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 [112] 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)](image)

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) configura-
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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 $\theta_H$ and azimuthal $\phi_H$ 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 $H_r(\theta_H, \phi_H)$).

**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 ($M_{\text{in}}$) (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
$H_c(\phi_H)$ 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°).

![Graph showing hysteresis loops](image)

**Fig. 3.** Hysteresis loops measured by L-MOKE for 15 ML Co film thickness and the angles $\phi_H = 0$ (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 $H_r(\theta_H, \phi_H)$ 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 [110] direction.

![Graph showing FMR dependence](image)

**Fig. 4.** FMR dependence $H_r(\theta_H, \phi_H)$ for 15 ML thick Co sample. Solid lines fitted using the anisotropy constants as follows: $K_u = 0.81$ MJ/m$^3$, $K_{vic} = -0.009$ MJ/m$^3$.
The following expression of the magnetic anisotropy was used for the FMR curves fitting

\[
E_A(\theta, \phi) = \left(K_v + \frac{2K_s}{d}\right)\left(1 - (\mathbf{m} \times \mathbf{v}_{\text{vic}})^2\right) - \frac{1}{2} \mu_0 M_s^2 \sin^2 \theta + K_{\text{vic}} \sin^2 \theta \sin^2 \phi
\]  

(1)

where \(K_v\) and \(K_s\) are the volume and surface anisotropy constants, respectively, \(M_s\) is the saturation magnetization; \(\mathbf{m}\) is the normalized magnetization vector and \(\mathbf{v}_{\text{vic}}\) is the normalized vector of the vicinity direction [10], \(K_{\text{vic}}\) is the step-induced uniaxial anisotropy constant. The fitted \(H_r(\theta, \phi)\) curves (with magnetic anisotropy constants \(K_v = 0.45\) MJ/m\(^3\) and \(K_s = 0.54\) mJ/m\(^2\)) are shown in Fig. 4 as solid lines. The solid line in Fig. 2 was calculated using \(K_v = 0.81\) MJ/m\(^3\) and \(K_s = -0.009\) MJ/m\(^3\) 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 \(H_\parallel\) applied along the hard axis (Fig. 3) gives a similar uniaxial in-plane anisotropy field \(H_{\text{vic}} = 2K_{\text{vic}}/M_s = 0.013\) T.

![Fig. 5. Remnant domain structure for 3 ML thick Co sample](image)

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 10] 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


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