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Accurate measurement of the in-plane magnetic anisotropy energy function $E_a(\theta)$ in ultrathin films by magneto-optics

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Abstract

We present a sensitive and precise determination of an arbitrary thin film magnetic anisotropy energy E_a (or E_a/M_S if the saturation magnetization M_S is not known) versus in-plane polar angle θ by means of initial inverse susceptibility and torque measurements under constant transverse bias field H_B. In this method coined **TBIIST**two magnetic fields H_L and H_B are applied in the plane of the film along directions defined by θ and $\theta-(\pi/2)$, respectively, and m_L the magnetization component in units of M_S is measured versus H_L around $m_L=0$. This readily provides two quantities $\chi^{-1}=(\partial H_L/\partial m_L)(m_L=0)$ the initial inverse susceptibility and $\Delta H=H_L(m_L=0)$ the field offset or torque at $m_L=0$, shown to be respectively related to the second $(1/M_S)(\partial^2 E_a/\partial\theta^2)(\theta-(\pi/2))$ and first $(1/M_S)(\partial E_a/\partial\theta)(\theta-\pi/2)$ derivatives of E_a. This, in turn, yields two determinations of $E_a(\theta)$ from $\chi^{-1}(\theta)$ and $\Delta H(\theta)$, respectively. Fourier analysis then easily resolves various contributions of different symmetries to the magnetic anisotropy. The magnetization $m_L(H_L)$ is measured with a conventional magneto-optical Kerr experiment in longitudinal geometry with respect to H_L and higher-order (nonlinear in m_L) contributions as well as polar or other contributions to the Kerr signal are carefully determined and corrected in order to obtain the desirable accuracy or even simply meaningful results. Typical acquisition times including all corrections are about a few minutes per angle θ. The power of the method is demonstrated on typical examples of epitaxial Fe layers on Si(0 0 1) and Si(1 1 1) substrates. For instance, it is shown that extremely small contributions up to the 12th order in-spin to the cubic magnetocrystalline anisotropy of iron are readily detected.

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1. Introduction

In magnetic materials the energy required to magnetize a crystal depends on the direction of the applied field. Ferromagnetic materials exhibit intrinsic easy and hard directions of magnetization reflecting the magnetic anisotropy. The two main sources of magnetic anisotropy are the dipolar and the spin–orbit interactions. The first one is a long-range effect that results in a contribution to the anisotropy which depends on the shape of the specimen, and is largely responsible for the inplane remanent magnetization observed in thin films. The second one, the so-called magnetocrystalline anisotropy, due to the spin–orbit interaction reflects the symmetry of the crystal. In thin films and low-dimension systems, the symmetry breaking at surfaces and interfaces, the strain induced by substrate-film lattice mismatch or between adjacent layers, the growth on stepped substrates, the lattices distortion, the roughness and the interdiffusion at interface and/or film surface induced by the deposition conditions can drastically modify the magnetic anisotropy compared to that in the respective bulk material. In particular, due to the symmetry reduction new additional lower order components of the anisotropy may be generated. The actual observed anisotropy contributions can be phenomenologically described by effective magnetic anisotropy constants K_n taking into account the crystal structure symmetry, the symmetry breaking at surfaces and interfaces and the shape modifications. K_n associated to the nth order magnetic anisotropy contribution usually include a volume term K_n^{Vol} and an interface term K_n^{Int} [1–6]:

$$K_n = K_n^{\mathrm{Vol}} + \frac{K_n^{\mathrm{Int}}}{Nd}, \tag{1}$$

where N and d are, respectively, the film thickness in atomic layers and the interlayer distance perpendicular to the film surface. The most general expression of the magnetic anisotropy free energy density of a single domain can be written as

$$E_{\mathrm{a}} = K_0 + \sum_n [K_n \times f_n(\alpha_i)]. \tag{2}$$

K_0 accounts for an isotropic contribution. The functions $f_n(\alpha_i)$ describe the dependence of the nth order anisotropy energy on the orientation of the magnetization expressed by the direction cosines (α_i) relative to a given reference frame.

Magnetic anisotropy plays a key role in the physics of low-dimensional magnetic structures that reveal fascinating new properties with respect to those of the corresponding bulk materials: it affects the orientation and magnitude of the magnetization, the nature of the domain walls, the frequencies of the spin wave excitations, and hence the thermodynamic behavior of the film. The knowledge of the magnetic properties in ferromagnetic low-dimensional systems correlated to their changes in morphology due to controlled surfaces, interfaces and shape modifications is important from a point of view of basic research as well as with respect to the application in thin magnetic film and spintronics [7–9]. In particular, accurate determination of the different magnetic anisotropy contributions is needed to better understand the relationship between structural properties induced by the growth conditions and the magnetic ones.

The magnetic anisotropy is usually deduced either from dynamical or static response of the magnetic system [10]. The ferromagnetic resonance (FMR) [10–12], strain-modulated ferromagnetic resonance (SMFMR) [13] and the Brillouin light scattering (BLS) [3,14] probe the spin dynamics of a film in order to extract the anisotropy fields. These techniques give precise results but they are experimentally challenging and costly. Much of the experimental anisotropy constants have been obtained by static measurements using various magnetometry techniques such as alternating gradient force magnetometry (AGFM) [15], vibrating sample magnetometry (VMS) [16], superconducting quantum interference device magnetometry (SQUID) [17]. Magnetometry techniques are spatially averaging and accurate values can only be obtained from hysteresis loops for the simple case of uniaxial anisotropy. Moreover, absolute measurements are extremely difficult in the case of thin films where the diamagnetic signal from the substrate is comparable or larger than the magnetic film signal. Furthermore, torque magnetometry