Influence of surface atomic steps on in-plane magnetic anisotropy of ultrathin Fe films on W(001)

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Previous magneto-optic Kerr effect studies of ultrathin epitaxial Fe films grown on stepped W(001) surfaces yielded evidence of in-plane uniaxial magnetic anisotropy with magnetization perpendicular to the steps. We report spin-polarized secondary electron emission spectroscopy studies of the same system that confirms this novel micromagnetic phenomena, and provides a more detailed characterization of the zero-field in-plane spin configuration as a function of initial applied field direction.

Recent scientific and technical advances have provided new opportunities for exploring the relationship between structure and magnetism.[1] The magnetic properties of thin films are strongly affected by their structure, as recently demonstrated by the discovery of perpendicular magnetic anisotropy in thin ferromagnetic films[2] and thickness-dependent interlayer oscillatory magnetic coupling.[3] Recently, a new magnetic phenomenon has been observed[4,5] for ultrathin films grown on deliberately modified substrates: step-induced magnetic anisotropy. Our recent magneto-optic Kerr effect measurements[4] have demonstrated the existence of a surface-step-induced in-plane magnetic anisotropy in ultrathin epitaxial Fe films grown on W(001) surfaces having uniform 25 Å wide steps along the [100] direction. Fe films grown on smooth W(001) surfaces exhibit little or no in-plane magnetic anisotropy, whereas magnetization curves determined using magneto-optic Kerr effect polarimetry show distinct evidence for a step-induced magnetic easy direction perpendicular to the step edges on the stepped W(001) surface.

Figure 1 displays the results of new magneto-optic Kerr effect measurements, similar to those indicated in Ref. 4, that were obtained using our new apparatus that also permits analysis of spin-polarized secondary electrons emitted from the magnetic films. The hysteresis loops of Fe films grown on flat and stepped W(001) acquired from longitudinal configuration magneto-optic Kerr effect measurements appear in Figs. 1(a) and 1(b), respectively. It is clear (from comparing the values of **H** required to saturate the two films) that the easy magnetization direction of 2 monolayer (ML) Fe films on the stepped W(001) substrate is perpendicular to the step edge at the measurement temperature ($\sim$100 K). However, the magneto-optic Kerr effect study[4] does not deal with the **H**=0 magnetization in detail. In particular, it is unclear whether the lack of parallel-to-step-edge remanence in the hysteresis loops obtained from films on the stepped surface, when **H** is parallel to the step edges, is due to a complete rotation of magnetization to a direction perpendicular to the step edge, or to antiferromagnetic coupling between the Fe strips.

It is interesting to point out that Berger *et al.*[5] have observed an easy axis parallel to the step edges on their vicinal Co/Cu(001) surfaces. An attempt was made by that group to explain their results in terms of the bulk magnetocrystalline constants for a cubic system. That model failed to account for the observed direction of **M** observed in their experiments, but could possibly account for our observed results. It is not surprising that a model based on bulk anisotropy fails: the surface magnetocrystalline anisotropy is strongly dependent on the electronic structure near the Fermi level;[6] and, it is well-established that the band structure, and hence, the near Fermi surface density of states in thin film systems are very different from those of the bulk. Clearly, the micromagnetic properties of systems exhibiting unusual anisotropy bear closer investigation.

In this article, we continue to experimentally explore surface-step induced magnetic anisotropy in the $p(1\times1)$ Fe on W(100) system by conducting spin-polarized secondary electron emission spectroscopy (SPSEES). Our new results confirm the step-induced in-plane magnetic anisotropy apparent from previous magneto-optic Kerr effect measurements, and yield additional information about the spin distributions in zero applied fields.

Our new surface magnetization analysis system incorporates multiple-cell molecular beam epitaxy (MBE) film growth capability, Auger electron spectroscopy (AES), low-energy electron diffraction (LEED), and medium energy electron diffraction (MEED), with two magnetic-sensitive techniques: SPSEES and magneto-optic Kerr effect polarimetry. A pneumatically controlled manipulator moves the sample between the thin film preparation level (MBE/LEED/MEED) and the magnetic spectroscopy level. The films were grown by electron beam heating the tip of a high-purity wire (pendent drop evaporator). Film thickness was monitored during growth by a quartz microbalance (located at 1/15 of the source-to-sample distance to enhance sensitivity) and by a quadrupole mass spectrometer in close proximity to the substrate. The experimental setup at the spectroscopy level is shown in Fig. 2. Two mirrors and a rotatable electromagnet, which provides a magnetic field of $\pm$2500 Oe either in the sample surface plane or normal to it, are mounted on a moveable stage which permits performing magneto-optic Kerr effect polarimetry at the same sample position as the SPSEES experiments are performed. The signal processing technique utilized to obtain hysteresis loops from the Kerr rotation has been described previously.[7] When the magneto-optic Kerr effect polarimeter is fully retracted, a coil mounted on a rotation device serves to magnetize the thin

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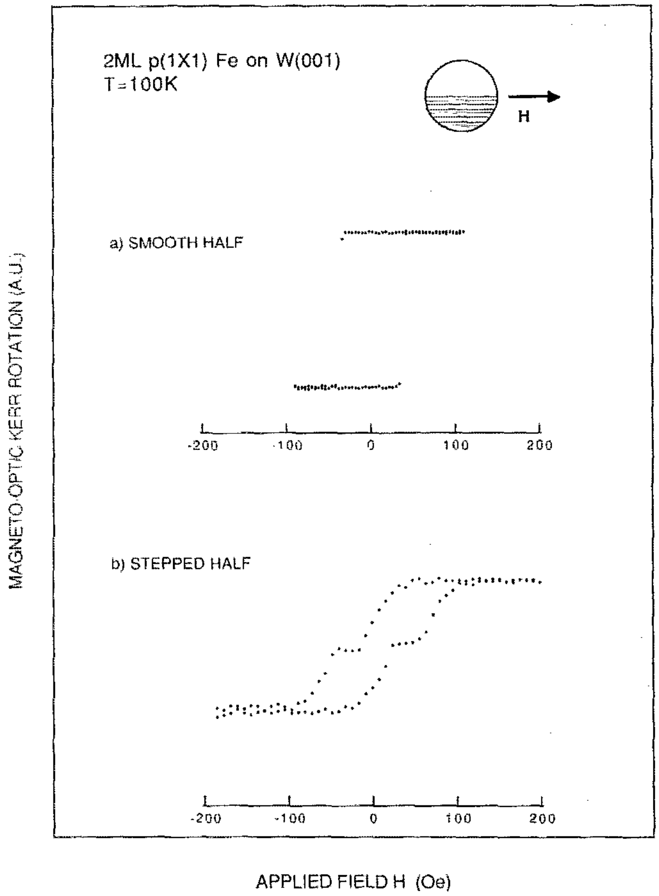

FIG. 1. Hysteresis loops of a 2 ML Fe film on the (a) smooth and (b) stepped-half of W(001) measured by the longitudinal magneto-optic Kerr effect with the applied magnetic field parallel to [100], i.e., the step direction. The incident light, from a diode laser, is *s*-polarized and has a wavelength of 670 nm.

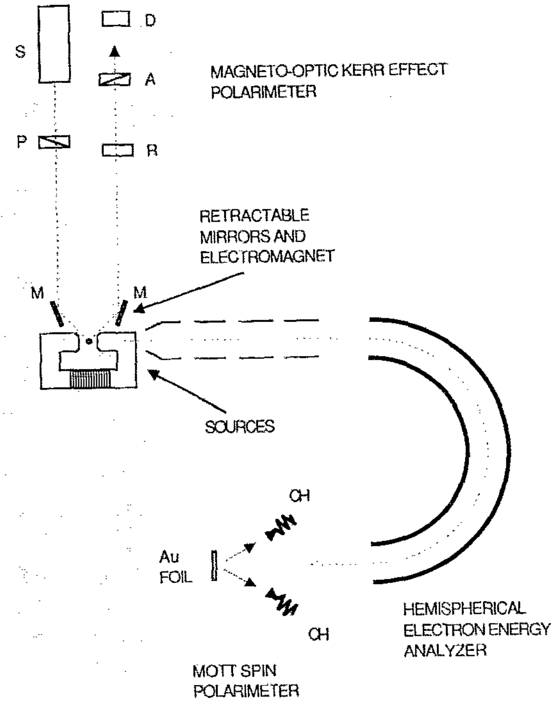

FIG. 2. Schematic of experimental setup. Details are described in the text. *S*: diode laser; *P* and *A*: Glan–Taylor linear polarizer; *M*: mirror, *R* quarter wave plate; *D*: photodiode; CH: channeltron.

film along any axis in its plane. Three possible excitation sources are available for the spin-polarized electron spectroscopy, an electron beam, UV radiation from a resonance lamp, or x rays from a commercial source. A 20 keV spin polarimeter,[8] installed on the exit slit flange of a commercial 150 mm hemispherical electron energy analyzer, has been modified to measure the two in-plane spin polarization components. A fifth retractable electron multiplier (incorporated into the second lens of the spin polarimeter) provides a convenient means of switching to the nonspin-polarized electron spectroscopies.

Our experiments were carried out using a bifacial W(001) substrate, illustrated in Fig. 1. One face had its surface normal oriented along the [001] direction to $\pm 1/2°$, the other at a vicinal angle of 4° yielding a surface with regular steps along [100]. From the splitting of spots in the LEED pattern, we deduced the steps were single atomic height, and that the terrace width was 25 Å with a statistical variation of 5 Å. This type of substrate permits direct comparison of thin-film magnetic properties on smooth and stepped surfaces under identical growth and measurement conditions. The thickness calibration was checked using thermal desorption of Fe/W(001).[9] The two film layers were grown at different substrate temperatures: the first ML at 900 K and subsequent layer at 250 K. All of the magneto-optical and spin-polarized secondary electron measurements were performed at substrate temperatures of 100 K. Sample quality was monitored by LEED and AES. Previous work by our group and others on Fe/W(001) has shown this system to be well-behaved, exhibiting excellent crystal structure, and reproducible long-range magnetic order when the Fe thickness is above 1 ML.[4,10,11]

Figure 3 displays SPSEES data that define the direction of remnant magnetization in both flat and stepped film systems after application of a magnetic field along various in-plane directions specified by the angle θ measured from a step direction (refer to the inset of Fig. 3). In the SPSEES experiments, 50 eV secondary electrons excited by a 500 eV electron beam were collected at normal emission and subsequently spin analyzed. Results from the films grown on the smooth half of the substrate indicate that remnant magnetization, which is proportional to the measured spin polarization *P*, tracks the applied field direction (i.e., $P_y/P_x=\tan\theta$). From inspection of corresponding SPSEES results for the stepped half, it is obvious that the steps tend to pin the remnant magnetization along the direction perpendicular to the step edges, even when the applied field is 10° from the steps. The films on stepped substrates exhibit a uniaxial anisotropy perpendicular to the step edge. Not only is the coercive force smaller for **H** perpendicular ($H_\perp$) to the step direction, but **M** alignment

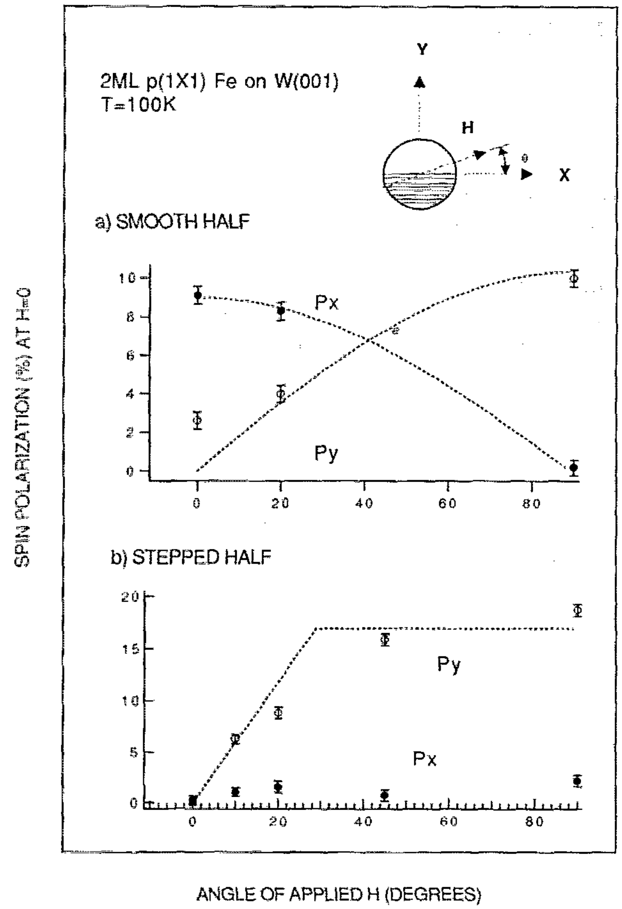

FIG. 3. Remnant magnetization spin-polarization components measured from (a) smooth-half, and (b) stepped-half of a 2 ML Fe film on W(001) as a function of applied magnetic field direction (refer to inset, upper right). Dashed curves in (a) correspond to $P_y = P_{y\,\max} \sin\theta$ and $P_x = P_{x\,\max}\cos\theta$. $P_y/P_x = \tan\theta$ corresponds to isotropic behavior. In panel *b*, P_x is determined to be essentially zero for all values of θ, but P_y varies from zero at $\theta=0$ to $P_{y\,\max}$ at $\theta=90°$. The dotted line suggests that P_y remains constant for $90° < \theta < \theta_{\mathrm{crit}}$, where θ_{crit} is defined by $H \sin\theta_{\mathrm{crit}} > H_{\mathrm{sat}}$. For $\theta < \theta_{\mathrm{crit}}$, the component of H along the easy direction (y direction) is insufficient to saturate the film, i.e., to form a single magnetic domain.

perpendicular to the steps is preserved at $H=0$. This confirms an earlier conclusion based on magneto-optic Kerr effect measurements, namely that the remnant magnetization is perpendicular to the step edges.

Scanning electron microscopy with spin polarization analysis of secondary electrons (SEMPA) has been used to study the magnetic anisotropy and domain structure of ultrathin Co films on stepped Cu surfaces.[5] No correlation of the domain shapes or wall orientation with respect to the step direction was observed, suggesting that domain wall pinning at steps may not be a dominant mechanism responsible for the uniaxial anisotropy in the Co on stepped Cu system. From Fig. 3, it is apparent that both P_x and P_y become zero on the stepped-half of our 2 ML $p(1\times1)$ Fe films on W(001) when $\theta=0$ (applied field parallel to the steps).[12] It is equally apparent from the square hysteresis loops obtained for $H_\perp$ to the steps that a single magnetic domain is formed in this configuration. The spatial resolution of our electron gun is ~0.1 mm;[13] therefore, the $H=0$ magnetic domains of our 2 ML $p(1\times1)$ Fe films on stepped W(001) must be smaller than 0.1 mm in order to measure $\langle M\rangle=0$. We cannot rule out the interesting possibility of antiferromagnetic alignment of adjacent microdomains formed by the terraces.

The mechanism underlying step-induced uniaxial anisotropy remains unclear. Our LEED structure analysis[11] of 1 and 2 ML $p(1\times1)$ Fe on smooth W(001) have characterized the expected tetragonal distortion of the film resulting from the large lattice mismatch (~10%). We have not thoroughly explored the structure of the stepped surface films, but there is no obvious indication of departures from the smooth film tetragonal structure (i.e., additional LEED spots corresponding to a uniaxial strain resulting from an incommensurate structure). Additional structural studies and model calculations are in progress and will be reported in a future publication.

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[12] Consistent with this, we have also observed nulls in the magneto-optic Kerr effect signals (Ref. 4).
[13] Spatial resolution of 0.1 mm would just be adequate to resolve individual domains in the Co on stepped Cu(100) of Ref. 5.