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Magnetic ordering in ultra-thin Co films grown on vicinal substrates

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The magnetic anisotropy of ultra-thin Au/Co/Au magnetic films epitaxially grown on vicinal monocrystalline (11–20) sapphire substrates with different miscut angles, covered with a Mo buffer, are investigated by means of ferromagnetic resonance and magnetooptical techniques. Changes in in-plane magnetic anisotropy symmetry were deduced from the shape analysis of magnetization curves and the angular dependence of the resonance field measured in the sample plane. Two-fold and four-fold symmetry was observed for different miscut angles. The preference of the domain wall orientation was observed. The experimental data are discussed taking into account the shape anisotropy, perpendicular uniaxial anisotropy, and step-induced uniaxial anisotropy.

Key words: *magnetic anisotropy; ultra-thin film; cobalt*

1. Introduction

Ultra-thin magnetic multilayers have been intensively investigated due to their interesting physical properties and possible applications for magnetic storage media. Magnetic anisotropy, spin-reorientation transition and self-organization in ultra-thin magnetic films grown on vicinal surfaces, i.e. substrates with ordered monatomic steps, are the properties that attract general attention. Magnetic films grown on vicinal surfaces have shown a strong correlation between the structure of the substrate surface and magnetic properties. In addition to magnetocrystalline anisotropy, an in-plane uniaxial anisotropy is induced when the film is grown on a stepped surface [1–3]. It can favour a magnetic moment alignment perpendicular to the steps [3] as well as parallel to the step edges [4, 5]. For Co layers, magnetic anisotropy strongly depends on thickness, with the spins flipping from the perpendicular to the in-plane orientation [6, 7]. In the

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present work, we report on magnetic anisotropy, magnetisation reversal, and domain structures in ultra-thin Co films grown by molecular beam epitaxy on vicinal sapphire substrates with miscut angles of 1° and 5°.

2. Experimental

Samples grown on sapphire single-crystal (11–20) wafers have the following structure: (i) a buffer layer of 20 nm Mo(110) deposited at $T = 1000$ °C, (ii) a 10 nm Au(111) under-layer deposited at room temperature and annealed at $T = 200$ °C for 30 minutes, (iii) a 2.4 nm Co layer, (iv) a 10 nm thick Au overlayer. The structures of the samples were monitored in-situ by RHEED and Auger spectroscopy.

Measurements were performed at room temperature by means of a magnetometer based on the magneto-optical Kerr effect (MOKE), a polarizing Kerr microscope in the polar configuration, and an FMR X-band spectrometer. Magnetization processes were studied in both longitudinal (L-MOKE) and polar (P-MOKE) configurations. A MOKE magnetometer with laser light with $\lambda = 640$ nm enabled the Kerr rotation and ellipticity to be determined. The laser beam was focused to a spot 0.5 mm in diameter.

3. Results and discussion

The measured resonance field (H_r) is related to magnetic anisotropy constants and enables the determination of the easy magnetization axes. An external magnetic field H was applied to the sample in different directions, defined by polar θ_H and azimuthal φ_H angles measured from the film normal and substrate miscut direction in the sample plane, respectively. By sweeping the amplitude of H, the resonance field H_r was determined for a selected direction defined by the angles θ_H and φ_H. The experimental dependence of H_r on the angle θ_H for samples with different miscut angles is shown in Figs. 1a, b.

An inclination of the easy magnetization axis of about 90° and 70° from the plane normal of samples with miscut angles of 1° and 5°, respectively, was deduced (see Figs. 1a, b). Figures1c, d depict the dependences of in-plane $H_r(\varphi_H)$ with two-fold and four-fold symmetries for samples with miscut angles of 1° and 5°, respectively.

P-MOKE hysteresis loops for different miscut angles are shown in Fig. 2. The loops measured for 1° and 5° miscut angles correspond to in-plane and out-of-plane magnetization orientations, respectively. For the monodomain sample, the magnetization inclination angle θ_{inc} (measured from the film normal) could be determined from the relation $\cos\theta_{\mathrm{inc}} = \theta_K(H_z = 0)/\theta_{K\mathrm{max}}$, where $\theta_{K\mathrm{max}}$ is the maximum polar Kerr rotation, and H_z is the magnetic field applied in the direction perpendicular to the film plane. The value of θ_{inc} close to 90° and about 70° could be calculated from Figs. 2a and 2b, respectively. The shape of the loops is strong evidence of magnetic anisotropy with a canted axis (by about 70° from the normal) for the sample grown on a substrate with a higher miscut. These results are consistent with FMR experiments (Fig. 1).

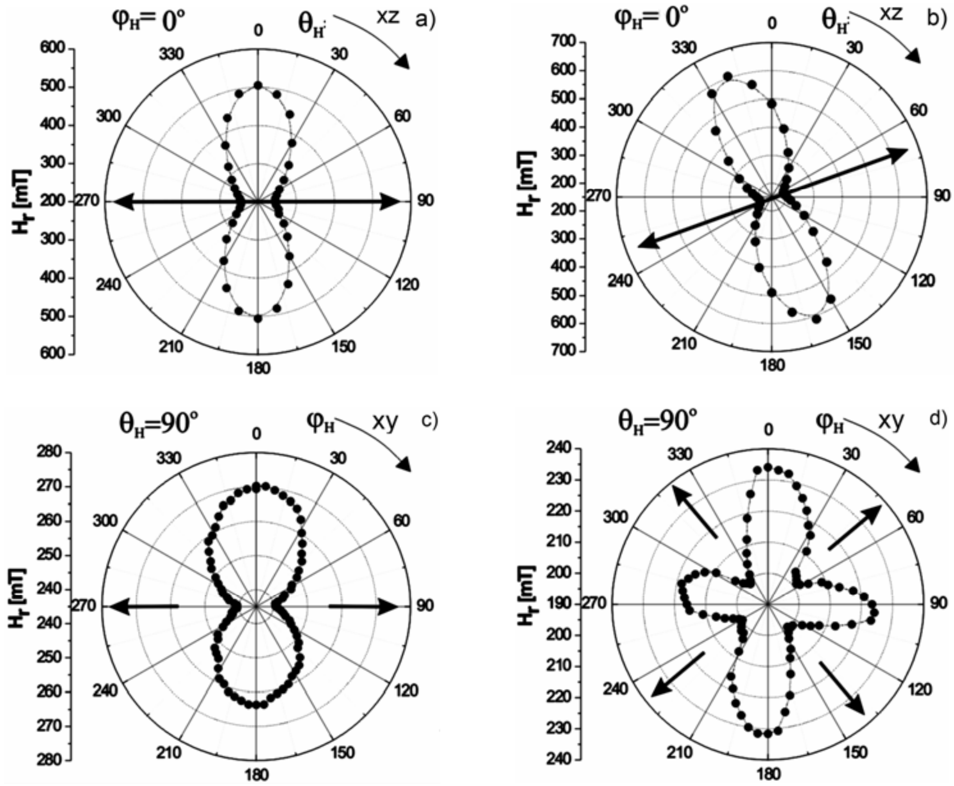

Fig. 1. The dependences of $H_r(\theta_H)$ for the samples with miscut angles of 1° (a) and 5° (b), and for the in-plane samples with miscut angles of 1° (c) and 5° (d)

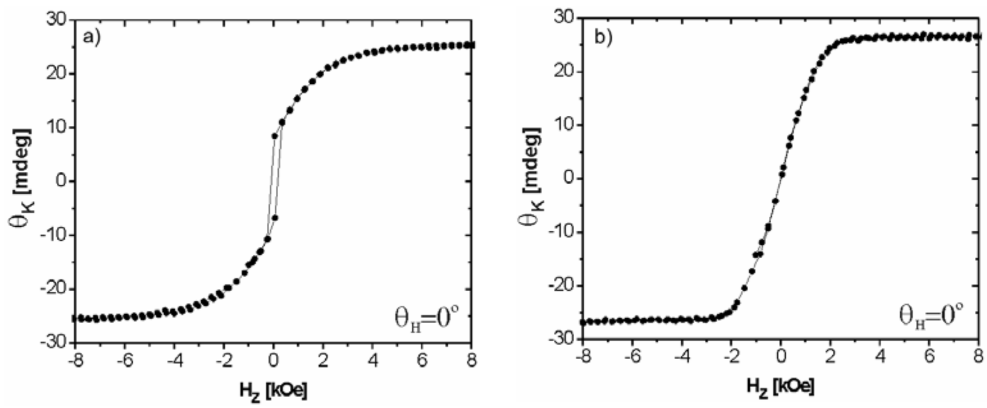

Fig. 2. Hysteresis loops measured as polar Kerr rotations for different miscut angles: a) 1°, b) 5°; for 1°, $\arccos(\theta_K(H_z = 0)/\theta_{K\max}) = 90°$, and for 5°, $\arccos(\theta_K(H_z = 0)/\theta_{K\max}) = 70°$

L-MOKE hysteresis loops measured in-plane magnetic fields H_x oriented at various directions with respect to the miscut direction are plotted in Fig. 3. Curves illustrating the magnetization process when the field is applied along the hard and easy directions, respectively, are shown in Figs. 3a, c for the sample with a 1° miscut angle. The L-MOKE magnetization curves are related to the in-plane two-fold symmetry observed in FMR measurements. In the case of a 5° miscut, a complex form of the hysteresis loops is observed (Figs. 3b, d). This can be explained by the presence of the two easy magnetization axes as found in the FMR experiment.

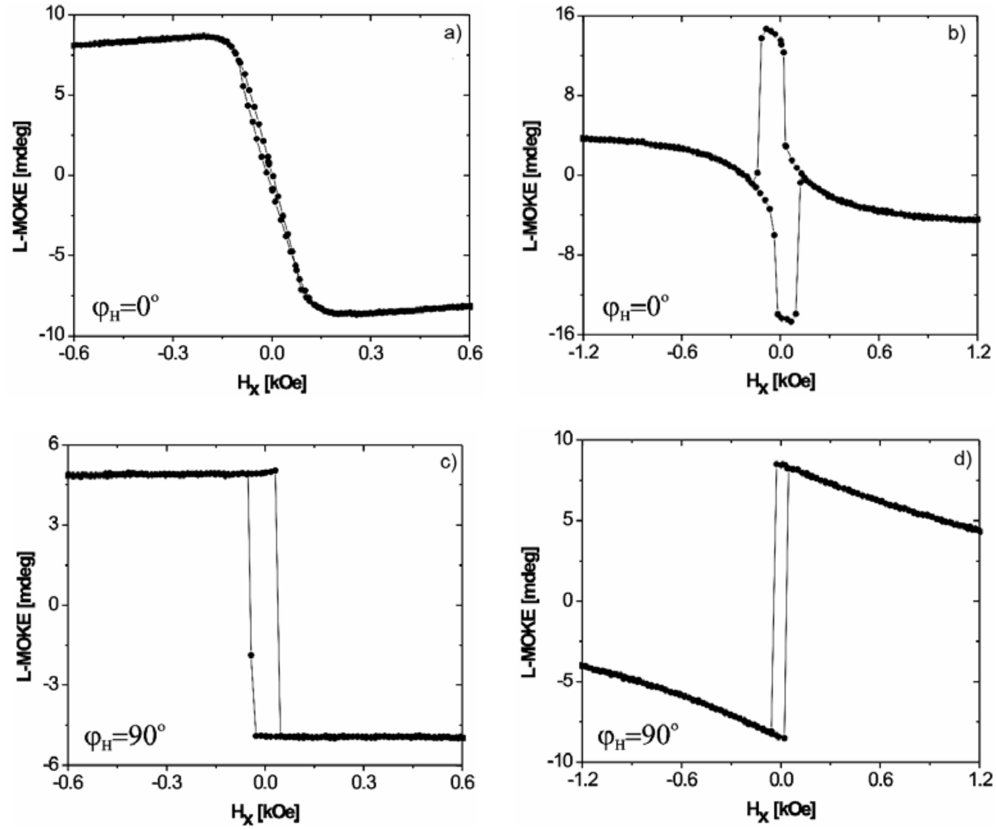

Fig. 3. Hysteresis loops measured as longitudinal Kerr rotations for miscut angles of 1° (a, c) and 5° (b, d) and various angles φ_H =0, 90°

The evolution of magnetic domain structure in the sample with a 5° miscut angle is presented for two steps of magnetization reversal in Fig. 4. The black and grey areas correspond to the change in domain structure after applying magnetic field pulses perpendicular to the film direction. The preference of domain wall orientation could be found in Fig. 4. A similar effect is observed in Ref. [8].

To analyse the experimental data, the following energy contributions were taken into account: (i) uniaxial anisotropy related to the miscut direction defined by the unit vector $\mathbf{v}_{\mathrm{mis}} = (\sin\theta_{\mathrm{mis}}, 0, \cos\theta_{\mathrm{mis}})$, (ii) shape anisotropy, and (iii) step-induced uniaxial in-plane anisotropy in the direction $\mathbf{v}_{\mathrm{step}}=(0, 1, 0)$:

$$E_A(\mathbf{m},\mathbf{v}_{\mathrm{mis}},\mathbf{v}_{\mathrm{step}}) = \left(K_{1v} + \frac{2K_{1s}}{d}\right)\left[1-(\mathbf{m}\cdot\mathbf{v}_{\mathrm{mis}})^2\right] - 2\pi M_S^2 \sin^2\theta$$
$$+K^{(2)}_{\mathrm{step}}\left[1-(\mathbf{m}\cdot\mathbf{v}_{\mathrm{step}})^2\right] + K^{(4)}_{\mathrm{step}}\left[1-(\mathbf{m}\cdot\mathbf{v}_{\mathrm{step}})^2\right]^2$$

where $\mathbf{m} = (\sin\theta\cos\varphi, \sin\theta\sin\varphi, \cos\theta)$ is a unit magnetization vector, and K_{1v} and K_{1s} are the volume and surface anisotropy coefficients [7] determined for a film with thickness d. The proposed formula well describes the magnetic anisotropy of the investigated samples.

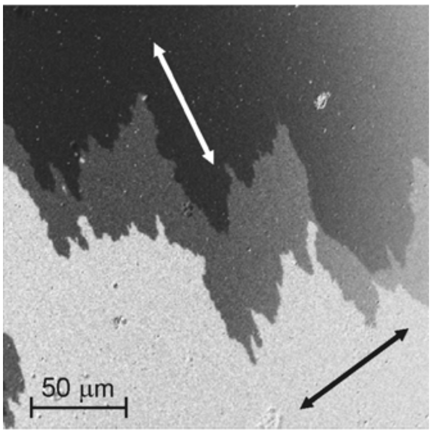

Fig. 4. Magnetic domain structure evolution in the sample with a 5° miscut angle (the black arrow shows the miscut direction); the sample initially saturated by a perpendicular magnetic field $H > 0$. The black and grey areas illustrate the change in the structure induced by $H < 0$ pulses. The white arrow illustrates preferential domain wall orientation

In conclusion, we suggest that the magnetic anisotropy of the Co layer can be tuned between (i) the easy out-of-plane axis, (ii) the two easy out-of-plane axes, and (iii) the easy in-plane axis, by changing the miscut angle of the vicinal substrates and Co thickness. Magnetic anisotropy induces a preference of domain wall orientation.

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