expansion increases the tip radius and consequently, in accord with Eq. (2), decreases both the driving force and tip velocity.

4. Conclusion

We have studied some aspects of dendrite growth in the magnetic domains of ultrathin cobalt films. The domain tip radius and wall surface energy density are the key parameters that control the dendrite growth of magnetic domains. We have demonstrated that dendritic domain structures exhibit the general features of dendrite pattern formation: avalanches and finger propagation dependent on tip curvature.

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