Linear and quadratic magneto-optical Kerr Effect in ultrathin Fe(001) films

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The magneto-optical Kerr effect (MOKE) is a widely employed technique for the characterization of ferromagnetic thin films. However, a quantitative analysis is usually hampered by the lacking knowledge of precise magneto-optical parameters. We report the thickness dependence (0–60 nm) of the linear and quadratic MOKE in epitaxial bcc-Fe(001) samples and extract a complete set of parameters for the quantitative description of the MOKE response of bcc-Fe(001).

The magneto-optical Kerr effect (MOKE) is probably the most important tool for the magnetometric characterization of thin-film samples relevant for spintronics. Among its most common applications are the quantitative determination of the coercivity, magnetic anisotropy, and interlayer exchange coupling from the analysis of hysteresis loops recorded with the MOKE signal. Other prominent applications are the investigation of spin dynamics in the time-domain and magnetic domain imaging. The main advantages of the MOKE over other techniques are its compatibility with high magnetic fields, surface sensitivity with a typical information depth of some 10 nm, a time resolution down to the sub-picosecond regime, and a reasonable spatial resolution of the order of about 0.5 μm. However, many applications of the MOKE neglect the absolute magnitude of the Kerr effect, which is given by the magnitude and phase of the complex Kerr angle. The reason is that the full quantitative MOKE information is generally not linked by simple analytic formulae to the material properties, i.e. indices of refraction n and linear and quadratic magneto-optical (MO) coupling parameters K and G of all involved layers.

Here we report on a magnetometric study of the MO response of bcc-Fe(001) wedge-type samples with thicknesses ranging from 0 to 60 nm. We have determined both components of the complex Kerr angle, the Kerr rotation θ and the Kerr ellipticity ϵ. Effects linear and quadratic in the magnetization, LMOKE and QMOKE respectively, are separated by fitting the hysteresis loops to a single domain model. The QMOKE, which is known to be anisotropic, i.e. dependent on the sample orientation, has been determined for both Fe(001)[110] and Fe(001)[100] directions parallel to the plane of incidence. By fitting the thickness dependence of LMOKE and QMOKE we are for the first time able to extract a full set of Fe material parameters n, K, $(G_{11}-G_{12})$, and G_{44} at a light wavelength of 670 nm [1].

Epitaxial bcc-Fe(001)(wedge)/Ag(1 nm)/Au(2 nm) films have been prepared by molecular beam epitaxy on a GaAs/Ag(001) buffer system. The Au capping layer has been chosen thick enough to prevent oxidation and thin enough to be able to determine large Kerr angles. The Ag interface layer prevents a possible alloying of Fe and Au. The Fe thickness has been varied continuously between 0 and 8 nm for sample A and stepwise in sample B with discrete Fe thicknesses of 5, 8, 12, 18, 24, 32, 44, and 60 nm. MOKE measurements were performed using light from a diode with a wavelength of 670 nm and a spectral half-width of less than 2 nm. The incident light is polarized in $\hat{p}$ direction (electric field component in the plane of incidence), and the angle of incidence is 15° with respect to the sample normal. A photo-elastic modulator (PEM) with diagonal modulation axis operating at $f = 50$ kHz, a polarizer oriented in $\hat{s}$ direction, and a homemade diode detector are used to convert the light intensity into an electrical voltage. With this setup the small f (50 kHz) component determined with a lock-in amplifier is to first order proportional to the $\hat{p}$-ellipticity ϵ times the reflected intensity, while the much larger $2f$ (100 kHz) is to first order proportional to the reflected intensity alone. By introducing a quarter wave plate between sample and PEM we are able to measure the $\hat{p}$-rotation θ instead of the ellipticity ϵ. The two Kerr angle components (θ and ϵ) are calculated by dividing the measured f component with and without quarter wave plate by the $2f$ component.

It is convenient to expand the complex Kerr angle $\Phi = \theta + i\epsilon$ as a function of the directional cosines of the magnetization [2], e.g. in longitudinal and transversal cosines $m_{l,t}$ for in-plane magnetization:

$$\Phi = \sum_{layers\ i} \left[l_i m_{l,i} + q_{1,i} m_{l,i} m_{t,i} + q_{2,i} m_{t,i}^2 + O(m^3) \right], \tag{1}$$

where l_i are the longitudinal, and $q_{1,i}$ and $q_{2,i}$ the quadratic response coefficients. The longitudinal coefficients l_i stem from the linear MO coupling parameter K alone and are isotropic as long as the FM layers have cubic symmetry. The quadratic coefficients are due to a combined effect of the linear and

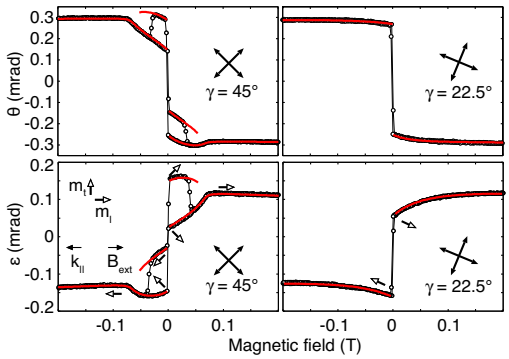

FIG. 1: Field dependence of measured (black) and calculated (red) Kerr ellipticity ϵ and Kerr rotation θ for a 60 nm Fe film. The direction of the magnetization is with short arrows, the easy axis directions of the magnetocrystalline anisotropy with crossed long arrows.

quadratic MO couplings and are anisotropic. For cubic systems the q coefficients have the form [2]:

$$q_1 = q_{001} + (q_{011} - q_{001})\sin^2(2\gamma) \quad (2)$$

$$q_2 = \frac{1}{2}(q_{011} - q_{001})\sin(4\gamma), \quad (3)$$

where γ is the angle between the in-plane component of the light wavevector and an in-plane Fe[001] direction. q_{001} and q_{011} are QMOKE constants for the plane of incidence parallel to the [001] and [011] directions, respectively. We determine l, q_{001}, and q_{011} by analyzing remagnetization loops recorded with different sample orientations γ. The explicit relations between l, q_{001}, and q_{011} and the MO coupling parameters K, $(G_{11} - G_{12})$, and G_{44} are given in [2].

Typical MOKE loops for a 60 nm Fe film are shown in Fig. 1. The experimental θ and ϵ curves are plotted in black. The red lines are fits to a single domain model taking into account the sample orientation γ, the cubic anisotropy parameter, and describing the Kerr angle via Eqs. (1–3). While the left loops recorded at $\gamma \approx 45°$, i.e. with field parallel to a hard [011] direction, depend on l and q_{011}, the right loops are recorded at $\gamma \approx 22.5°$ and, therefore, depend on l and both q_{011} and q_{001}. The simultaneous fitting of the loops for both orientations γ yields a full set of MOKE response coefficients l, q_{001}, and q_{011}.

The thickness dependence of the experimental LMOKE and QMOKE measured in [011] direction are shown in Fig. 2 by red circles and blue triangles for sample A and B, respectively. QMOKE is also measured in [001] direction, but not shown here, see [1]. The slope of all curves begins to asymptotically flatten at about 40 nm, which determines the MOKE information depth. The non-monotonic thickness dependence indicates that the additivity law [3] is generally not valid. Black, dotted lines show the thickness dependences of LMOKE calculated using literature values for the indices of refraction and the linear MO coupling. Obviously, these calculations fail to describe θ properly. The red and blue lines are the result of our fits based on the full 4×4 matrix formalism [4] using fixed indices of refraction for Ag and Au

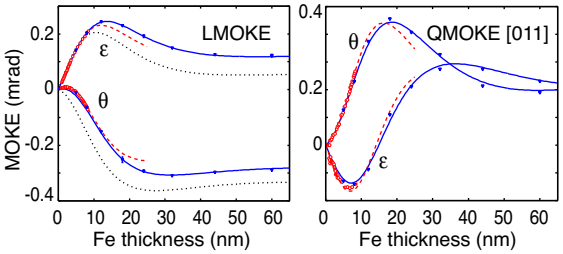

FIG. 2: Thickness dependence of the measured (red circles and blue triangles for sample A and B, respectively) and calculated (lines) LMOKE (left) and QMOKE for the Fe[011] direction (right) parallel to the plane of incidence. The black, dotted line is calculated from literature parameters.

from literature as specified above, and treating the index of refraction and the MO couplings of Fe as free parameters. The red and blue curves correspond to the data of samples A and B, respectively. The fit results and a comparison to literature values are given in [1]. It turns out that a satisfactory fit over the whole thickness range with only one thickness-independent set of material parameters is impossible. The fit to the data of sample A with smaller thicknesses results in a significantly (10%) larger index of refraction with different phase as compared to the thicker sample B. On the other hand, the MO coupling parameter K mainly differs in phase by about 10°, while the absolute values are in rather good agreement (<3%). Thus, it seems that the difference between thin and thick Fe layers is mainly of optic rather than of magneto-optical origin. Possible explanations for the thickness dependence are: (i) The tensile strain of the Fe due to the small lattice mismatch of 0.7% between Fe and the Ag substrate (ii) a relaxation of the lattice constant of Fe for larger thicknesses resulting in a thickness dependence of the optic properties of the Fe layer, (iii) altered electronic properties of the thin Fe layer due to the proximity to the noble metal substrate and the capping layers, and (iv) interfacial MOKE contributions, which have been neglected in the theoretical description.

To our knowledge this is the first report of the second-order MO coupling constants of Fe. They are comparable to the first-order constants and thus, of general significance for the theoretical and quantitative description of the MOKE.

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