

Magnetization of Pt in the Co/Pt(110) system investigated with surface x-ray magnetic diffraction: Evidence for in-plane magnetic anisotropy

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Ultrathin films of Co were deposited *in situ* on a well-prepared Pt(110) single-crystal surface and the induced magnetization of the Pt atoms at the interface was investigated with resonant magnetic surface x-ray-diffraction measurements at the L absorption edges of Pt. The measurements indicate that the magnetization of the Pt atoms extends to three atomic layers below the Co film and that a strong in-plane magnetic anisotropy exists. The easy direction of magnetization in the surface plane is perpendicular to the close-packed atomic rows in the Pt substrate. [S0163-1829(99)12129-5]

I. INTRODUCTION

Cobalt/platinum multilayer systems have attracted a great deal of attention in the last few years due to the possible practical applications in magnetic storage and also due to the rich phenomenology that they exhibit. Normally, when the thickness of the Co layers is small (less than 1 nm), the easy direction of magnetization is perpendicular to the surface and the saturation magnetization of the Co is larger than that of bulk Co due to contribution of the polarized Pt atoms.^{1,2} The origin of the magnetic anisotropy is related to a large variety of structural parameters including the existence of an interface, the crystallographic structure of the films, the strain in the ferromagnetic layer, the interfacial roughness, the flatness of the films resulting from different growth conditions, and the interface alloying and interdiffusion, to mention some of them. In order to try to get some additional insight into this complex scenario we have investigated the structure of the Co/Pt(110) system with x-ray diffraction and with resonant x-ray diffraction the magnetism of the Pt atoms in the interface region. Previously published work² on Co/Pt multilayers grown on a Pt(110) substrate reports strong uniaxial anisotropy in the film plane. We have confirmed this finding in Co ultrathin films grown on Pt(110) by measuring the induced magnetization of the Pt, which shows pronounced in-plane anisotropy. A tentative explanation based on the structure of the Co overlayer film is given. Also, from our measurements, we conclude that the induced magnetization of the Pt atoms extends to three atomic layers below the Co overlayer. The present paper is organized as follows. Section I A summarizes our previous results, Sec. II treats some basic theoretical aspects of the resonant magnetic diffraction technique that are important for analyzing experimental results, Sec. III gives details of the experiments, Sec. IV shows the results and discussion of the Pt magnetization, and Sec. V gives the conclusions.

A. Previous work

In a previous paper we reported a structural study of the Co/Pt(110) system³ that we briefly summarize. The crystal lattice was described with the commonly used basis in surface studies³ which consists of three orthogonal vectors,

\mathbf{A}_1 , \mathbf{A}_2 , \mathbf{A}_3 , parallel to the $[\bar{1}10]$, $[001]$, and $[110]$ directions, respectively, with $\mathbf{A}_1 = \mathbf{A}_3 = a_0/\sqrt{2}$ and $\mathbf{A}_2 = a_0$ (bulk lattice constant of Pt). The surface plane is spanned by \mathbf{A}_1 and \mathbf{A}_2 . The atoms along the \mathbf{A}_1 direction form close-packed atomic rows. Before Co deposition, the Pt surface has the well known missing row reconstruction where one of every two compact atomic rows in the surface is missing. After deposition of three Co layers, a set of crystallographic data were collected. Analysis of these data revealed that the originally missing rows in the Pt substrate were occupied with Co atoms and that a significant mixing of Co and Pt occurred within the $[110]$ rows. This Co/Pt intermixing was almost exclusively restricted to this plane since the layer below was found to have 96% Pt, and the layer above 100% Co. Also, it was found that the interlayer spacing in the Co overlayers were contracted from 6 to 18 % compared to the interplanar distance in bulk Pt. The imperfection in the growth caused an incomplete filling of the Co layers. The Co concentrations on the layers above the intermixed one were found to be 100%, 48%, and 15%. Co grows in the Stranski-Krastanov mode and it forms elongated prismatic clusters on the Pt substrate when growth proceeds. The crystallites have triangular sections in the \mathbf{A}_2 - \mathbf{A}_3 plane with the largest side in contact with the Pt substrate. They have the fcc structure and their lateral faces are (111) planes forming an angle of 109.5°. For a Co deposit of six atomic layers the approximate dimensions of the crystallites in the \mathbf{A}_1 , \mathbf{A}_2 , and \mathbf{A}_3 directions are, respectively, 216, 47, and 17 Å.

II. MAGNETIC CRYSTAL TRUNCATION RODS

The essential idea of the resonant magnetic scattering process⁴ is that when the x-ray photon energy, $h\nu$, of the incoming beam coincides with an absorption energy of a magnetic atom where intense dipolar transitions occur (for example, the L_{III} edge of Pt atoms), an additional contribution to the atomic scattering amplitude appears which adds to the nondispersive, dispersive, and absorptive atomic form factors. This additional term consists of three additive parts, but one of them which is real at the resonance conditions is particularly important and it is the only one that we will

discuss in this paper. This part is nonzero in the vicinity of the absorption edge energy. Its magnitude depends on the difference of density of states between the majority and minority spin bands in a magnetized atom in a solid. We will design it as n_m referring to the number of unpaired or “magnetic” electrons in the atom. n_m is expressed in units of the electron radius r_0 and it is a negative quantity for the L_{III} -associated dipolar transition (see Ref. 5 for details and sign conventions). The resonant term also depends on some geometrical selection rules as (if $h\nu$ =absorption energy)

$$f_{res} = n_m(\mathbf{e}_f \times \mathbf{e}_i) \cdot \mathbf{m}, \quad (1)$$

where \mathbf{e}_f and \mathbf{e}_i are the unit vectors along the polarization directions of the outgoing and incoming x-ray beams and \mathbf{m} is a unit vector in the direction of the magnetization of the sample. In Eq. (1) we have omitted two terms that may be ignored in the present discussion since they do not change sign upon magnetization reversal. Suppose a horizontally polarized incoming beam with $\mathbf{e}_i=(0,0,1)$, as it is often the case in synchrotron beams. For an arbitrary scattering angle, $(\mathbf{e}_f \times \mathbf{e}_i) = (e_{fy}, -e_{fx}, 0)$. If the sample is magnetized as $\mathbf{m} = (0,0,1)$, the resonant term is zero. This is the situation that we found in our experiments when the surface of the sample is magnetized in the perpendicular direction since our sample is mounted with the surface in a vertical plane (Sec. III gives more details). Thus, in our experimental setup we are only sensitive to the in-plane magnetization. By applying a magnetic field that reverses \mathbf{m} the sign of f_{res} changes; therefore the diffracted intensity, which is proportional to the square of the magnitude of the total diffusion factor of an atom, will have crossed terms which will change sign upon field reversal causing the asymmetry ratio

$$R = \frac{I\uparrow - I\downarrow}{I\uparrow + I\downarrow}$$

to be nonzero ($I\uparrow$ and $I\downarrow$ are the intensities measured in both field directions). The measured asymmetry ratio depends on the atomic coordinates, on the reciprocal space H , on K (in-plane) and L (out-of-plane) coordinates, on n_m , and on other parameters such as the intensity of the white line of the absorption edge and the magnitude of the dispersive and absorptive parts of the atomic scattering factor.

The ordinary crystal truncation rods, which are the intensity distributions as a function of the L coordinate for fixed H and K , provide crystallographic information on the atomic coordinates in the direction z of the surface normal. In a similar way, the magnetic crystal rods $R(L)$ contain additional information such as the magnitudes of n_m for different atomic planes along the surface normal.

A. Additivity of R for different magnetized layers

To fix the ideas, suppose a Pt crystal surface covered with a ferromagnetic Co overlayer which is magnetically saturated by means of an applied external magnetic field. The Co overlayer induces magnetism into several Pt planes in the vicinity of the Co/Pt interface. The total structure factor of the crystal may be written as

$$F_{tot} = \sum_j (f_{nr} + f_{res})_j \cdot \Phi_j + F_{nr},$$

where the index j refers to the magnetized Pt atoms, f_{nr} is the nonresonant part of the scattering factor, Φ_j refers to the phase factors of the magnetized Pt atoms (i.e., $e^{[2\pi i(x_j H + y_j K + z_j L)]}$), and F_{nr} refers to the structure factor of the rest of the sample (Pt substrate and Co overlayer) which exhibits no resonant effect. The asymmetry ratio measured upon inverting the applied field will be proportional to the odd terms of $|F_{tot}|^2$ which are

$$\sum_j (\pm n_{mj}) (\mathbf{e}_f \times \mathbf{e}_i) \cdot \mathbf{m} |(\Phi_j^* F_{nr} + \Phi_j F_{nr}^*)|, \quad (2)$$

where \pm corresponds to both field directions and n_{mj} refers to the magnetism of Pt layer j . Expression (2) is a sum of terms, one for every magnetized Pt layer. It indicates that the asymmetry ratio corresponding to a stacking of magnetized layers is equal to the sum of the asymmetries of the individual layers. The linearity of R is practical upon calculation of magnetic rods from aprioristic models since each magnetic layer may be calculated separately. Also, if we suppose that only one Pt atomic plane is magnetized, then the magnitude of R is directly proportional to the magnetization (n_m) of that layer.

B. Zeros of R

There are two cases that we want to discuss where $R = 0$. The first one occurs when bulk Bragg conditions are satisfied. In our example of the Co/Pt system, on the basis of general physical arguments, only a few Pt atomic planes near the interface are expected to be magnetized by the ferromagnetic film. When a Bragg condition is fulfilled in the Pt crystal, the magnetically sensitive part of the diffracted intensity will be completely negligible compared to the total diffracted intensity since in such a case $I\uparrow - I\downarrow$ will be eight or nine orders of magnitude smaller than $I\uparrow$ or $I\downarrow$. The second case is associated with discontinuities in R which occur when $I\uparrow = I\downarrow = 0$.

Let us concentrate on the Pt(110) surface that we will suppose for simplicity of the discussion that is unreconstructed and terminated as the bulk. We consider the topmost four atomic planes at $z=0, 1/2, 1,$ and $3/2$ in lattice units. The (x,y) coordinates of the atoms in the surface cells are $(0,0)$ or $(1/2,1/2)$ for z integer or fractional, respectively. For the $H=0, K=1$ rod, the structure factor of these planes is proportional to $1 - e^{(i\pi L)} + e^{(i2\pi L)} - e^{(i3\pi L)}$, which has zeros at $L=0.5$ and $L=1.5$. At these zeros, the real part of the structure factor changes sign, causing the asymmetry factor to change sign abruptly. In our example, the real part of the structure factor has positive slope at $L=0.5$ and negative at $L=1.5$, resulting in different signs of the asymmetry ratio. The inset on Fig. 1 shows the amplitudes of the different planes at $L=0.5$ and 1.5 . As may be seen for $z=1/2$ and $3/2$ they differ in sign for both values of L . To illustrate this idea let us suppose that only the topmost plane at $z=3/2$ is magnetized and that the resonant part of the atomic structure factor is 0.005 (we define here as 1 the atomic form factor of the Pt atoms). Then the asymmetry ratio resulting from the

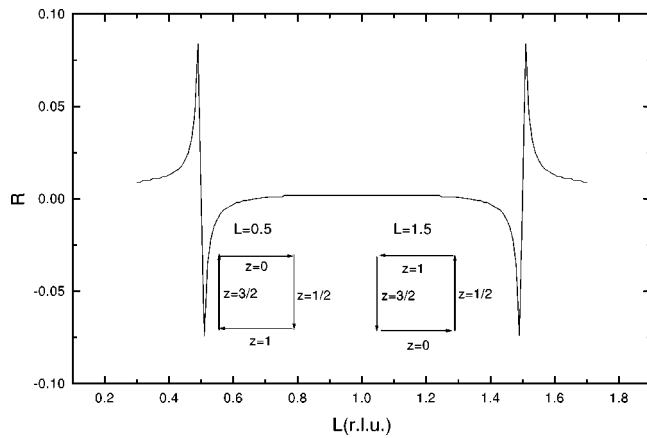


FIG. 1. Calculated asymmetry ratio for four atomic Pt(110) planes with the topmost plane magnetized. The inset shows the diffracted amplitudes of each plane for $L=0.5$ and $L=1.5$.

four Pt planes is displayed in the continuous line in Fig. 1. The curve has inverted signs at the vicinities of $L=0.5$ and 1.5 . Similar calculations, assuming that other Pt planes are magnetic, result in the following. $R(L)$ looks identical to the curve in Fig. 1 if the magnetized plane is the one at $z=0$, and it is identical except for the sign which is opposite if the magnetic planes are those at $z=0.5$ and 1 . Recalling the linearity in R that we mentioned above, it turns out that $R(L)$ is zero if the two topmost planes or all four planes are equally magnetized. This example illustrates how interference effects may complicate the shapes and magnitudes of the $R(L)$ curves.

C. Effect of Co deposition

The example just mentioned is oversimplified; in reality one has to add the substrate and the Co overlayer in order to have the overall structure factor of the sample. The effect of adding a nonmagnetized Pt substrate on the $R(L)$ curves as the one in Fig. 1 is a very pronounced smoothing of the sharp discontinuitylike features. The addition of overlayer Co atoms in Pt lattice sites causes strong interferences with the Pt which again modify substantially the magnetic rods. To illustrate this, we have calculated $R(L)$ for an ideal Co/Pt system. All the atoms have been positioned in bulk Pt positions and the missing row reconstruction of the Pt has been ignored. The atomic form factor of Pt used in the calculations includes the dispersive and absorptive parts. Also, the actual detector geometry which enters in Eq. (1) has been included. The results for the $(01L)$ magnetic rod are displayed in Fig. 2.

Referring to Fig. 2(a) which was evaluated by assuming only one magnetic Pt layer at the interface, we may observe that the positions of the zeros of $R(L)$ for one, two, or three Co overlayers are at $L=1.73$, 1.40 , and 1.26 , respectively, i.e., they shift to lower L values for increasing Co thickness. Inspection of Figs. 2(b) and (c) reveals the same trend. Let us consider next an overlayer of two Co planes: The zeros are at $L=1.40$, 1.40 , and 1.42 for one, two, and three magnetized Pt planes, respectively. The above results illustrate that the zeros of $R(L)$ do not depend on how many Pt layers are magnetic, but mostly depend on the thickness of the Co overlayer contributing to the diffracted intensity. Also, the curves

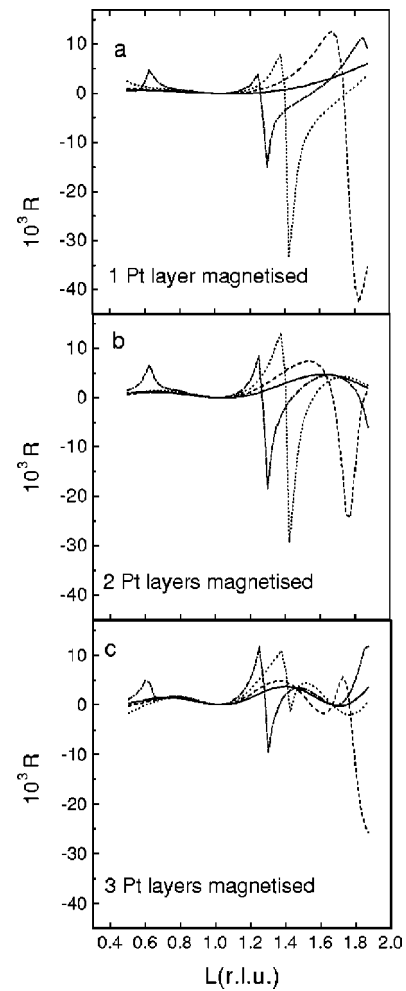


FIG. 2. Calculated magnetic crystal truncation rods for a bulk terminated Pt(110) crystal surface covered with Co atoms in bulk Pt lattice positions. Panel (a) corresponds to one magnetized Pt layer (the one in contact with the Co). The curves correspond to different thickness of the Co overlayer: zero atomic layers (continuous), one (dashed), two (dotted), and three (dashed-dotted). Panel (b) corresponds to an identical calculation as that of panel (a) except that two equally magnetized Pt layers have been considered. Panel 3 is for three equally magnetized Pt planes.

for two Co layers show that having a greater number of magnetized Pt layers causes the asymmetry ratio to be more evenly distributed above and below $R=0$.

III. EXPERIMENTAL

The experiments have been made at the surface diffraction beamline of the ESRF previously described.⁶ The end station consists of a high-precision diffractometer coupled to a UHV chamber containing facilities for sample preparation and characterization, including several evaporators for *in situ* film growth experiments. The Pt(110) crystal surface was prepared with standard treatments until a good reconstructed surface with terraces of linear dimensions of several tens of nm were achieved.

Resonant magnetic measurements were done with a photon energy coinciding with the L_{III} absorption edge of Pt (11.564 keV). In order to optimize the photon flux, the gaps of the two undulators generating the x-ray beam were ad-

justed so as to have the high-brilliance third harmonic of the undulators tuned to the desired energy. Measurements of the magnetic asymmetry ratio were performed by applying a magnetic field of approximately 1.2 kG, created by a permanent NdFe magnet located inside the UHV chamber that could be rotated by means of a motorized rotary feedthrough. The sample surface was in a vertical plane and the field direction was in the plane of the surface pointing either upwards or downwards. A typical measurement of the asymmetry ratio was performed by collecting the diffracted intensity with the magnetic field pointing upwards during 15–30 s, then the same measurement was repeated with inverted field sense. The above pair of measurements was repeated 16 or 32 times in order to achieve a statistical error bar of less than 0.001. The stability of the x-ray beam was crucial in order to achieve reproducible results. Thus, the asymmetry ratio of the direct beam was also measured since it was observed that beam instabilities or drifts resulted in asymmetries comparable to the magnetic ones. Standard stable conditions gave asymmetries in the incoming beam of less than 10^{-4} which were considered acceptable for the magnetic experiments. As the measurements were done at the Pt L_{III} absorption energy, strong L fluorescence contamination was contained in the scattered beams. It was largely reduced by inserting an analyzer crystal (graphite) in the detector arm of the diffractometer. Cobalt was deposited on the Pt crystal kept at room temperature by means of an electron-beam evaporator. During deposition the pressure was in the low 10^{-10} mbar range. The magnetic crystal truncation rods (MCTR) were measured at fixed incidence angle (0.25° or approximately 1°) while varying the exit angle in order to sweep a range of values of perpendicular momentum transfer L . For low values of L (i.e., for small exit angles), the resonant amplitude becomes small since \mathbf{e}_f approaches \mathbf{e}_i in Eq. (1). Therefore the best data in the MCTR are obtained at high L in the rods.

IV. RESULTS AND DISCUSSION

A. Magnetic crystal truncation rods: Induced magnetization of Pt

MCTR data were collected for the (01L) and (10L) Pt crystal truncation rods for a variety of Co coverages (Fig. 3). We will focus first on the (01L) series. As shown in Fig. 3, all the values of R are smaller than 1%. At $L=1$ which is the only bulk Bragg reflection accessible, $R=0$ indicating that the bulk of the Pt crystal is not magnetized, as expected. The nonzero R values in the figure arise from Pt magnetism at the interface with the Co film. For three atomic layers of Co, the MCTR shows two maxima. At the highest value of L measured (1.5), R is positive although the data points show a negative slope in that region. For thicker Co coverages, zeros of R are measured at $L=1.40$, 1.38, and 1.38 for four, seven, and eight Co layers, respectively. The shift of the zeros of R to lower values of L when the Co thickness increases results from an interference effect between the Co overlayer and the Pt surface as discussed previously in Sec. II. Also, the data in panels (b), (c), and (d) show at $L\sim 1.40$ the discontinuity type of shape discussed above. The comparison of Figs. 2 and 3 reveals that the experimental data resemble the curve obtained for one or two magnetized Pt layers covered with a

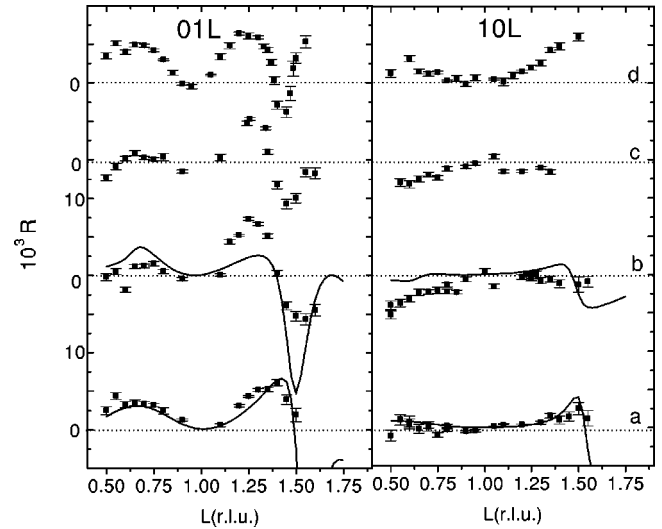


FIG. 3. Experimental results for the MCTR's (01L) and (10L) for different Co deposited coverages in atomic layers. (a) 3.0, (b) 4.3, (c) 7.0 and (d) ~ 8 . The continuous lines are calculated (see text).

Co film approximately two atoms thick. It appears that the disorder in the Co film means that effectively only approximately two atomic layers interfere significantly with the substrate.

The crystallographic and stoichiometric results described in Sec. I A were used as fixed input to a model to fit the magnetic CTR. We assumed that the induced magnetization in the Pt could be described with three parameters, n_{m3} , n_{m2} , and n_{m1} , for the magnetization in the intermixed Co/Pt plane (n_{m3}) and the two atomic planes immediately below (n_{m2} and n_{m1}). The continuous curve in Fig. 3(a) is obtained with $n_{m1}=n_{m2}=-0.1$ and $n_{m3}=-0.15$. The error bars on these values have been estimated to be around 20%. Thus, the induced magnetization at the interface extends to three atomic Pt planes in contrast with our previous results in Co/Pt(111) (Ref. 7) where it was found that only the topmost Pt plane in contact with the Co overlayer had nonnegligible magnetization. On the other hand, the magnitude of the n_m values found in the (110) interface are smaller than that of the (111) interface that was -0.5 . The continuous curve Fig. 2(b) (4.3 atomic layers) is the result of a calculation by assuming the same n_m values as those obtained for three atomic layers and the same crystallographic structure and stoichiometries (except for the Co coverages of the overlayer which were increased to account for the additional Co). The calculated curve has the correct shape and it reproduces well the positions of the maxima and minima but not their amplitudes. The reason for that is probably related to the insufficiently precise structural determination of the interface likely due to the existence imperfections and disorder which were largely ignored in the modeling. As may be observed in Fig. 2(b), the discontinuitylike shape of the (01L) MCTR is preserved for higher coverages.

B. In-plane magnetic anisotropy

Let us now discuss the (10L) rods in Fig. 3. The magnitudes of R are lower in these rods and the singularitylike shapes are absent. The continuous curve through the data

points in curve (a) was obtained, as for the (01L) rod, by freezing the structure and varying n_{m1} , n_{m2} , and n_{m3} which were found to be $n_{m1} = n_{m2} = 0$ and $n_{m3} = -0.07$. The same values of n_m were used to evaluate the continuous curve in panel (b). The different R values for the (01L) and (10L) MCTR has a magnetic origin since crystallographically the rods are virtually identical. This means that the induced magnetization of Pt shows a strong in-plane anisotropy. A possible explanation for this almost-zero magnetization of Pt in the (10L) rods compared to that in the (01L) rods may be found by inspecting the scattering geometry. It turns out that the sample positions for the measurements of the (01L) MCTR are such that the close-packed atomic rows running along the \mathbf{A}_1 surface direction are roughly perpendicular to the direction of the external magnetic field whereas for the (10L) measurements these are roughly parallel. Getting more into the details, in the z -axis diffractometer geometry used in our experiments, the change in the L reciprocal space coordinate is directly related to the varying exit angle of the scattered beam. In order to keep the in-plane diffraction condition satisfied, the sample has to be rotated along its surface normal. For $(H, K, L) = (1, 0, 1)$ which is the middle point of our measuring range, the angle that \mathbf{A}_1 forms with the magnetic field is approximately 23° whereas for $(0, 1, 1)$ it is 114° . These angles vary approximately $\pm 12^\circ$ from the above values when L reaches the extremes of our measured L interval. Thus, the relatively small asymmetry values measured in the (10L) rod compared to the (01L) ones, are an indication that the \mathbf{A}_1 surface direction (along the close-packed atomic rows) is not an easy magnetization direction in the plane of the surface, but that on the contrary the \mathbf{A}_2 direction is the easy one. This result is in contrast with the measurements in Ref. 5 for a bulk disordered CoPt alloy where the authors found that the crystallographic closed-packed directions were the easy directions of magnetization. However, our result is in agreement with the recent report by Hope *et al.*⁸ where it was found with magneto-optical measurements that ultrathin Co deposits (similar thickness as ours) on Cu(110) exhibited in-plane anisotropy with the easy axis in the direction perpendicular to the compact atomic rows.

As mentioned in Sec. I A, Co forms elongated prismatic clusters with the fcc structure and lateral faces consisting in (111) planes. Since [111] directions are the bulk magnetocrystalline easy axes of fcc Co,⁹ one may guess that in the crystallites, that direction will also be the easy one. If the magnetization vector is normal to any of the lateral faces of the crystallites, its components along \mathbf{A}_2 and \mathbf{A}_3 directions are nonzero but the component along \mathbf{A}_1 is zero. Therefore it seems natural on the basis of symmetry arguments that the in-plane easy direction will be \mathbf{A}_2 and not \mathbf{A}_1 as we effectively found experimentally. Additionally, one may note that the shape anisotropy of the elongated Co clusters favors the \mathbf{A}_1 direction.

Another interesting aspect is the following. As noticeable in Fig. 3, deposition of three atomic layers of Co already results in a significant anisotropy since the two MCTR's are clearly different. For this low coverage, the Co crystallites have to be very small but the coverage appears to be enough to establish the fcc structure for the Co. In fact, in a different

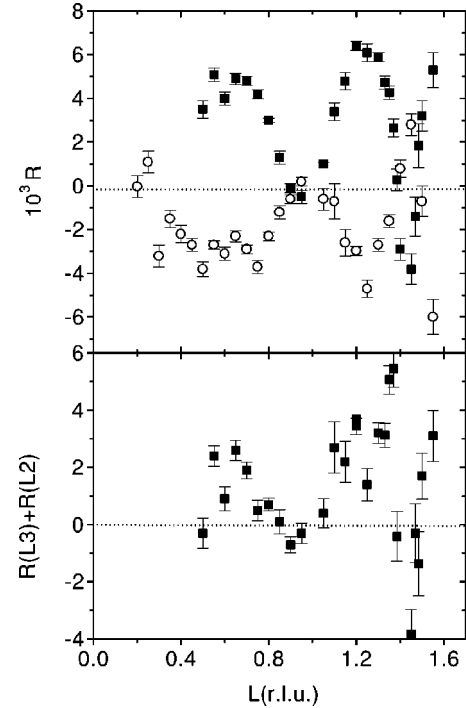


FIG. 4. Upper panel: (01L) MCTR measured at the L_{III} Pt absorption edge (filled circles) and at the L_{II} edge (empty circles) for ~ 8 atomic layers of Co on Pt(110). Lower panel: sum of the above two data sets.

experiment, we deposited only two atomic Co layers and the result was that the asymmetry ratio was zero within our experimental accuracy.

C. Dichroism

Circular magnetic dichroism with circularly polarized x rays is a very well established tool in surface magnetism research. It is based in the different absorption of left-handed and right-handed polarized beams.¹⁰ Very often the experiments are done not by using the two helicities of the beam, but by using only one and inverting the sample magnetization with an external field which produces identical results on the basis of symmetry arguments. The dichroic signal is then obtained by subtracting the absorption spectra for two opposite orientations of the magnetic field. On the basis of the above ideas, we have done similar measurements with our plane-polarized beams and diffraction conditions.

Figure 4 shows in the upper panel the (01L) MCTR for a Co film of about eight layers on Pt(110) measured at the L_{III} absorption edge at 11.564 keV (filled symbols) and at the L_{II} absorption edge at 13.273 keV (empty circles). As may be seen, the data sets have opposite signs and they look rather symmetric around $R=0$. The situation resembles circular magnetic dichroism experiments which also show different signs of the dichroic signals at both absorption edges. Also, the absolute values of R in Fig. 4 are smaller for the L_{II} data than for L_{III} . This is clearly seen in the lower panel of Fig. 4 which is a plot of the sum of the two upper data sets. There are two main reasons for the larger asymmetries at L_{III} than at L_{II} . The first has to do with the different values of the atomic amplitudes intervening in the diffracted intensities for both dipolar transitions (different f 's and edge jumps), i.e., it

has to do with the different atomic details of both resonant processes. The second, more interesting for magnetism, is related to the sum rules originally derived for circular magnetic dichroism experiments.¹¹ The first of these rules states that the integral, extended to both absorption edges, of the normalized dichroic signal is directly proportional to the expectation value of the orbital angular momentum in the direction of the magnetization. The translation of this rule to our diffraction experiments is as follows. If the values of the atomic amplitudes for both transitions are precisely known and also the atomic structure at the interface is well determined, then by fitting the MCTR's at the L_{III} and L_{II} absorption edges, the values of n_{mj} [see Eq. (1)] could be determined for both resonances (j refers to the different Pt atomic planes). In such a case the differences $n_{mj}(L_{III}) - n_{mj}(L_{II})$ are directly proportional to the expectation value of the angular momentum of the magnetized Pt atoms in layer j . Therefore, one could determine the relative contribution of the orbital magnetic moment to the total magnetic moment of the Pt atoms at different atomic planes at the vicinity of the ferromagnetic overlayer. Although the above discussion may be considered somewhat speculative due to the stringent conditions that need to be satisfied (in particular, a precise crystallographic determination in realistic systems may be very difficult), the quality of the data in Fig. 4 is sufficiently good to have reasonable future expectations, at least in well defined model systems.

V. CONCLUSIONS

Resonant surface x-ray diffraction proves to be a useful tool for detailed investigation of the magnetization of the Pt atoms at the Co/Pt(110) interface. The full capabilities of this method occur when the crystallography of the interface is well determined since the magnetic information is coupled to the crystallographic structure via the atomic scattering factors. In the present case, disorder at the interface complicates the analysis of the magnetization. However, it has been established that the magnetization of the Pt atoms extends to at least three atomic planes below the Co overlayer and that a strong in-plane anisotropy exists. The easy magnetization direction is perpendicular to the compact atomic rows of the Pt substrate. A tentative explanation is given based on the fact that the Co crystallites on the surface have the fcc structure and closed-packed (111) facets which are normal to the easy magnetization directions for fcc Co. Also, it has been shown that comparison of magnetic crystal truncation rod data taken at the L_{III} and L_{II} edges might show how the orbital magnetic moment of the Pt atoms varies as a function of depth in the interface region.

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