Surface morphology and magnetic anisotropy of obliquely deposited Co/Si(111) films

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We report an investigation on magnetic anisotropy of Co/Si(111) films deposited at oblique incidence. An in-plane uniaxial magnetic anisotropy (UMA) with the easy axis perpendicular to the incident flux plane was observed to superimpose on sixfold magnetocrystalline anisotropy of Co films. We built a total energy model to investigate the magnetization reversal mechanism around hard axis. The simulated value of UMA is $K_u=1.7 \times 10^5 \text{ erg/cm}^3$, which is consistent with $K_{\text{shape}}=1.1 \times 10^5 \text{ erg/cm}^3$ calculated from scanning tunneling microscope image. This good agreement suggests the in-plane UMA is mainly originated from the shape of the oblique deposited Co stripes. © 2010 American Institute of Physics. [doi:10.1063/1.3463458]

The effect of surface morphology on magnetic anisotropy has attracted much attention in recent years. The interaction between the deposited atoms and the atoms on the surface modifies the trajectory of the deposited atoms, which is called steering effect, and causes the inhomogeneous distribution of adatoms. In the oblique incident deposition, such steering effect is important and generally introduces grains that are elongated perpendicular to the plane of incident flux direction. This elongated grains always result in an in-plane uniaxial magnetic anisotropy (UMA) as depositing magnetic materials. Furthermore, Bubendorff et al. proposed a correlation function to calculate the surface morphology induced shape magnetic anisotropy from actual surface image. On the side of manipulating magnetic anisotropy, the UMA was usually introduced to impose on forthfold magnetic anisotropy, including Fe on MgO(001) and Co on Cu(001) to manipulate the magnetization reversal process. Depending on the strength and orientation of the UMA, magnetic hysteresis curves around the hard axis of the UMA with two and three steps are observed. A coherent rotation model based on the total energy also has been adopted to interpret the magnetization reversal mechanism. However, the UMA superimposed on the sixth-fold magnetic anisotropy and the origin of the UMA were less reported.

In this paper, we fabricated Co film on Si(111) substrate by oblique incident deposition, investigated the magnetization reversal mechanism by using magneto-optical Kerr effect (MOKE) and built a total energy model to investigate the magnetic hysteresis curves near the hard axis. Moreover, we investigated the surface morphology induced magnetic shape anisotropy by calculating the height self-correlation function through the actual scanning tunneling microscope (STM) image. The good agreement of the UMA constant value obtained from energy model and surface morphology image implies that the in-plane UMA is mainly from the long-range dipolar interactions between the spins on the surface.

The samples were prepared in a molecular beam epitaxy (MBE) system with a base vacuum of $10^{-10}$ mbar by using the electron gun evaporation at room temperature. Nominal thickness of 10 nm Co film was deposited on Si(111) substrates at an angle of 60° with respect to the surface normal and with azimuth along the y direction, i.e., perpendicular to the surface steps on the substrates, as shown in Fig. 1(a). The growth rate was fixed at 4 Å/min. For comparison, another 10 nm thick Co film was fabricated by normal incident deposition with the same growth rate. The STM image as indicated in Fig. 1(b) shows the surface of the oblique deposited sample. The clear grains are elongated perpendicular to the incident plane of the atomic flux and form stripe structure.

![FIG. 1. (Color online) (a) Sketch map of deposition direction and the external field $H_{\text{ext}}$ orientation $\varphi$ for MOKE measurement. (b) (150×150 nm²) STM images of 60° oblique incidence deposited Co film; the arrow indicates the incident atomic flux direction. (c) (150×150 nm²) STM images of normal incidence deposited Co film. (d) Cartesian coordinates for Co film and the UMA on Si(111) surface.](https://example.com/fig1.png)
with root mean square (rms) roughness of 0.65 nm. However, for the normal incidence deposited Co film, the STM image as shown in Fig. 1(c), demonstrates that the grain distribution on the film surface is isotropic and the rms roughness is much less (~0.12 nm) than that in the oblique deposited one. The elongated grains and the striped structure in Fig. 1(b) can be interpreted as a consequence of the self steering effect during deposition. Before performing the ex situ MOKE measurement, the films were covered by a 25 Å thick protective NaCl layer.

The magnetic hysteresis loops were measured at various magnetic field orientation \( \varphi \) as defined in Fig. 1(a). The representative loops shown in Fig. 2 change gradually from the obtuse rectangle shape to the square one, then to the sheared one with almost no remanence, and finally to the rounded hysteresis loop when the applied field rotates from \( \varphi = 210^\circ \) to \( 70^\circ \). The evolution for the external field \( H_{\text{ext}} \) orientation dependence of magnetic hysteresis loop indicates the global easy axis of the Co film is at \( \varphi = 0^\circ \), \( 180^\circ \), i.e., along the stripe direction where the hysteresis loop is with best rectangular ratio. The magnetic hysteresis loop measured around the hard axis, \( \varphi = 70^\circ \), shows the unexpected peaks, which is not in the oblique deposited one. The elongated grains and the striped structure corresponding experimental ones measured at \( \varphi = 70^\circ \), \( 80^\circ \), and \( 90^\circ \), are shown in Fig. 2. The best fitting parameters \( K_1 \) and \( K_2 \) are the first- and second-order cubic magnetocrystalline anisotropy constants of Co(111) films, \( K_u \) is the UMA constant. The unit vectors \( \vec{u} \) and \( \vec{n} \) represent the UMA and the film surface’s normal direction, respectively. We use the room temperature values \( K_1 = 1.6 \times 10^6 \text{ erg/cm}^3 \) and \( M_s = 1422 \text{ emu/cm}^3 \) for Co. Our STM data for the Si(111) surface show that the average step width \( L \) of the Si(111) is about 60 nm, and the step height \( h \) is 0.3 nm. From the tangent angle formula \( \varphi = \tan^{-1}(h/L) \), we can calculate the normal direction \( \vec{n} \) of Co film surface is tilted by \( \sim 0.28^\circ \) with respect to the [111] direction. In order to meet such tilt in the theoretical calculations, the polar and azimuthal angles of \( \vec{n} \) are set as 54.7° and 44.5° [Fig. 1(d)]. Besides these, due to the asymmetric variation in \( H \), around \( \varphi = 90^\circ \) and \( 270^\circ \) in Fig. 3 and several hysteresis loops around \( \varphi = 90^\circ \), \( 88^\circ - 91^\circ \), are all with almost zero remanence, \( 2^\circ \) misalignment of vector \( \vec{u} \) with the [110] direction is assumed. Correspondingly, the polar and the azimuthal angles of vector \( \vec{u} \) are set as 88.4° and 136.2°, respectively [Fig. 1(d)]. The calculated hysteresis loops as well as the corresponding experimental ones measured at \( \varphi = 70^\circ \), \( 80^\circ \), and \( 90^\circ \), are shown in Fig. 2. The best fitting parameters are obtained as \( K_1 = 1.7 \times 10^5 \text{ erg/cm}^3 \) and \( K_2 = 7.2 \times 10^5 \text{ erg/cm}^3 \). The disagreement between the calculated and the experimental curves a \( \varphi = 90^\circ \) is likely due to the nonuniform reversal mode of the Co film.

Furthermore, in order to specify the two possible origins of the UMA in the oblique deposited Co stripes: magneto-elastic effects due to internal strain effect and long-range dipolar interactions between spins which is controlled by the shape of the deposit, we use the surface profile to estimate the morphology induced magnetic shape anisotropy. Considering the obliquely deposited Co film, the shape factor for the surface morphology is definitely related to its height distribution \( e(\theta) \), which can be obtained from the STM images. By properly choosing the self-correlation function \( g_0(\theta) \), in

\[
E = K_1(\alpha_1^2 \alpha_2^2 + \alpha_2^2 \alpha_3^2 + \alpha_3^2 \alpha_1^2) + K_2(\alpha_1 \alpha_2 \alpha_3)^2 - K_u(\vec{M}_s \cdot \vec{u})^2 + 2 \pi(\vec{M}_s \cdot \vec{n})^2 - \vec{M}_s \cdot \vec{H},
\]

where \( K_1 \) and \( K_2 \) are the first- and second-order cubic magnetocrystalline anisotropy constants of Co(111) films, \( K_u \) is the UMA constant. The unit vectors \( \vec{u} \) and \( \vec{n} \) represent the UMA and the film surface’s normal direction, respectively.
which considering the height variation for any two points in a STM image and the angle at the height direction, the film roughness can be described as follows:

\[
g_{ij}(\vec{r}) = \frac{1}{S} \int_S d^2 \vec{r} \frac{\partial e}{\partial j}(\vec{r}_0) \left(1 + \frac{e(\vec{r}_0) - e(\vec{r}_0 + \vec{r})}{r} \right)^2 \right)^{1/2},
\]

where \(S\) is the nominal film surface. Obviously, the partial derivations of the film height \(e(\vec{r})\) are of especial interests: \(\partial e(\vec{r})/\partial i\) and its distribution determines the \(g_{ij}(\vec{r})\). The components of shape tensor \([N]\) can be written as follows:

\[
N_{ij} = \frac{1}{4\pi d} \int_S \frac{d^2 \vec{r}}{|\vec{r}|} g_{ij}(\vec{r}),
\]

where \(d\) is the film thickness.

Using the above equations, the magnetic shape anisotropy can be calculated:

\[
K_{\text{shape}} = \frac{1}{2} \mu_0 M_s^2 \left(N_{xx} - N_{yy}\right),
\]

where \(N_{xx} - N_{yy}\) is the demagnetization factor.

Taking the center point in the STM image as reference, we calculated the self-correlation function \(g_{ij}(\vec{r})\) for all the point in the image. Figure 4(a) is the \(g_{ij}(\vec{r})\) spatial arrangement calculated from the corresponding STM image (shown below) for the Co film oblique deposited at 60°. In Fig. 4(b), projection of \(g_{ij}(\vec{r})\) on the x-y plane shows clear striped structures, which results in the easy axis for the superimposed UMA of the Co film along the grains stripe direction. This conclusion is consistent with the MOKE measurements. Consequently, \([N]\) and \(K_{\text{shape}}\) can be obtained through the above equations, thus we get \(N_{xx} = 0.1195, N_{yy} = 0.2279,\) and \(K_{\text{shape}} = 1.1 \times 10^5 \text{ erg/cm}^3\). Figures 4(c) and 4(d) are the calculated results for Co film deposited at normal incidence. The striped patterns in the x-y plane projection of \(g_{ij}(\vec{r})\) are almost vanished, which indicates the morphology of the film is isotropic. The corresponding \([N]\) and \(K_{\text{shape}}\) are calculated as \(N_{xx} = 0.0109, N_{yy} = 0.0253,\) and \(K_{\text{shape}} = 1.5 \times 10^4 \text{ erg/cm}^3\). The magnitude of \(K_{\text{shape}}\) is one order less than the value for sample deposited at the oblique incidence. The large difference between the calculated \(K_{\text{shape}}\) for the Co film deposited at oblique incidence and at normal incidence, and the good agreement of \(K_u\) estimated from both the coherent rotation (\(K_u = 1.7 \times 10^5 \text{ erg/cm}^3\)) and the self-correlation function (\(K_{\text{shape}} = 1.1 \times 10^5 \text{ ergs/cm}^3\)) indicate that the origin of UMA is mainly due to the long-range dipolar interaction between the spins on the surface which is fabricated at oblique incidence.

In summary, the elongated and the striped Co grains which are perpendicular to the incident atomic flux direction were deposited at oblique incidence. In addition to the six-fold magnetocrystalline anisotropy of Co film, an in-plane UMA with the easy axis perpendicular to the incident plane was observed. Furthermore, we built a total energy model to investigate the magnetization reversal mechanism near the hard axis. The UMA constant \(K_u\) estimated to be \(1.7 \times 10^5 \text{ erg/cm}^3\) according to the coherent rotation is in good agreement with the calculated value (\(K_{\text{shape}} = 1.1 \times 10^5 \text{ erg/cm}^3\)) by applying the height self-correlation for the STM image. This agreement suggests that the long-range dipolar interaction between the spins on the surface is the major origin of the UMA.

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