The reorientation transition in Co/Au(111)

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The spin reorientation transition in as-grown wedge-shaped Co/Au(111) films has been analyzed. Two critical thicknesses have been detected just like in the annealed case. Here, these are shifted to smaller values. The behavior of the system can be explained on the basis of the thickness-driven trajectory in the anisotropy space of the system. Both the first and second anisotropy constants have been determined: $K_{1s} = 0.66$ mJ/m^2, $K_{2s} = -0.12$ mJ/m^2. They are both smaller by modulus than their counterparts from the annealed case. The results provide quantitative evidence for the increase of surface anisotropy after annealing. © *1997 American Institute of Physics.*
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In recent years, the spin reorientation transitions have come into the focus of vigorous interest which has been backed up by the amazing progress in the preparation of well-defined monolayer films. The availability of ultrathin magnetic structures makes it possible that the thickness dependence of the anisotropy may be used as a tuning parameter to drive the reorientations, quite unlike the bulk reorientations where one is bound to rely on temperature-related variations only for the investigation of spontaneous reorientations. A very ingenious way to probe the thickness-dependent properties is the combined use of wedge-shaped films and spatially resolving techniques. In a single experiment one can image with high precision the effects on magnetization induced by the variation of thickness.

Quite recently, the thickness dependence of magnetic microstructure in Co/Au(111) films has been studied in wedge-shape geometry by means of scanning electron microscopy with polarization analysis of the secondaries (SEMPA).[1,2] Strong correlation between domain structure and morphology has been identified as originating in the three-dimensional growth of cobalt on the reconstructed Au(111) surface. On annealing, the cobalt film becomes smooth causing the vertical domains to become very large and comparable in size with the wedge dimensions. In the as-grown films, on the other hand, the domain structure displays small vertically magnetized domains of a typical size of several microns (Fig. 1).[3]

The SEMPA technique and the preparation of the films has been described elsewhere.[1,4] The reorientation transition in the annealed system has already been studied in detail and explained consistently within the framework of the general anisotropy flow concept.[2,5,6] Here we present an extension to as-grown films of our previous investigations of the spin reorientation behavior. The experimental analysis proceeds quite like in the case of the annealed films with the important difference that now temperature variations have to be avoided to prevent annealing effects. The results are presented in Fig. 1. The two images were obtained with different orientation-dependent polarization detection axes of the spin analyzer.[4] Both patterns were taken simultaneously and display precisely the same portion of the film. Figure 1(a) shows the domain structure with vertically magnetized domains; black and white correspond to magnetization pointing in and out of the surface, respectively. The film thickness increases from right- to left-hand side. At the low-thickness (right-hand) side, one can observe the onset of ferromagnetism at about 2 monolayers (ML).[7] The black and white domains can be clearly recognized in a particular thickness regime, while they disappear again on the thicker side. This indicates that with increasing thickness on approaching the left-hand side of the image in Fig. 1(a) one crosses the critical thickness for spin reorientation. This is proven by the in-plane domain pattern in the second image [Fig. 1(b)] which exhibits domains only on the thicker side of the wedge. The domains seem to be elongated along the direction of magnetization. At present we cannot give any explanation for this, since it would be far too speculative without a better knowledge of the in-plane anisotropies. It turns out experimentally that in-plane domains appear above a certain thickness $d_2=(4.10\pm0.05)$ ML [see Fig. 1(b)].[8] After applying a magnetic field along the vertical direction, we observe that the vertical phase is driven up to d_2, exhibiting a single-domain configuration in close analogy to the observations for the annealed film. The vertically magnetized domains in Fig. 1(a), however, are found only at considerably lower thicknesses. The line corresponding to d_2 lies far away from any vertically magnetized domain. In that image domains disappear at d_1 which is considerably shifted toward lower thicknesses. Due to the existence of small domains, d_1 can only be determined with a somewhat higher uncertainty than d_2. We find that $d_1=(3.7\pm0.1)$ ML. The significant shift is a direct consequence of the effective magnification which is attained by virtue of the wedge geometry by mapping a change in thickness as small as parts of a ML onto a clearly observable micrometer-large lateral structure.

The salient physics underlying the observations is in the competition between magnetocrystalline, shape, and surface anisotropies. In the vicinity of the reorientation transition their contributions to the magnetic anisotropy free energy cancel in the lowest approximation which is why the contribution K_2 becomes a quantity of crucial importance for the possible generic types of transition. Two characteristic borderlines were found in the annealed films as well. This signals coexistence of phases with vertical and out-of-plane magnetization within a small but clearly detectable range of film thicknesses (d_1,d_2). Furthermore, it has been demonstrated that both surface anisotropies K_{1s} and K_{2s} can be determined from the relevant thicknesses, identified in the

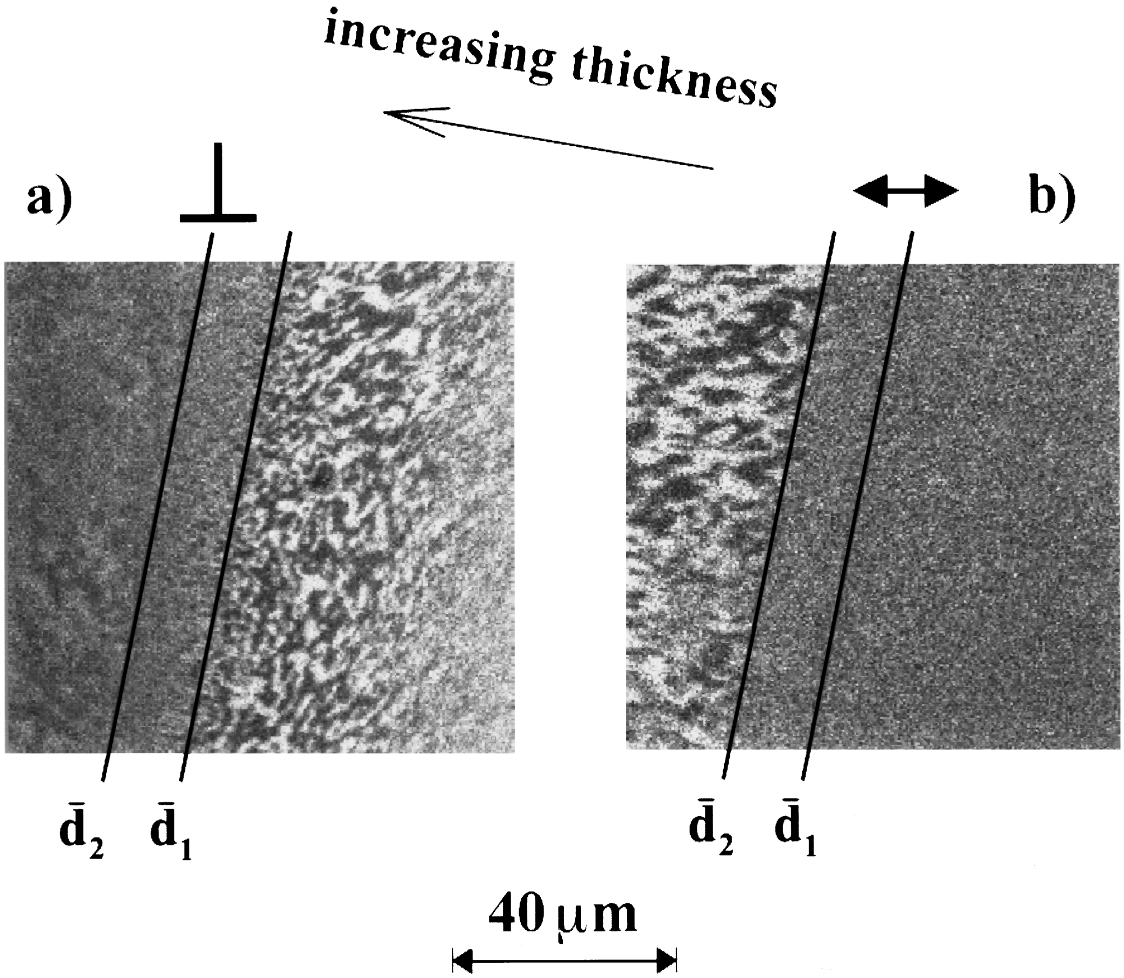

FIG. 1. Domain images of a cobalt wedge on Au(111) in the virgin state. (a) gives the vertically magnetized domain pattern, (b) gives the domain distribution with in-plane magnetization orientation. White/black domains represent magnetization pointing out of/into the film surface for (a) and right-/left-hand side in the plane for (b), respectively. Both images were taken simultaneously and show precisely the same part of the sample. The film thickness increases from right- to left-hand side ranging from ≈1.8 ML to ≈5 ML. d_1 and d_2 correspond to the critical thicknesses.

images of the micromagnetic structure.[2] As a matter of fact, a considerable amount of the efforts in the field of ultrathin films has been, and is currently being, invested into the quantification of the surface values. The surface constants are defined in connection with the phenomenological ansatz,[9,10]

$$K_1(d)=K_{1b}+\frac{K_{1s}}{d}, \tag{1}$$

$$K_2(d)=K_{2b}+\frac{K_{2s}}{d}, \tag{2}$$

with d for thickness, b for bulk, and s for the effective contributions of both interfaces of the film. Within the interpretational scheme of Ref. 5, one obtains

$$K_{1s}=(\tfrac{1}{2}\mu_0 M_S^2-K_{1b})\overline{d_2}, \tag{3}$$

$$K_{2s}=\tfrac{1}{2}[(\tfrac{1}{2}\mu_0 M_S^2-K_{1b})(\overline{d_1}-\overline{d_2})-2K_{2b}\overline{d_1}], \tag{4}$$

where M_S is the saturation magnetization. The characteristic thicknesses that appear in the above relations deserve special attention. At d_2, the lowest-order (first) anisotropy contribution is zero, while d_1 is defined by the equation $K_2(d_1)=-\tfrac{1}{2}[K_1(\overline{d_1})-\tfrac{1}{2}\mu_0 M_S^2]$.[5] To apply Eqs. (3) and (4) to the calculation of the surface constants, one needs to determine d_1 and d_2 and feed them in together with the bulk values for K_{1b}, K_{2b}, and M_S. At room temperature, the bulk values are $K_{1b}=5.0\times10^5$ J/m^3, $K_{2b}=1.25\times10^5$ J/m^3, and $M_S=1.440\times10^6$ A/m.[11] It then follows from Eqs. (3) and (4) that for the as-grown film at room temperature $K_{1s}=0.66$ mJ/m^2 and $K_{2s}=-0.12$ mJ/m^2. The interpretational scheme[5] provides for a consistency check in that the quantity of the dimensionality of energy density (i.e., of bulk anisotropy energy)

$$b=[K_{1s}K_{2b}+K_{2s}(\tfrac{1}{2}\mu_0 M_S^2-K_{1b})]/K_{1s}$$

must be negative if the system is really driven by the thickness variation to pass through a region of coexistence in the anisotropy space. We find explicitly that $b=-0.27\times10^5$ J/m$^3<0$. It is not only the sign of the quantity that is remarkable but its absolute value as well. Indeed, this quantity is significantly smaller than the bulk values given above. Hence, the high-resolution imaging leads to a high-resolution anisotropy determination as well, sensitive to anisotropy energy densities which are several times less than the second bulk anisotropy constant.

It is quite intriguing to compare with the respective values of the surface anisotropy constants for the annealed film.[2] Indeed, the qualitative appearance of the SEMPA images in both as-grown and annealed cases is the same, thus confirming that the same type of thickness-driven transition occurs in both cases. The borderlines corresponding to the characteristic thicknesses are markedly shifted in the annealed film when compared with the as-grown one, signaling different surface anisotropy contributions in this case. For the annealed wedge of cobalt on Au(111), one finds $\bar{d}_1=4.75$ ML and $\bar{d}_2=5$ ML, yielding $K_{1s}=0.80$ mJ/m^2 and $K_{2s}=-0.14$ mJ/m^2, and $b=-0.15\times10^5$ J/m^3 at room temperature.[2]

The comparison of both sets of values for K_{1s} and K_{2s} indicates that in the as-grown film the surface constants are smaller by absolute value. Hence, annealing increases the effective surface anisotropy in the system as previously reported for some magnetic multilayers.[12]

The surface constants have been obtained under the assumption that the demagnetizing energy is the same as for the annealed film. One can rule out the possibility of the difference being due to magnetostatic changes: On annealing the film gets smoother and, correspondingly, the demagnetizing factor increases which should cause the critical thicknesses to decrease in contradiction with what we observe. One can thus conclude that the observed trend is due to changes in the surface anisotropies only.

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