Surface Topography and Anisotropy of Co(1100)/Cr(211) Bilayers

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Abstract—Correlation between the thickness of the nonmagnetic layer and the magnetic anisotropy of epitaxial Co(1100)/Cr(211)/MgO(110) bilayers was studied experimentally and analyzed theoretically. The Co thickness was held constant at 200 Å while the thickness of the Cr layer was varied between 6 and 100 Å. Coercivity was found to decrease with increasing thickness of a continuous Cr layer; at low temperatures the observed data are in good agreement with a model of roughness induced magnetostatic anisotropy energy.

I. INTRODUCTION

It is known that the magnetic anisotropy of magnetic multilayers depends on the thickness of the magnetic layers and that it follows a $1/t$ dependence [1-4]. The role of the nonmagnetic layers is, as a rule, neglected [5]. Recently, however, giant magnetoresistance phenomena have been observed in both bilayer and multilayer Co/Cr systems grown on MgO [6] and it was found that not only the thickness of the magnetic layer but also that of the nonmagnetic layer influence the magnetic properties of films grown by molecular beam epitaxy (MBE). An analysis of the relationship between nonmagnetic layers and magnetic anisotropy is therefore called for.

The above mentioned dependence on the thickness of the magnetic layer is attributed to the two film surfaces which give rise to the so called magnetic surface anisotropy [1-5]. Besides the symmetry breaking at the surface [1-3], surface roughness and the associated stress

in the magnetic layer have also been shown to contribute to the thickness variation of the anisotropy energy [4,5]. To the best of our knowledge, however, the role of nonmagnetic layers has only been discussed theoretically [5] while experimental data were, to date, lacking.

Here we use atomic force microscopy (AFM) to analyze *ex situ* the surface topography of epitaxial Co(1100)/Cr(211)/MgO(110) bilayers. At constant thickness of the Co layer the anisotropy variation results from variations of its surface topography inherited from the Cr layer of variable thickness. We model the rough surface by the function

$$h(x) = \begin{cases} h_0 & \text{if } 2n < x/l < 2n+1 \\ h_0 + R & \text{if } 2n+1 < x/l < 2n+2 \end{cases} \quad (1)$$

where the mean crenella height R and length l are deduced from AFM data. The Co surface has different properties along two orthogonal directions and for this reason we use l_x and l_y (see Fig.1 and Table I); the in-plane magnetic anisotropy differs along these directions as well. The roughness induced magnetostatic anisotropy is then calculated by means of a Fourier analysis [4]. The demagnetization fields arising on the crenellated film surface allow the magnetization vector to deviate from the in-plane direction and the coercivity of the film is consequently decreased. Variations of magnetic anisotropy due to magnetostriction are not considered here because of the negligible lattice mismatching between Co(1100) and Cr(211) [6]. The agreement between calculated and experimental data is found, after matching a single parameter, to be remarkably good.

II. EXPERIMENTAL METHOD

The Co(1100)/Cr(211) bilayers were prepared by MBE on chemically precleaned MgO substrates which were rinsed in an ultrasonic cleaner. The detailed growth conditions were reported in Ref. 6. The Co thickness (t_{Co}) was maintained at 200 Å for all samples, while the thickness of

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the nonmagnetic, Cr, layer (t_{Cr}) was varied. MOKE and SQUID were used to analyze the magnetic properties of the films between 10 and 300 K. The saturation magnetization of the bilayers was found to vary with temperature but not with t_{Cr} .

Fig.1. *Ex situ* AFM image of the Co layer at $t_{Cr} = 50 \text{ \AA}$ and line profiles along the two nonequivalent orthogonal directions which are clearly discernible here. The *mean* values of R , l_x and l_y given in Table I were deduced from a series of these plots.

The measured values of coercivity at 10 K and of the surface topography parameters are shown, as functions of t_{Cr} , in Table I.

The entire series of AFM measurements was carried out by a single AFM tip, the *mean* values of the parameters R , l_x and l_y were obtained from analysis of line profiles such as are shown in Fig.1. It should be noted that the difference between l_x and l_y gradually disappears with increasing t_{Cr} where, moreover, the surface roughness of the film becomes larger [7].

TABLE I
Coercivity and roughness for $t_{Co} = 200 \text{ \AA}$ at 10 K

$t_{Cr} [\text{\AA}]$	$H_c [\text{Oe}]$	$R [\text{\AA}]$	$l_x [\text{nm}]$	$l_y [\text{nm}]$
6	525	59	143	200
20	580	3	71.4	100
50	442	10	41.6	142.9
100	265	11	33.3	90.9

III. RESULTS AND DISCUSSIONS

In Fig.2 we present a comparison between the measured and calculated [4, 5] values of coercivity versus the thickness of the nonmagnetic Cr layer. A large discrepancy between theory and experiment exists at $t_{Cr} = 6 \text{ \AA}$. We find that the ultrathin Cr layers is discontinuous, with part of the Co layer deposited directly on MgO. The magnetic properties of this film are, with no trace of angular properties, and the resultant surface is extremely rough (see Fig.3). The discrepancy between theory and experiment is in this case be attributable to the inhomogeneous composition of the film. It is remarkable, however, that coercivity decreases almost *linearly* with increasing thickness of the *continuous* nonmagnetic layer.

Fig. 2. Coercivity H_c versus Cr thickness for $200 \text{ \AA}$ Co layer at 10 K, * experimental and $\circ$ theoretical values. The lines merely guide the eye. The $t_{Cr} = 20 \text{ \AA}$ value was used to fit the one adjustable parameter of the theory.

The present analysis is in good agreement with *low* temperature data while at higher temperatures the calculated roughness induced magnetostatic anisotropy gradually becomes inconsistent with experimental data, possibly due to spin reorientation effects in Co [8].

Fig. 3. AFM image of the Co layer surface for $t_{\text{Co}} = 50 \text{ \AA}$ (above, compare Fig.1); all bilayers with $t_{\text{Cr}} \geq 20 \text{ \AA}$ exhibit this topography, however, their RMS surface roughness gradually increases as expected (see e.g. Ref.7). Shown below is the Co surface with the ultrathin Cr layer, $t_{\text{Cr}} = 6 \text{ \AA}$. Note the change in scale and in topography.

IV. SUMMARY

In summary, we have studied the surface and magnetic properties of $\text{Co}(1\bar{1}00)/\text{Cr}(211)$ bilayers and found that the thickness of the nonmagnetic Cr layer influences significantly the magnetic anisotropy of the system.

According to the present analysis this dependence may be attributed solely to the roughness induced magnetostatic anisotropy while magnetostriction anisotropy may be neglected due to the small mismatch between the $\text{Co}(1\bar{1}00)$ and $\text{Cr}(211)$ layers [6]. Deviations from the theoretically predicted behavior are found only at elevated temperatures.

For very thin Cr layers (here exemplified by $t_{\text{Cr}} = 6 \text{ \AA}$) some of the Co atoms may be directly deposited on the MgO substrate, giving rise to an inhomogeneous Co phase with significant stresses to which we attribute the discrepancy between observed and calculated coercivity values.

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