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Magnetic properties of ultrathin Co(0001) films on vicinal Si(111) substrate

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In the present work we report on magnetization reversal process, anisotropy and domain structures in ultrathin Au/Co(0001)/Au films deposited on vicinal Si(111) substrates. The measurements were performed using a magneto-optical Kerr effect based magnetometer, a polarizing optical microscope and a ferromagnetic resonance spectrometer. Co thickness induced spin-reorientation from out-of-plane into in-plane magnetization was studied. Changes of in-plane magnetic anisotropy symmetry were deduced from shapes of magneto-optical hysteresis loops and from analysis of angular dependences of the resonance field. The experimental data have been discussed taking into account both uniaxial out-of-plane anisotropy and step-induced uniaxial in-plane anisotropy. A preferential orientation of domain walls in 3ML thick Co films was observed. The finding is explained by the step-induced magnetic anisotropy.

Key words: *magnetic anisotropy; ultrathin films; cobalt; domain structure*

1. Introduction

Ultrathin Au/Co/Au structures have been intensively studied due to their strong perpendicular anisotropy [1] making them ideal candidates for application in magnetic memory devices. For magnetic ultrathin films, parameters such as growth mode [2], interface roughness [3], substrate nature and orientation play a key role in their structural and magnetic properties such as crystal phase, magnetic anisotropy energy, Curie temperature, spin-reorientation transition (SRT), etc. Magnetic films grown on vicinal surfaces, where density of monoatomic height steps and their orientation are tunable with the miscut angle and miscut direction, exhibit a strong influence on their magnetic properties [4]. Steps on a vicinal Pt surface strongly influence both magnetic anisotropy and the magnetic moment of Co atoms rows [5]. In addition to the magnetocrys-

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talline anisotropy, a uniaxial in-plane anisotropy is induced by a stepped surface. For systems such as Fe/Ag(001) and Co/Cu(001), the induced easy axis is aligned with the step edges [6] whereas in the case of Fe grown on stepped W(001) and stepped Pd(001) it is perpendicular to the step edges [7].

In our work, we focused on the magnetic properties of a Au/Co/Au structure grown on a vicinal Si(111) surface.

2. Sample preparation

A vicinal Si(111) substrate 2° misoriented with respect to the $[\bar{1}\bar{1}2]$ direction was prepared under UHV conditions by flashing with direct current heating up to 1250 °C during a few seconds. The temperature was checked by a thermocouple up to 550 °C and by an infrared pyrometer for higher temperatures. After substrate processing, the silicon surface is constituted of single- and triple-layers high steps (Fig. 1). Such a Si(111) surface with 7×7 reconstructed terraces was examined [8]. A schematic representation of the vicinal surface and basic crystallographic orientations are shown in Fig. 1.

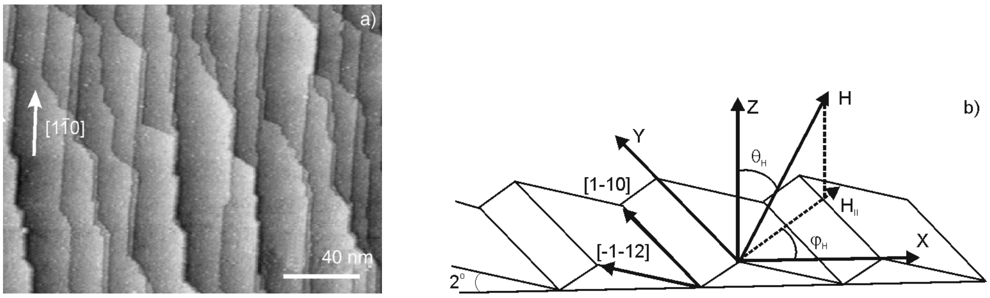

Fig. 1. In-situ STM image (a) and schematic representation of vicinal Si(111) surface (b)

The following structures were deposited by the molecular beam epitaxy on the vicinal Si(111) substrate: a Cu buffer layer 4 monolayers (ML) thick, deposited at 100 °C (i); other layers were deposited at room temperature: 30 ML thick Au(111) underlayer (ii), $d = 3$, 5, 7 and 15 ML thick Co layers (iii) and 30 ML thick Au cover layer (iv). Cobalt deposited on the Au(111) surface is expected to form the *hcp* Co(0001) crystallographic phase [1].

3. Results and discussion

Magnetic properties of the samples at room temperature were studied using magneto-optical Kerr effect (MOKE) using a magnetometer with the laser light of $\lambda = 640$ nm. Magnetization reversal processes enabled one to determine the Kerr rotation and ellipticity in both polar (P-MOKE) and longitudinal (L-MOKE) configurations with perpendicular $H_\perp$ and in-plane $H_\parallel$ magnetic field applied. The magnetic anisotropy was studied using a ferromagnetic resonance (FMR) X-band spectrometer. The external magnetic field was applied to the sample along directions defined by polar θ_H and azimuthal φ_H angles measured, respectively, from the film normal and substrates miscut directions in the sample plane (Fig. 1). The measured resonance field (H_r) is related to the magnetic anisotropy constants and enables determination of the easy magnetization axes (minima in $H_r(\theta_H,\varphi_H)$).

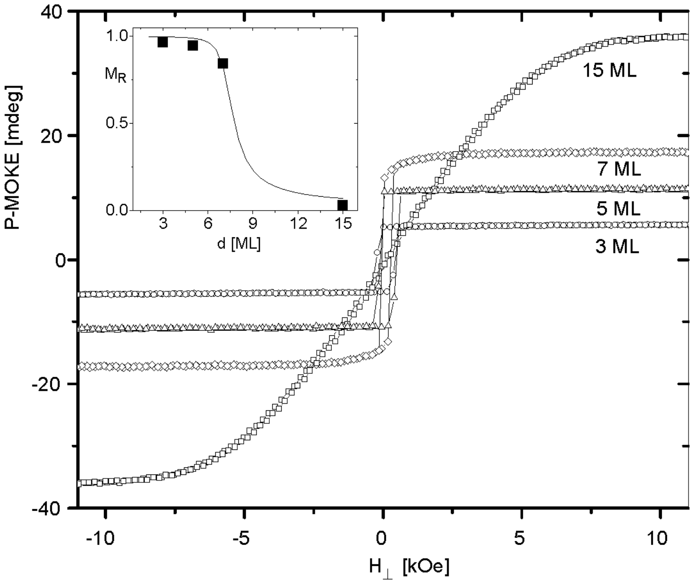

Fig. 2. Hysteresis loops measured by P-MOKE for 3, 5, 7, 15 ML Co film thickness. Inset: dependence of normalized remnant magnetization on the Co thickness; experimental data (dots) and solid line calculated assuming anisotropy constants (Eq. (1)) defined from the resonance field H_r

Figure 2 shows P-MOKE hysteresis loops and normalized remanent magnetization $M_R = M_{(H=0)}/M_s$ (inset) for various Co film thicknesses. A canted magnetization state could be deduced from the magnetization curve recorded for 7 ML Co films. In general, the reorientation could be tuned by overlayer and/or underlayer structures [2, 9]. The SRT undergoes for about 9 ML thick Co film, in gold envelope, deposited on a flat substrate. Thus the morphology of our vicinal substrate influences decrease of the SRT thickness.

Figure 3 shows L-MOKE hysteresis loops for the 15 ML Co thick film with the magnetization mainly in the sample plane. The influence of the step-edges of the vicinal surface on the magnetic anisotropy was deduced from azimuthal dependence of the normalized in-plane ellipticity remanence (M_{in}) (Fig. 3, inset a)). The $[1\bar{1}0]$ direction appears clearly as an easy axis with a square L-MOKE hysteresis loop when the field is applied in this direction and the loop with a negligible hysteresis for the field applied in the perpendicular direction. The azimuthal dependence of the coercive field

$H_c(\varphi_H)$ in the sample plane was studied by L-MOKE for a 15 ML thick Co film (Fig. 3, inset b)). The plot gives additional evidence for the hard axis orientation along the direction perpendicular to the step edges (0° and 180°).

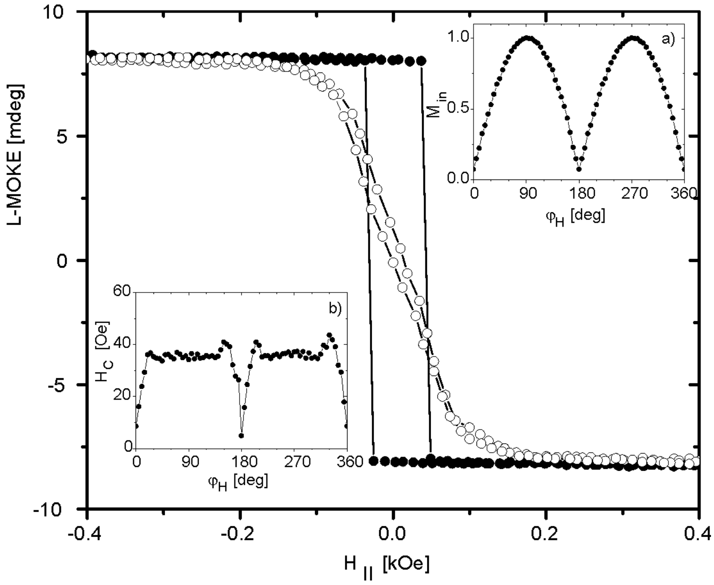

Fig. 3. Hysteresis loops measured by L-MOKE for 15 ML Co film thickness and the angles $\varphi_H = 0$ (open circles) and 90° (full circles). Insets show angular dependences measured by L-MOKE of: a) normalized in-plane ellipticity remanence, b) coercivity field

The angular dependences of the resonance field $H_r(\theta_H, \varphi_H)$ for 15 ML thick Co film are plotted in Fig. 4. The magnetic anisotropy symmetry can be deduced from these dependences. Figure 4 shows that the easy magnetization axis is close to the $[1\bar{1}0]$ direction.

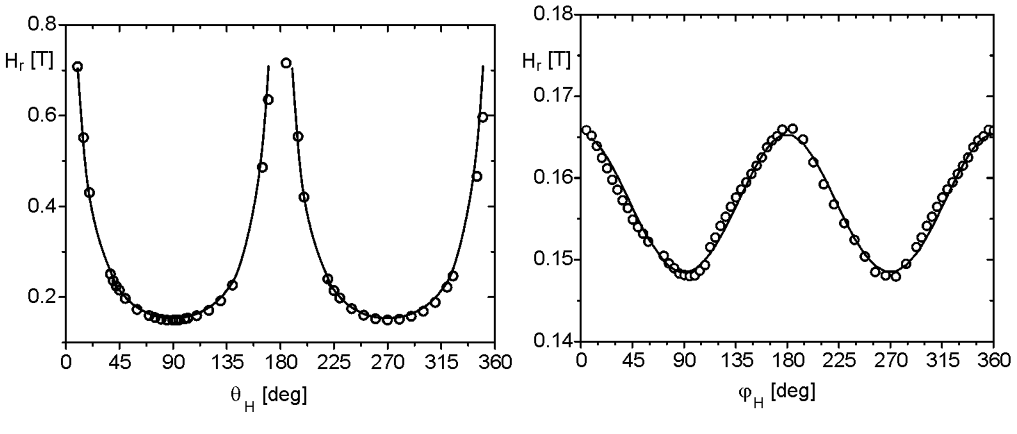

Fig. 4. FMR dependence $H_r(\theta_H; \varphi_H)$ for 15 ML thick Co sample. Solid lines fitted using the anisotropy constants as follows: $K_{u1} = 0.81$ MJ/m^3, $K_{vic} = -0.009$ MJ/m^3

The following expression of the magnetic anisotropy was used for the FMR curves fitting

$$E_A(\theta,\varphi,d)=\left(K_V+\frac{2K_s}{d}\right)\left(1-\left(\mathbf{m}\times\mathbf{v}_{\mathrm{mis}}\right)^2\right)-\frac{1}{2}\mu_0M_s^2\sin^2\theta+K_{\mathrm{vic}}\sin^2\theta\sin^2\varphi \qquad (1)$$

where K_v and K_s are the volume and surface anisotropy constants, respectively, M_s is the saturation magnetization; **m** is the normalized magnetization vector and $\mathbf{v}_{\mathrm{mis}}$ is the normalized vector of the vicinity direction [10], K_{vic} is the step-induced uniaxial anisotropy constant. The fitted $H_r(\theta_H, \varphi_H)$ curves (with magnetic anisotropy constants $K_{u1} = (K_v + 2K_s/d) = 0.81$ MJ/m^3, $K_{\mathrm{vic}} = -0.009$ MJ/m^3) are shown in Fig. 4 as solid lines. The solid line in Fig. 2 was calculated using $K_v = 0.45$ MJ/m^3 and $K_s = 0.54$ mJ/m^2 anisotropy constants. The uniaxial out-of-plane anisotropy constant is in agreement with that expected of the *hcp* Co phase [2, 11]. Analysis of the magnetization curve recorded for $H_{\|}$ applied along the hard axis (Fig. 3) gives a similar uniaxial in-plane anisotropy field $H_{\mathrm{vic}} = 2K_{\mathrm{vic}}/M_s = 0.013$ T.

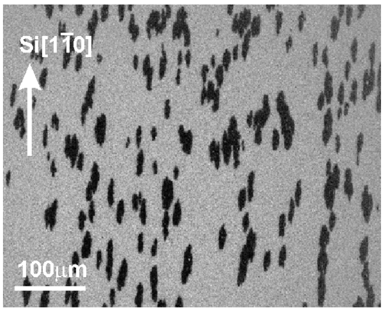

Fig. 5. Remnant domain structure for 3 ML thick Co sample

P-MOKE microscopy is a powerful tool to study magnetization reversal processes in magnetic film with a perpendicular anisotropy [12]. Figure 5 shows the remanent domain structure image recorded for a 3 ML thick Co film. The preference of domain wall orientation along the $[1\bar{1}0]$ direction is well visible. The preference could be explained by a step-induced in-plane magnetic anisotropy determined from both FMR and L-MOKE measurements. A similar preference of domain wall orientation structure was also observed in ultrathin Co film deposited on a vicinal sapphire substrate [13].

4. Conclusion

Au/Co/Au structures were grown on a vicinal Si(111) surface with various thicknesses of Co layers. The symmetry of the magnetic anisotropy observed by both MOKE and FMR is connected with growth of *hcp* Co(0001) film. The out-of-plane and step-induced uniaxial in-plane magnetic anisotropies were studied in a 15 ML thick Co film. The anisotropies were found to strongly influence the domain wall propagation along the step edges of the vicinal surface.

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References

[1] CHAPPERT C., LE DUANG K., BEAUVILLAIN P., HURDEQUINT H., RENARD D., Phys. Rev. B, 34 (1986), 3192.

[2] KISIELEWSKI M., MAZIEWSKI A., TEKIELAK M., WAWRO A., BACZEWSKI L.T., Phys. Rev. Lett., 89 (2002), 087203.

[3] VAZ C.A.F., STEINMULLER S.J., BLAND J.A.C., Phys. Rev. B, 75 (2007), 132402.

[4] LEE S., PARK S., FALCO C.M., J. Magn. Magn. Mater., 240 (2002), 457.

[5] GAMBARDELLA P., DALLMEYER A., MAITI K., MALAGOLI M.C., EBERHARDT W., KERN K., CARBONE C., Nature, 416 (2002), 301.

[6] KAWAKAMI R.K., ESCORCIA-APARICIO E.J., QIU Z.Q., Phys. Rev. Lett., 77 (1996), 2570.

[7] CHOI H.J., KAWAKAMI R.K., ESCORCIA-APARICIO E.J., QIU Z.Q., PEARSON J., JIANG J.S., LI D., OSGOOD R.M. III, BADER S.D., J. Appl. Phys., 85 (1999), 4958.

[8] WEI J., WANG X.-S, GOLDBERG J.L., BARTELT N.C., WILLIAMS E.D., Phys. Rev. Lett., 68 (1992), 3885.

[9] LANGER J., HUNTER DUNN J., HAHLIN A., KARIS O., SELLMANN R., ARVANITIS D., MALETTA H., Phys. Rev. B, 66 (2002), 172401.

[10] STUPAKIEWICZ A., GIENIUSZ R., MAZIEWSKI A., POSTAVA K., WAWRO A., BACZEWSKI L.T., Phys. Stat. Sol. (b), 243 (2006), 202.

[11] JEONGA J.-R., BLAND J., LEE J.-W., PARK Y.-S., SHIN S.-C., Appl. Phys. Lett., 90 (2007), 022509.

[12] POMMIER J., MEYER P., PÉNISSARD G., FERRÉ J., BRUNO P., RENARD D., Phys. Rev. Lett., 65 (1990), 2054.

[13] STUPAKIEWICZ A., TEKIELAK M., MAZIEWSKI A., ZABLOTSKII V., BACZEWSKI L.T., WAWRO A., J. Magn. Magn. Mater., 316 (2007), e136.

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