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Magnetic anisotropy of submonolayer Pt films grown on Ni(110)

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Abstract

About one atomic layer of Pt was deposited on a Ni(110) surface to investigate the magnetic anisotropy of the interface. The magnetization of Pt atoms was probed with resonant magnetic x-ray diffraction and the magneto-optical Kerr effect was utilized to probe the average magnetization of the Ni in the near-surface region. Our results show that the magnetization of the Pt atoms in the surface plane depends on the direction of the applied field. While the $[\bar{1}10]$ direction shows a hysteresis cycle of the Pt film typical of an easy magnetization axis, the [001] direction has a hard axis behaviour. In contrast, the Ni(110) substrate shows similar cycles for the two directions. A possible explanation, based on the formation of an anisotropic superstructure, as observed by means of surface x-ray diffraction, is suggested.

1. Introduction

Thin films, multilayers and alloys involving Pt and Ni have attracted much interest in recent years, mainly due to their perpendicular magnetic anisotropy [1–4] opening the possibility of interesting technological applications related to polar magneto-optical devices and high recording densities [5]. As the magnetic properties of multilayers are to a large extent determined by their structure at the interfaces between the different materials, the structural and magnetic characterization of single interfaces is very important. The increased difficulty in measuring relevant physical parameters in single interfaces may require the use of relatively sophisticated techniques. Here we report results on the magnetic anisotropy of submonolayer Pt films deposited on Ni(110) studied by means of surface x-ray diffraction. This technique has been used both in its standard mode for crystallographic determination and also in the resonant mode to extract magnetic information.

2. Experimental details

The experiments were carried out in the ultrahigh-vacuum system coupled to a six-circle diffractometer of the Surface Diffraction Beamline (ID3) at the European Synchrotron Radiation Facility [6]. The Ni(110) substrate was a disc of 10 mm of diameter and 3 mm thick. Its surface, which is highly anisotropic since it consists of parallel close-packed rows of atoms along the $[\bar{1}10]$ direction (in the standard cubic basis) separated by $\sqrt{2}$ times the nearest-neighbour atomic distance, was cleaned and prepared with sputtering (2 keV Ar^+)/annealing (800 °C) cycles leading to surface mosaicities of around 0.04°. Ultrathin Pt films were grown on top of the Ni(110) substrate at 2×10^{-10} mbar pressure and at room temperature with a water-cooled electron bombardment evaporator. Their thicknesses were calibrated monitoring, during the deposition, the temporal evolution of the specularly reflected x-ray intensity in antiphase scattering geometry. Under these circumstances the intensity displays an oscillatory behaviour (for a layer-by-layer growth) which allows one to accurately determine the surface coverage [7].

In order to extract information on the magnetization of surface Pt atoms we performed resonant diffraction experiments as described in detail elsewhere [8]. In short, the photon energy was precisely tuned to the Pt L_{III} absorption edge energy (11.564 keV). Then, a magnetic field parallel to the crystal surface was applied to the sample while measuring the diffracted intensity from the interface. By inverting the field direction, the magnetic contribution to the scattered intensity could be isolated. More precisely, if $I_\uparrow$ and $I_\downarrow$ denote the diffracted intensities for the two field directions, the asymmetry ratio $R = (I_\uparrow - I_\downarrow)/(I_\uparrow + I_\downarrow)$ turns out to be proportional to the magnetization of the Pt film along the field axis. In addition, as the photon energy is tuned to the Pt absorption edge, R is not sensitive to the magnetism of the substrate Ni atoms.

In figure 1 we show in more detail the way in which $R(H)$ is being measured. We assume that the magnetization curve of the Pt films is described by the hysteresis cycle marked with dashed curves, which is a centrosymmetric cycle. Figure 1(a) describes how $R(H)$ is measured for fields $H_1 > 0$. To do this, the field is increased to $H_{max} > 0$, then it is reduced to H_1 and $I(H_1)$ is measured. Then, the field is reduced from H_1 to the minimum negative value H_{min}, then it is increased to $-H_1$ (following the lower branch of the cycle) and $I(-H_1)$ is measured. From the above values, $R(H_1) = (I(H_1) - I(-H_1))/(I(H_1) + I(-H_1))$ is obtained.

On the other hand, to determine $R(H_2)$ for $H_2 < 0$, see figure 1(b), H is increased to H_{max}, and then it is reduced to H_2. The magnetization is in the upper branch of the cycle and the intensity $I(H_2)$ is measured. Then, the field is reduced to H_{min} and subsequently it is increased to the positive $-H_2$, where the intensity $I(-H_2)$ is measured, now in the lower branch of the cycle. With these two quantities, the asymmetry ratio for negative fields H_2 is obtained as $R(H_2) = (I(H_2) - I(-H_2))/(I(H_2) + I(-H_2))$.

Using this procedure, half of the hysteresis cycle can be determined, as indicated by the continuous curves in figures 1(a) and (b). Our results on Pt magnetization were obtained using the method described above. For visual clarity and to facilitate the comparison with the cycles obtained from Kerr measurements, we applied to the half-cycles that were actually measured an inversion symmetry in order to display the magnetization curves in the usual way with complete hysteresis cycles.

3. Results and discussion

A film of 0.7 atomic layers (AL) of Pt was grown at room temperature on the clean Ni(110) substrate and subsequently it was annealed to 375 °C for a few minutes to improve its ordering.

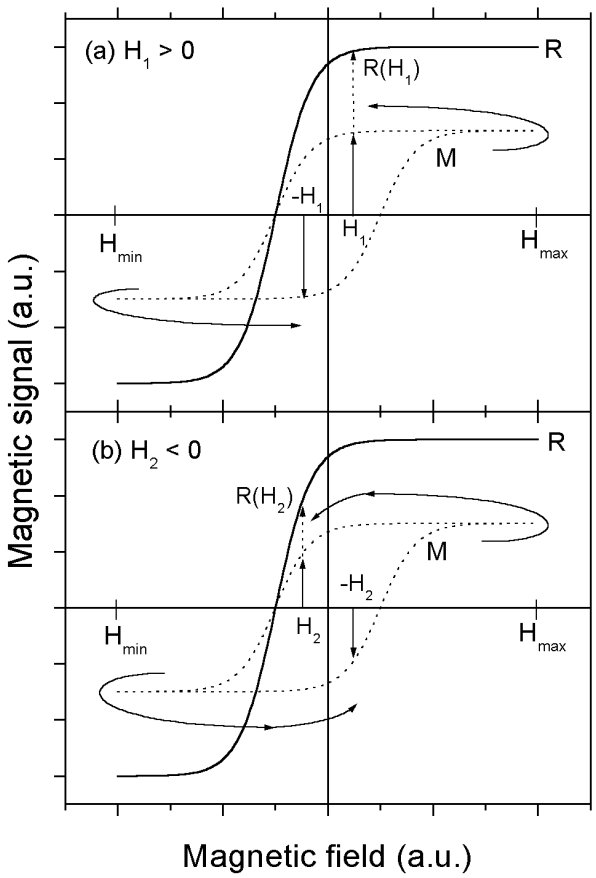

Figure 1. The procedure used to determine the dependence of the asymmetry ratio on the magnetic field, $R(H)$. (a) The case of positive field. (b) The case of negative field. See the text for details.

The magnetization of the substrate Ni atoms was monitored by means of the transverse magneto-optical Kerr effect (MOKE). This technique is not sensitive to the magnetization of the Pt atoms since their concentration is negligible compared to that of the Ni atoms within the penetration depth of the laser beam (about 100 Å) and since the magneto-optical response of magnetized Pt atoms is much smaller than that of Ni. Figures 2(a) and (b) show the MOKE hysteresis cycles obtained for the Ni(110) substrate, after deposition and annealing of the Pt film. The cycles were obtained by applying the magnetic field along two perpendicular directions in the surface of the sample, either the $[\bar{1}10]$ or the [001]. The two curves are similar and show coercivities around 240 G.

The main result of the present report is displayed in figure 3, which shows the asymmetry ratio, R, as a function of the magnetic field for the same Pt film of 0.7 AL. In contrast with the magnetic behaviour of the Ni substrate, the two directions, $[\bar{1}10]$ and [001], display different magnetic responses, as may be seen in figures 3(a) and (b). Whereas the application of the field along the $[\bar{1}10]$ direction results in a cycle similar to the corresponding one for the Ni substrate, with a coercive field of about 240 G, the [001] direction displays an R versus field dependence characteristic of a hard axis, since it shows an approximately linear relation between magnetization and magnetic field, crossing the origin of the graph, that is, having zero remanence. The results in figures 2 and 3 indicate that whereas the magnetization of the

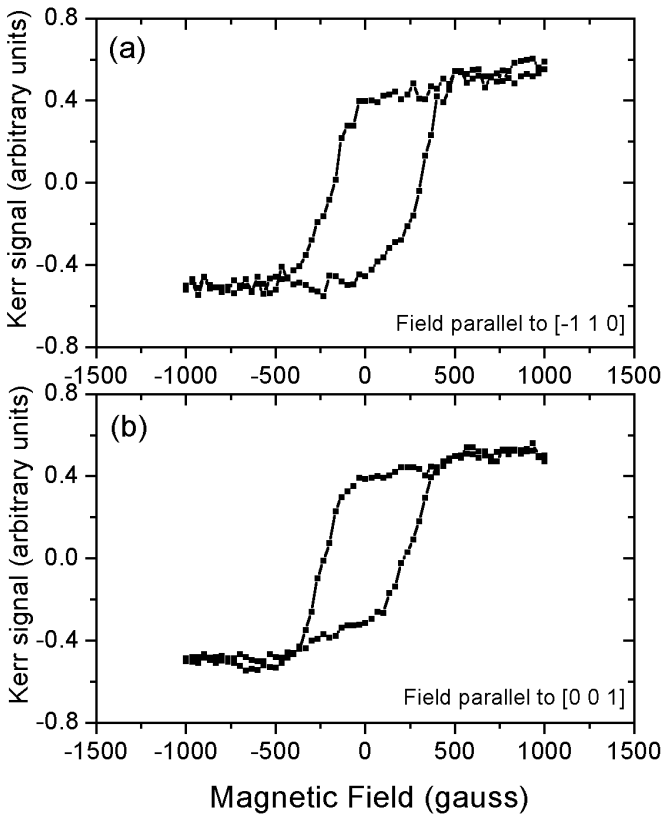

Figure 2. MOKE cycles measured (a) with the applied magnetic field parallel to the [$\bar{1}$10] direction or (b) parallel to the [001] direction.

interface Pt atoms seem to mimic that of the Ni atoms in the [$\bar{1}$10] direction, this is no longer the case along the [001] direction. Along the latter, it is harder to align the Pt magnetization with the applied field than to align the average Ni magnetization in the surface region. These results were reproduced twice for films of 0.7 AL of Pt and also observed in films of 0.9 AL.

To interpret the results properly, one has to keep in mind the different sensitivities of the two types of measurement. Whereas the resonant scattering probes the magnetization of the surface Pt atoms, this is not the case for the MOKE measurements due to the penetration of the laser beam. As the contribution of the topmost Ni plane to the MOKE signal is only a few per cent, it may be unobservable in practice. What probably occurs is that the surface Ni atoms display an anisotropic magnetization which induces that observed in the Pt films. This surface magnetic anisotropy of Ni has to be caused by hybridization of Pt and Ni electrons since the clean Ni surfaces do not seem to exhibit such an effect, as has been shown in the work of Zhang *et al* [9], who compare spin-polarized low-energy electron diffraction (SPLEED) and MOKE measurements, observing that the magnetization of the topmost Ni atomic planes is similar to that at ∼100 Å below the surface. The magnetic anisotropy that we observe in the Pt/Ni interface has to be understood as an example of interface magnetic anisotropy similar to those in other interfaces such as Co/Pt [10] or Fe/Ce [11].

In order to get further insight into the above findings, we compared the dependence of the magnetization curves on the applied field of a 0.7 AL Pt film before and after an

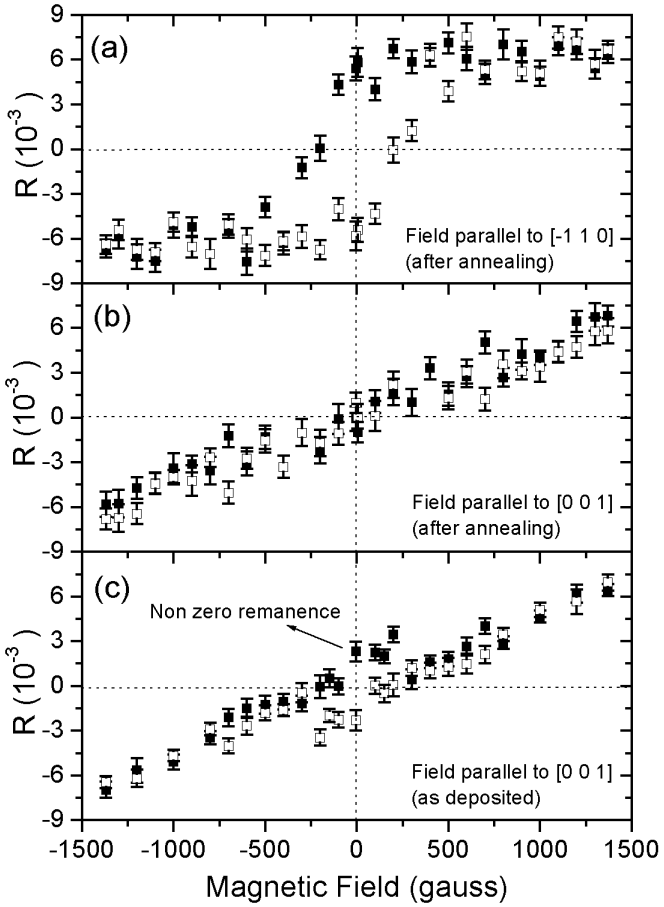

Figure 3. The asymmetry ratio, R, of a 0.7 AL Pt film grown on Ni(110). Filled symbols show the measured upper branch and open symbols the symmetrized lower branch of the cycles. (a) Film annealed at 375 °C and magnetic field parallel to the $[\bar{1}10]$ direction. (b) Film annealed at 375 °C and magnetic field parallel to the [001] direction. (c) As-deposited film (not annealed) and magnetic field parallel to [001].

annealing to 350 °C. For the $[\bar{1}10]$ direction, the dependence of R on the field was unchanged. However, for the hard direction [001], the annealing caused a small difference. The as-deposited film (figure 3(c)) showed an R versus field dependence softer than that after the annealing (figure 3(b)). Although the statistics of the data is not too good, it can be observed in figure 3(c) that the experimental curve crosses the vertical and horizontal axes at non-zero values, indicating non-zero remanence and a coercivity of about 250 G. Thus it appears that annealing caused a 'hardening' along the [001] direction, leading to zero remanence. This 'hardening' effect was, in fact, correlated with a structural change at the interface, as evidenced by the surface x-ray diffraction measurements shown in figure 4. The notation used in this figure corresponds to the usual tetragonal basis of surface crystallography in which the reciprocal-space axes H, K and L are parallel to the $[\bar{1}10]$, [001] and [110] standard cubic directions respectively; that is, the H- and K-axes are parallel to the surface of the crystal and the L-axis is perpendicular to it. The corresponding reciprocal-space basis vectors are $A1^* = 2.521$ Å^{-1}, $A2^* = 1.783$ Å^{-1}, $A3^* = 2.521$ Å^{-1}. As figure 4(a) illustrates, along the

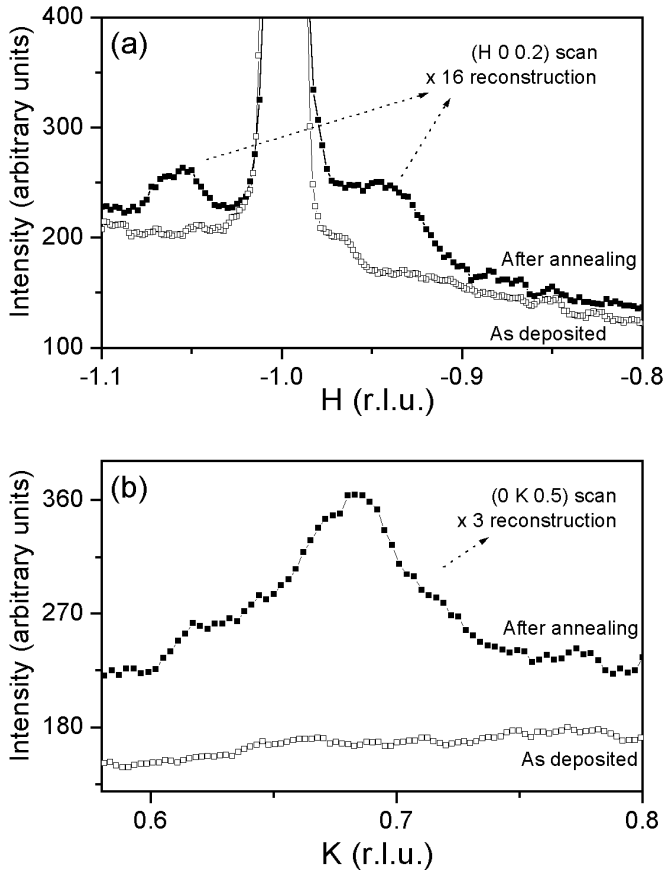

Figure 4. Radial scans in reciprocal space of a 0.7 AL Pt film grown on Ni(110). (a) A scan along the H-direction, before (open squares) and after (filled squares) annealing. (b) A scan along the K-direction, before (open squares) and after (filled squares) annealing.

H-direction, annealing leads to the appearance of two weak satellites located at $\Delta H = \pm 0.06$ reciprocal-lattice units (rlu) around the Ni reflection at $H = -1$ rlu. An approximate fit to their widths results in a coherence length of about 110 Å. The satellites in figure 4(a) are the fingerprints of a new surface periodicity of $(0.06)^{-1} = 16$ times that of the Ni crystal. Along the K-direction, another weak signature of surface ordering induced by annealing is also apparent in figure 4(b). The broad peak corresponds to ordered dimensions of about 65 Å and its position at $K = 0.67$ rlu (as well as that of other peak at $K = 1.32$ rlu, not shown) is consistent with a periodicity of three times that of the Ni. This $\sim(16 \times 3)$ anisotropic re-structuring of the interface reported here reminds us of the case of submonolayer Au films deposited on Ni(110), which develop a (6×3) superstructure consisting of chains of Au atoms on top of the Ni substrate as evidenced by previous STM work [12]. It is likely that chains of Pt atoms do also form on Pt/Ni(110), perhaps through a mechanism involving exchange between Pt adatoms and Ni surface atoms [13, 14], favouring the magnetization along the $[\bar{1}10]$ direction relative to the magnetization along the [001] axis. The enhancement of the in-plane angular magnetic anisotropy observed after annealing could be related to the development of long-range ordering in the chains. Further research is needed to confirm this idea.

4. Conclusions

In conclusion, we have observed anisotropic magnetization of submonolayer Pt films grown on Ni(110) by means of resonant diffraction measurements at different magnetic field intensities. Moreover, the magnetization of the Pt does not mimic the average magnetization of the near-surface Ni atoms along the [001] direction, as monitored by MOKE. Both effects are probably related to the structural anisotropy of the interface.

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