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Properties of Co(11$\bar{2}$0) /Mo(100) /MgO(100) bilayers

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Abstract

Co(11$\bar{2}$0)/Mo(100)/MgO(100) bilayers were grown using molecular beam epitaxy; the thickness of the Co layer was 200 Å and that of the Mo buffer 0, 6, 20 and 50 Å, respectively. Their magnetic, electric and surface properties were studied as functions of the non-magnetic buffer layer thickness and coercivity, resistivity and magnetization at 1 T were found to be correlated with surface roughness. The static scaling exponent was determined to be $\alpha = 0.58 \pm 0.02$ for all films, regardless of the roughness and topography of their surface.

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Keywords: Co thin films; Magnetic hysteresis; Surface topography; Scaling; Electric conductivity

1. Introduction

We present here a review of the surface, magnetic and electric properties of Co(11$\bar{2}$0)/Mo(100) and Co(100) films grown using molecular beam epitaxy (MBE) on MgO(100) substrates. Our aim is firstly to correlate the three sets of measurements and secondly to determine the scaling properties of the film surfaces and compare them with analytic models of film growth [1]. Only a few studies of the Co/Mo system have been published to date [2–4], the present work was motivated by our previous studies of the closely related Co(11$\bar{2}$0)/Cr(100) bilayers [5] and superlattices [6] whose structure is identical to that shown in Fig. 1 but the length of the Cr unit cell is 2.88 Å so that Mo, with 3.14 Å, offers a more favorable epitaxial relation to the MgO substrate.

2. Sample preparation and experimental procedure

All films were grown in Eiko EL-10A MBE system (base pressure less than 2×10^{-10} Torr) in which pure elements (99.99%) of Co and Mo were evaporated using independent electron beam evaporators. Growth pressure was maintained below 5×10^{-9} Torr and deposition rate was about 0.1 Å/s. The epitaxial grade MgO substrate was polished, chemically precleaned and rinsed in an ultrasonic cleaner before being outgassed at 1000°C for 30 min under ultrahigh vacuum in the MBE chamber. Temperature was held at 800°C during deposition of the Mo layer and at 300°C during the subsequent Co deposition. Diffusion of Mo into the Co layer is thus rather unlikely but diffusion of Co into Mo, where it may form an alloy [7], cannot be excluded. The deposition rate and film thickness were measured by Leibold Inficon XTC quartz crystal monitor and calibrated later by ellipsometry and X-ray diffrac-

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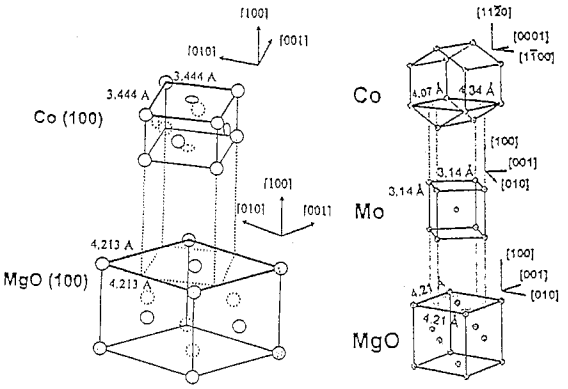

Fig. 1. A schematic diagram showing the geometry, unit cell and epitaxial relationships of fcc-MgO(100) with fcc-Co(100) (left) and with bcc-Mo(100) and hcp-Co(11$\bar{2}$0) (right).

tometry. A 15 keV reflection high energy electron diffractometry (RHEED) beam was adjusted to approximately 2 to 3° and the diffraction patters were monitored in-situ during and after growth. Crystal orientation was determined ex-situ by X-ray diffraction (XRD).

Hysteresis and surface properties were studied ex-situ, at room temperature, on freshly grown samples, using the magneto-optical Kerr effect (MOKE) and Park SFM-BD2-210 atomic force microscope (AFM) respectively. Saturation magnetization at 1 T was measured in SQUID and resistivity at zero applied magnetic field was determined using the standard four probe technique. The thickness of the Co layer, t_{Co}, was 200 Å in all cases while the thickness of the Mo buffer, t_{Mo}, was varied between 0 and 50 Å. According to our studies of ultrathin films the Co layer is oxidized to a depth of less than 8 Å.

3. Surface topography and statistics

The topography of the Co(100) and Co(11$\bar{2}$0) surfaces is apparent from Fig. 2. The Co(100) surface is smooth, but marred by large openings of pinned film growth which, according to line profiles, reach to the MgO substrate. The Co(11$\bar{2}$0) surface over Mo buffer, on the other hand, is granular for all $t_{Mo} > 0$. Interesting is the sample with mean Mo thickness of 6 Å: The Mo growth is island-like [1] and at this stage the islands do not yet coalesce into a continuous layer so that Co is deposited in part directly on the substrate. In magnetic hysteresis loops (see Section 4) the contribution of the fcc-Co(100) is then readily discernible and its presence is confirmed by X-ray data (not shown) which reveal also an admixture of bcc-Co(200). A 20 Å Mo layer is continuous and the resultant Co surface is much smoother though it retains the granular topography.

The RMS roughness w_A of the Co surface, measured over 1 μm^2, is given as function of t_{Mo} in Table 1. As expected [1] w_A decreases with decreasing thickness of the *continuous* buffer layer i.e. with decreasing total film thickness, but the extremely rough films deposited on the thin discontinuous Mo buffer do not conform to this rule. We noted already that the epitaxial relations for Mo are here more favorable than for Cr and correspondingly we find that at 6 Å $w_A^{(Cr)} = 61.16$ Å $> w_A^{(Mo)}$ (see Table 1)

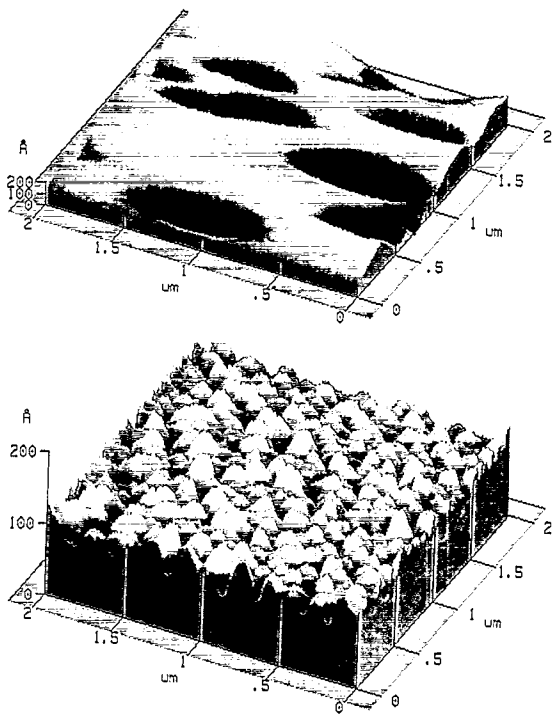

Fig. 2. AFM images of the surfaces of Co(100) (top) and of Co(11$\bar{2}$0)/Mo(100) with $t_{Mo} = 20$ Å (bottom). Note the change in vertical scale corresponding to change in surface roughness. The Co layer thickness is 200 Å in both cases.

Table 1
The surface roughness w_A measured over 1 μm^2, the static exponent α, the coercivity H_c measured at 45° from the easy axes (see Fig. 3), resistivity ρ and saturation magnetization M_s at 1 T versus the thickness t_{Mo} of the Mo buffer layer. Room temperature data. The value of M_s (corrected for contribution of the diamagnetic substrate) is found to be essentially independent of $T \geq 10$ K while H_c and ρ vary with T

t_{Mo} (Å)	w_A (Å)	α	H_c (Oe)	ρ ($\mu\Omega$/cm)	M_s (10^{-3} emu/cm^2)
0	16.47	0.565	78	4.549	11.04
6	40.84	0.608	336	14.97	0.174
20	14.91	0.564	131	1.837	14.22
50	42.75	0.584	333	2.418	5.130

while at 20 Å $w_A^{(Cr)} = 14.62$ Å $\approx w_A^{(Mo)}$. The coalescence of the island-like Mo layer thus takes place at a smaller mean thickness than the coalescence of the Cr buffer.

In all we encounter here three kinds of surfaces: Co(100), Co(11$\bar{2}$0) and their mixture deposited on discontinuous Mo buffer. Following Tong et el. [1] we used the AFM line profile analysis package to evaluate the surface roughness $w(L)$ along a straight line as function of the length L. According to scaling theory at short distances

$$w(L) \propto L^{\alpha} \tag{1}$$

where α is the so called static scaling coefficient. The measurement results are summarized in Table 1. For all studied Co surfaces $\alpha = 0.58 \pm 0.02$ regardless of their structure, roughness and buffer composition (Mo, Cr and no buffer). Moreover, according to the AFM images the grains forming the Co(11$\bar{2}$0) surface are somewhat oblong, with aligned long axes and measurements in two perpendicular directions with respect to these axes yielded the same value for α. The fundamental mechanism involved in the film growth (and subsequent oxidation) is thus apparently the same in all cases and analytically is best approximated by the Lai-Das Sarma growth equation [1] for which $\alpha \to 2/3$. The substrate scaling properties (where $\alpha \approx 1$) are not preserved.

4. Magnetic and transport properties

According to Fig. 1 the Co/Mo/Mgo(100) system is invariant under rotation by 90° of the hcp-Co unit cell about the Mo[100] axis. The system thus exhibits bi-axial magnetic anisotropy corresponding to island nucleation and growth in which the Co layer is divided into regions with easy axes aligned with equal probability along the MgO[001] and MgO[010] directions. The bi-axial symmetry, however, is partially broken since the film is not exactly isotropic [8] and for the magnetic energy density we write

$$E = -\sum_{i=1}^{2}\left[K_i\left(\vec{\nu}_i \cdot \vec{M}_i\right)^2 + \vec{H} \cdot \vec{M}_i\right] \tag{2}$$

where $\vec{\nu}_1 \cdot \vec{\nu}_2 = 0$ are the two easy axes orientations, $\vec{M}_i$ are the in-plane mean magnetization vectors in the two regions and from simulated and measured hysteresis loops we estimate that $K_1/K_2 < 1.15$ for mismatch of the anisotropy constants. The magnetic regions of the Co layer could not, as yet, be identified with the grains visible in the AFM images. At $t_{Mo} = 6$ Å the hysteresis loops are modified by the presence of fcc-Co deposited directly on the substrate (see Fig. 3). In this case, obviously, the biaxial symmetry is still partially preserved, in contrast to the $Co_{200}Cr_6MgO(100)$ film (not shown) whose hysteresis properties are found to be perfectly isotropic.

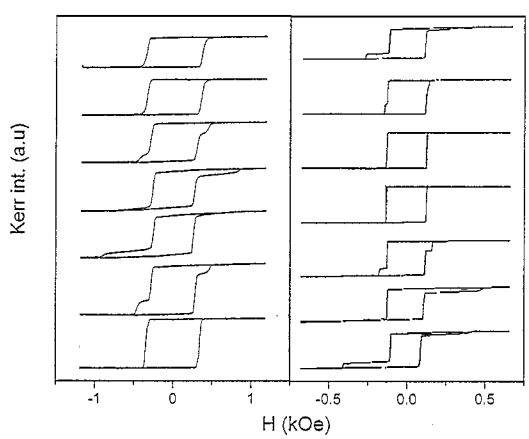

Fig. 3. MOKE hysteresis curves for $t_{Mo} = 6$ Å (left) and 20 Å (right). From bottom to top, the in-plane field is applied at an angle 0°, 15°, ···, 90° to the two easy axes of biaxial symmetry. No out of plane magnetization component (polar MOKE) was detected.

In Table 1 we also record the coercivity H_c (measured at 45° from one of the two easy axes), resistivity ρ and saturation magnetization (measured at 1 T along one of the two easy axes) as functions of the buffer thickness. Both coercivity and resistivity are found to exhibit direct correlation with surface roughness, the former effect may be ascribed to induced surface anisotropy [9] and the latter one to electron scattering on surface imperfections. On the other hand, due to the occurrence of demagnetizing fields [9] on the rough surface the saturation magnetization M_s measured in applied field of 1 T is found to be inversely correlated with w_A and, in particular, the M_s value of the very rough film with $t_{Mo} = 6$ Å is found to be two orders of magnitude lower than that of the smooth film with $t_{Mo} = 20$ Å.

In summary, therefore, we conclude that magnetic and transport properties of thin Co films depend, through surface effects, very strongly on the thickness of the buffer layer which determines the overall roughness of the film. By contrast, the scaling properties of the surface are found here to be totally independent of the buffer thickness and film structure.

Acknowledgements

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