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Surface Magneto-Optical Kerr Effect Study of Magnetization Reversal in Epitaxial Fe(100) Thin Films

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Research Article

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ABSTRACT

Surface Magneto-optic Kerr Effect (SMOKE) technique is used to study the magnetization rotation in single crystalline Fe thin films, deposited onto MgO (100) substrates by magnetron sputtering, with thicknesses, t_{Fe}, varied within the range from 70 Å to 250 Å. The crystalline structure and epitaxial relation are determined employing X-ray diffraction (XRD). The SMOKE loops are interpreted in the framework of a phenomenological model for coherent rotation of the magnetization. The switching behavior of these films is characterized by two different reversal regimes. In films with thicknesses less than a critical value ($t_{Fe}<t_c$), there is a superposition of the magneto crystalline anisotropy to an uniaxial in-plane anisotropy, and as a consequence the magnetization rotation is non-coherent with motion of Néel and Bloch domain walls. As the thickness is increased from the critical thickness, and the uniaxial anisotropy is overwhelmed by the magneto crystalline anisotropy, the magnetization reversal turns coherent with Bloch domain walls motion. The thickness dependence of all anisotropy constants follow a function of $1/t_{Fe}$ as expected for interface effects.

INTRODUCTION

During the last years, the magneto-optical properties of ferromagnetic thin films and multilayers have attracted much attention due to their applications in a variety of technological devices, such as [1-3]: magneto-optical sensors, high efficiency magnetic recording heads, magnetic access random memories, etc. One of the most interesting phenomena occurring at the sub-Nano metric level is the Surface Magneto-optic Kerr Effect (SMOKE). Originally discovered by Kerr in 1876 [4], this phenomenon originate from the circular birefringence induced by a magnetic field when linearly polarized light interacts with a reflecting surface. In a ferromagnetic (FM) the intensity of the magneto-optical (MO) reflected signal is proportional to the sample magnetization. In the case of a thin film, SMOKE technique can be used as standard probe in the study of hysteresis curves [5], magnetic domains and magnetic anisotropies [6,7] and in applications in magnetic recording and high density storage [8]. Although the magnetization reversal in FM thin films has been widely studied, still an object of interest since it is the key to understand the micro magnetic processes in matter, while also permitting fundamental studies in magnetism. Besides this, when the FM material is in contact with a semiconductor give rise to hybrid structures offering possibilities for a range of new applications.

Experimentally, magneto-optic techniques can be used in three basic configurations, depending on the orientation of the applied field with respect to the plane of incidence: longitudinal, polar, and transversal. In the longitudinal configuration (LMOKE) the magnetic field is applied parallel to the plane of incidence and in the plane of the sample. Here, the reflected signal is directly proportional to the component of the magnetization along the magnetic field. In the polar Kerr effect of PMOKE, the field is parallel to the plane of incidence and perpendicular to the plane of the film, and the signal proportional to the out-of-plane magnetization. In the transversal configuration (TMOKE), the magnetic field is perpendicular to the plane of incidence, and in the plane of the film. In this case, the dependence of the MO signal on the magnetization is more complicated, since is a non-linear function of both in-plane magnetization components. In practice, MO methods are very simple and of easy implementation in comparison

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with other magneto metric techniques, such as VSM or SQUID, and in contrast with these, allow us to measure all magnetization components independently.

EXPERIMENTAL PROCEDURE

Fe films within thicknesses in the range from 70 Å to 250 Å were grown by dc magnetron sputtering onto commercial electronic grade MgO (001) wafers, with cleavage edge direction [110]. Magnetrons assure a continuous magnetic field of the order of 10 Oe during all the growth process. Before deposition, the substrates were cleaned in ultrasound baths of acetone and ethanol for 10 min, and then dried in nitrogen gas flow. Neither a buffer layer on the substrate nor a cover layer on the magnetic film was used. The base pressure of the system prior deposition was 2.0×10^{-7} Torr.

The films were deposited in a 3.4×10^{-3} Torr argon atmosphere in the sputter-up configuration, with the substrate at a distance of 9 cm from the target. The purity of the Ar gas and the Fe target was 99.999% y 99.9%, respectively. The substrate temperature was maintained at 130°C, with a supplied electric power of 20 W. The film thickness was controlled using a calibrated quartz crystal, with deposition rate of the order of ~1 Å/s. The crystallographic quality of the Fe films was tested by X-Ray Diffraction (XRD) in a Siemens D5000 diffractometer, with Cu K_α radiation in the Bragg-Brentano configuration.

The hysteresis curves of the Fe(t_{Fe})/MgO(001) films were measured by SMOKE in the longitudinal configuration. In this configuration the MO signal is directly proportional to the component of the magnetization parallel to the applied field. The measurements were performed at room temperature and with magnetic fields up to 1kOe. The samples were irradiated with a He-Ne (632.8 nm) radiation linearly polarized at 45° with respect to the plane of incidence (θ_p = 45°), and modulated at an angle θ_m = 0° with a photoelastic modulator at a frequency ω=50° kHz. The angle of incidence was fixed at 60° were the MO absorption of Fe is maximum. Before detection, the signal passes through an analyzer in the 2ω mode in order to select the corresponding magnetization component. The hysteresis loops were taken at several positions of the applied magnetic field with the help of a goniometer, which allowed us to rotate the samples plane.

RESULTS AND DISCUSSION

Figure 1 shows a high-angle θ-2θ x-ray diffraction pattern for a 100 Å thick Fe film. Besides the peak from the substrate, the only observed Bragg peak from the Fe film is at 2θ=65.38°, which is associated with a reflection from the Fe(200) plane. The measured lattice parameter was a_0=2.852 Å. Compared to the bulk Fe lattice parameter of 2.866 Å, the compressive strain is -0.49%. These observations indicate the high crystalline quality of the films with a well-defined growth orientation in the (100) plane. The in-plane epitaxial relation was inferred by comparison of the substrate cleavage direction [110] with the magnetic easy and hard axes obtained by MOKE, and assuming that the Fe film behaves as in the bulk. The following epitaxial relations were obtained: [100]Fe|| [110] MgO and [010]Fe || $[\bar{1}10]$ MgO.

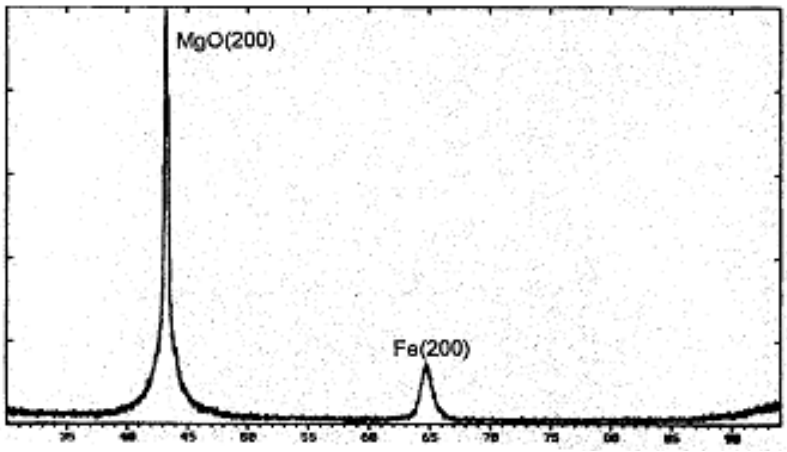

Figure 1. Specular x-ray diffraction pattern from a Fe(100 Å)/MgO(001) film.

The hysteresis curves for the samples Fe (70 Å)/MgO (001) and Fe (100 Å)/MgO (001), are shown in **Figures 2 and 3**, respectively. These loops were taken with the magnetic field, H, parallel to the cubic axes of bcc Fe [110], [100], $[\bar{1}10]$ and [010]. In very thin films, these curves are characterized by a single irreversible transition when *H* || [110], $[\bar{1}10]$ and [010] with non-equivalent hard axes [110], $[\bar{1}10]$ In the case when the magnetic field *H* || [100], the magnetization curve is asymmetric and characterized by two irreversible transitions fields, with a remanence $M_R/M < 1.0$. In films with thicknesses t_{Fe}>100 Å, the hysteresis loops show a symmetric profile at all field positions with equivalent easy and hard axes. To fully understand the magnetization reversal of iron thin films, we use a model in which the magnetization rotates coherently with magnetic free energy

$$E(\theta,\phi) = -HM\sin\theta\cos(\phi-\phi_H) + \frac{K_1}{4}\left(sen^2 2\theta + sen^4\theta\, sen^2 2\phi\right) + 2\pi M_{eff}^2\cos^2\theta + K_u\, sen^2\theta\, sen^2\phi \quad (1)$$

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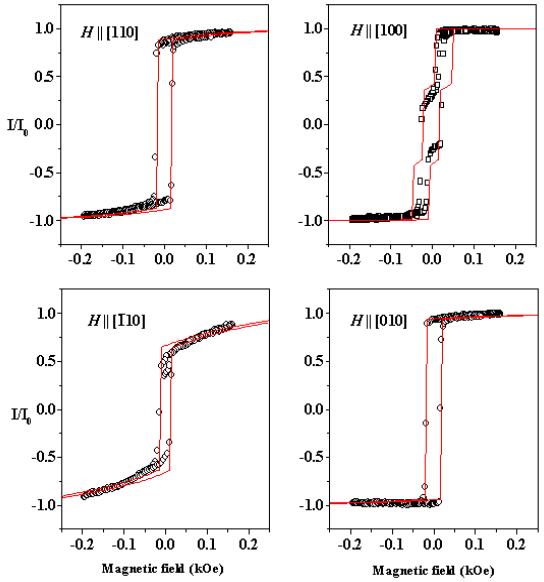

Figure 2. MOKE hysteresis loops for Fe (70 Å)/MgO (001), with the magnetic field applied parallel to the cubic crystallographic axes of Fe [110], [100], $[1\bar{1}0]$ and $[010]$. The continuous curves were calculated as described in the text.

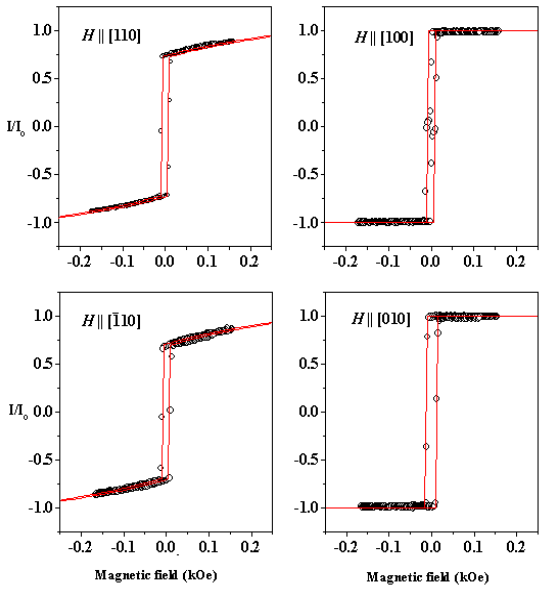

Figure 3. MOKE hysteresis loops for Fe (100 Å)/MgO (001), with the magnetic field applied parallel to the cubic crystallographic axes of Fe [110], [100], $[1\bar{1}0]$ and $[010]$. The continuous curves were calculated as described in the text.

In whereθ and φ are the polar and azimuthal angles of the magnetization vector, respectively; M is the saturation magnetization; K_1 is the first order cubic magneto crystalline anisotropy constant; K_u is the uniaxial in-plane anisotropy constant; φ_H is the azimuthal angle of the applied field with respect to the [100] direction; M_{eff} is the effective magnetization defined by $4\pi M_{eff} = 4\pi M\text{-}2K_N/M$, and K_N the perpendicular anisotropy constant. The origin of the uniaxial anisotropy in these films is the compressive strain observed from the XRD spectra. The theoretical hysteresis loops are calculated taking the component of the magnetization parallel to the applied field

$$\frac{M(H)}{M} = \cos(\phi_0 - \phi_H), \tag{2}$$

Where φ_0 is the equilibrium position of the magnetization in the film plane, calculated numerically taken the minimum of the magnetic free energy for each field orientation. The best match between the experimental curves and the model is obtained using the parameters listed in **Table 1**. The agreement between theory and experiment is reasonable for samples with thicknesses t_{Fe} > 100Å, where only a single transition is observed. However, for thinner films the theoretical curve departs from the experimental hysteresis loop at H || [100], where two irreversible transitions are observed. This is an indicative that in these films, the magnetization rotation is non-coherent. Other studies in epitaxial Fe/GaAs films suggest that the switching of the magnetization is determined by the rotation of Néel and Bloch domain walls, under the action of uniaxial and magnetocrystalline anisotropies [9].

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The variation of the anisotropy fields with respect to the film thickness is shown in **Figure 4**. The solid lines in panels in **Figures 4a and b** are functions following a dependence $1/t_{Fe}$ as expected for interface and surface effects. The inset in **Figure 4b** is the rate of change between the in-plane uniaxial and magneto crystalline constants, K_u/K_1.

Table 1. Anisotropy constants obtained from SMOKE loops.

t_{Fe} (Å)	$4\pi M_{eff}$ (kOe)	$2K_1/M$ (kOe)	$2K_u/M$ (kOe)
70	11.7	0.27	0.07
90	15.7	0.36	0.015
100	16.5	0.42	0.012
115	17.2	0.44	0.012
130	17.4	0.46	0.011
150	18	0.51	0.01
185	18.5	0.5	0.011
200	18.9	0.52	0.012
230	19.25	0.53	0.011
250	19.5	0.55	0.011

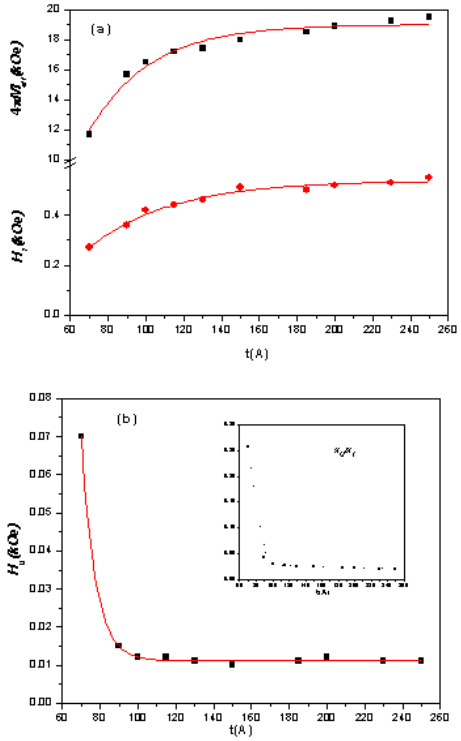

Figure 4. Thickness dependence of the anisotropy constants of Fe/MgO(001) thin films. The solid lines represent functions of $1/t_{Fe}$. The inset in (b) is the ratio K_u/K_1. The dashed line is a guide for the eyes

This allows us to quantify the effects of the magnetic anisotropies on the magnetization reversal process in Fe thin films. As the film thickness is decreased below a critical thickness of about 100 Å, the value of K_u/K_1 increases rapidly from ~0.025 up to ~0.26. This establishes a competition between the uniaxial and cubic anisotropies, and as a result a non-coherent rotation of the magnetization occurs due to a transition from Néel-to-Bloch domain wall motion, as explained[9,10]. This behavior is of interest since provides a tunable switching property that can be of importance in micro magnetic device applications. On the other hand, in films thicker than 100 Å where the magneto crystalline anisotropy overwhelms the uniaxial anisotropy, the magnetization switching is coherent and mainly determined by the rotation of Bloch domain walls.

CONCLUISON

We have studied the magnetization reversal in single crystalline Fe/MgO(001) thin films using in-plane SMOKE magnetometry. A critical thickness of about 100 Å separating two switching regimes is observed. In films with thicknesses t_{Fe}>100 Å, the cubic anisotropy is superposed to the uniaxial anisotropy. Due to this anisotropy superposition the reversal process is determined by a non-coherent rotation of the magnetization, with Néel-to-Bloch domain walls motion. For t_{Fe}>100 Å the magnetization reversal is coherent and controlled by the cubic magneto crystalline anisotropy, with Bloch domain walls motion. The anisotropy constants of the films are determined from the SMOKE loops, using a phenomenological model for coherent rotation of the magnetization. All anisotropies follow the trend $1/t_{Fe}$.

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