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Study of ultrathin Co films grown on Si(111) substrates

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Ultrathin Co films were grown on vicinal Si(111) substrate with Cu buffer layers. Room temperature ferromagnetic behaviour of Co layer thicker than 4 monolayers was confirmed by the magneto-optical Kerr effect. Ferromagnetic resonance measurements have proven the coexistence of the magnetocrystalline anisotropy along with the growth- and vicinal induced uniaxial out-of-plane and in-plane contributions. Multi-jump hysteresis loops were observed for selected in-plane orientations of magnetic field which is explained by the competition of different anisotropy contributions.

Key words: *magnetic anisotropy; ultrathin films; cobalt; vicinal substrate*

1. Introduction

Ultrathin magnetic materials have been intensively investigated due to their interesting physical properties and technological application. Vicinal substrates are very popular templates for the self-organized growth of magnetic nanostructures and nanoparticles [1, 2]. In the case of growth of a thin magnetic film, the vicinality induces new terms in the expression of the magnetic anisotropy energy. When the film is grown on a stepped surface [3–6], the following contributions to magnetic anisotropy are usually considered: the magnetocrystalline, shape, and both out-of plane and in-plane uniaxial magnetic anisotropies.

In the present work, we investigate the magnetization reversal and magnetic anisotropy of ultrathin Co films grown on vicinal Si(111) substrates. Due to a strong reactivity between Co and Si, cobalt is deposited on a Cu buffer layer. The growth of cobalt on copper substrates has been intensively studied because the fcc Co crystalline structure can be stabilized [7]. The combination of cubic magnetocrystalline anisotro-

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py with step induced anisotropy was studied in the Co/Cu(001) system [3, 8]. However, a systematic study on Co/Cu(111) films has not been carried out.

2. Experimenal details

The following structures were deposited by molecular beam epitaxy on a vicinal Si(111) substrate with 2° misorientation towards the $[\bar{1}\bar{1}2]$ direction. The surface was prepared under ultra high vacuum by direct current heating up to 1250 °C for a few seconds. The temperature was checked using a thermocouple up to 550 °C and by infrared pyrometer above. As seen by STM after preparation, the surface is constituted of monoatomic steps separated by 7×7 reconstructed terraces [9]. Step-edge orientation on the substrate was along the $[1\bar{1}0]$ Si direction. The buffer layer of 4 Cu monolayers (MLs) was deposited at 100 °C and was expected to form Cu silicide [10]. Our previous investigations by the second harmonic generation technique [11] showed that Cu coverage reproduces vicinal character of the Si substrate. 3, 5, 7 and 15 MLs of Co were then deposited at room temperature (RT) on the Cu surface. Finally a 30 ML Au capping layer was grown at RT.

Measurements were performed at RT using a magneto-optical Kerr effect (MOKE) based magnetometer and ferromagnetic resonance (FMR) X-band spectrometer. The MOKE magnetometer with laser light of $\lambda = 640$ nm enabled determination of the Kerr rotation and ellipticity for both polar (p-MOKE) and longitudinal (l-MOKE) experimental configurations. The measurements of the l-MOKE hysteresis loops were performed with the magnetic field applied at different azimuthal orientations defined by φ_H, the angle in the plane of the sample referenced from miscut direction.

3. Results and discussion

The p-MOKE hysteresis loops for various Co thicknesses are presented in Fig. 1, pointing to the absence of ferromagnetism for the Co coverage below 5 ML. This may be explained by the formation of Co compounds with Cu and Si [12, 13]. Lowering of the Curie temperature is expected at such interfaces [4].

Out-of-plane magnetization components were observed for the 7 ML Co thickness. A canted magnetization state is deduced from the magnetization curves, as shown in the inset of Fig. 1. Mainly in-plane magnetization state is expected from p-MOKE loop measured for 15 ML Co.

The FMR technique is useful in a direct determination of the magnetic anisotropy. Measurements of the angular dependence of the resonance field (H_r) are related to the magnetic anisotropy constants and enable determination of the easy magnetization axes (minima in H_r). The experimental dependence of the resonance field H_r in function of the angle φ_H for the 15 ML Co sample is shown in Fig. 2 (dots).

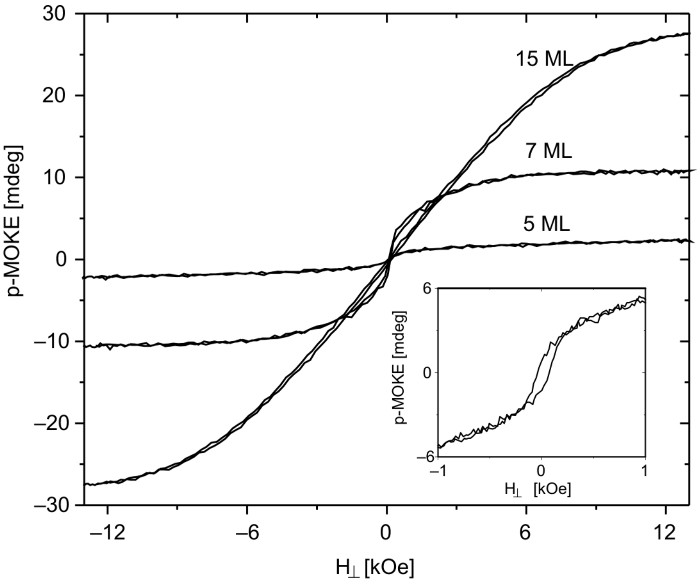

Fig. 1. Polar Kerr rotation hysteresis loops for 5, 7, 15 ML thicknesses of Co; inset: 7 ML Co hysteresis loop for magnetic field up to 1 kOe

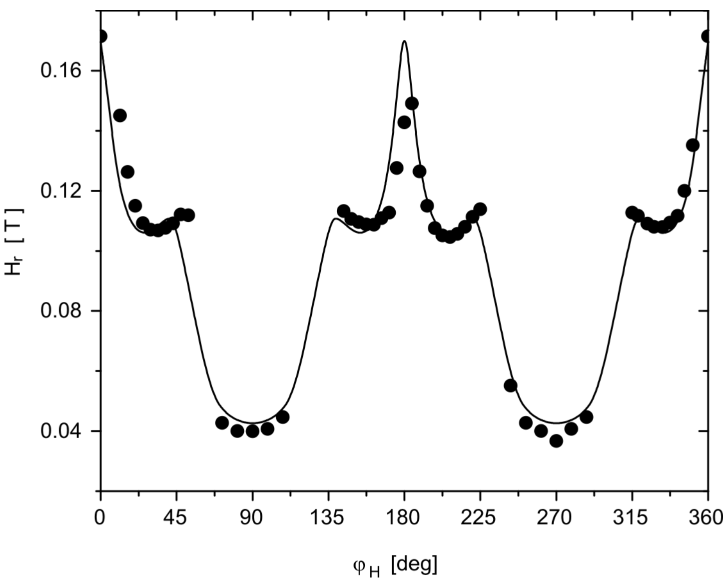

Fig. 2. The $H_r(\varphi_H)$ characteristic for the Co sample15 ML thick. The solid line represents the fit corresponding to: $M_s = 1420$ kA/m, $K_{u1} = 0.53$ MJ/m^3, $K_{vic} = -0.03$ MJ/m^3 and $K_1 = 0.14$ MJ/m^3

The easy magnetization axis corresponding to the cubic and uniaxial step-induced anisotropy was deduced by analyzing the $Hr(\varphi_H)$ dependence, shown in Fig. 2. From the $Hr(\varphi_H)$ curve, the easy magnetization axis is determined to be near 90° and 270°

related to the $[1\bar{1}0]$ Si direction. In addition, a six-fold symmetry is visible. In our analysis of the experimental data, we have taken into consideration: the uniaxial anisotropy related to the miscut direction defined by the unit vector $\mathbf{v}_{\text{mis}} = (\sin\theta_{\text{mis}}, 0, \cos\theta_{\text{mis}})$ [14] (i); the demagnetization term (ii); the step-induced uniaxial in-plane anisotropy (iii) and the magnetocrystalline anisotropy (iv) [15]. The resultant expression is:

$$\begin{aligned} E_A(\theta,\varphi) &= K_{u1}\left[1-\left(\mathbf{m}\mathbf{v}_{\text{mis}}\right)^2\right] - \frac{1}{2}\mu_0 M_s^2 \sin^2\theta + K_{\text{vic}}\sin^2\theta\,\sin^2\varphi \\ &+ K_1\left(\frac{1}{4}\sin^4\theta + \frac{1}{3}\cos^4\theta - \frac{\sqrt{2}}{3}\sin^3\theta\cos\theta\sin 3\varphi\right) \end{aligned} \tag{1}$$

where K_{u1} is the uniaxial perpendicular anisotropy constant, K_{vic} is the uniaxial in-plane step-induced anisotropy constant, K_1 is the first cubic magnetocrystalline constant, $\mathbf{m} = (\sin\theta\cos\varphi, \sin\theta\sin\varphi, \cos\theta)$ is the unit magnetization vector, θ is the angle between the magnetization direction and the sample plane normal, φ is the angle of the in-plane magnetization orientation relative to the miscut direction. The formula well describes the magnetic anisotropy, as shown by the fitted (solid) line in Fig. 2.

Hysteresis loops of the 15 ML Co film were investigated by l-MOKE where the magnetic field $H_{||}$ was applied in the sample plane (Fig. 3).

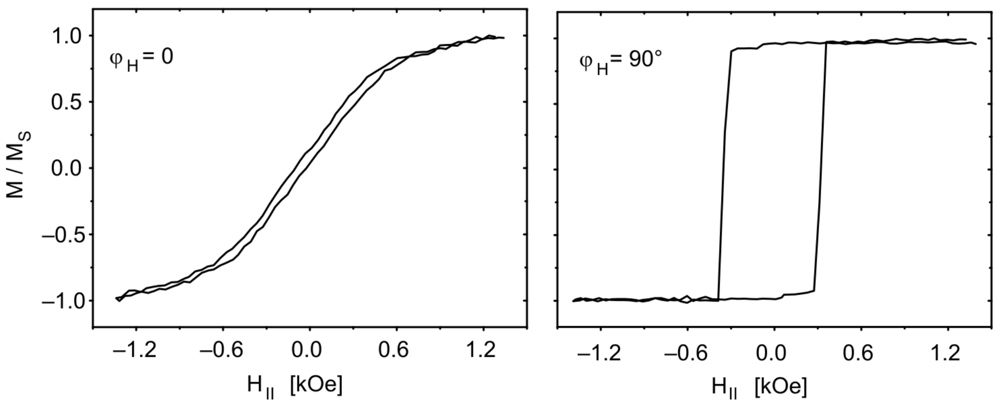

Fig. 3. Hysteresis loops measured by l-MOKE for Co 15 ML thick in the hard ($\varphi_H = 0$) and easy directions ($\varphi_H = 90^\circ$)

The magnetization reversal exhibits two jumps for $H_{||}(\varphi_H = 90°)$ at about 60 and 300 Oe. This is related to the nonequivalent easy axis, asymmetrical for projection of cubic anisotropy contribution to the (111) plane. Such a reversal has been observed for cubic materials deposited on vicinal substrates [6].

Figure 4 shows the azimuthal dependence of the coercive field H_C in the sample plane studied by l-MOKE for the 15 ML thick cobalt film. This plot presents six minima with a clear hard axis appearing in the direction perpendicular to the steps edges

(0° and 180°). The maxima of the $H_C(\varphi_H)$ dependence near 90° and 270° are related to the uniaxial step-induced magnetic anisotropy.

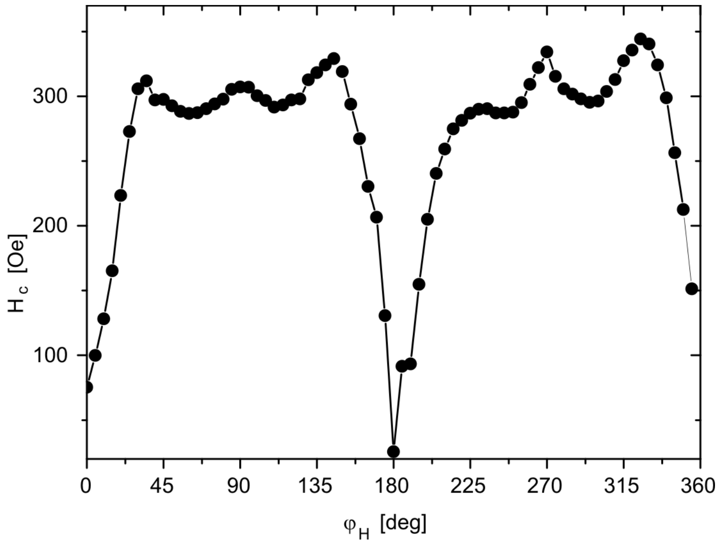

Fig. 4. Measured angular dependence of the coercivity field H_C for a 15 ML Co film

This dependence can be explained by the presence of local minima near 60°, 120°, 240° and 300° which represent the contributions of the cubic symmetry of the Co films. The coercive field dependence is thus in agreement with the FMR experiments.

4. Conclusion

We have demonstrated that Co thin films grown at RT using Cu as a buffer layer on Si(111) vicinal surfaces are ferromagnetic at about 4 ML. For a 15 ML deposited Co film, the magnetic anisotropy is a competition of the cubic magnetocrystalline anisotropy and the uniaxial anisotropy induced by the vicinal substrate. The angular dependence of the FMR field curve was fitted and the values of the anisotropy constants were calculated. This complex anisotropy induces a multi-jumps reversal process.

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