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Letter to the Editor

Experimental method for separating longitudinal and polar Kerr signals

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Abstract

A new procedure is presented which can be easily applied to separate longitudinal and polar Kerr signals. The method is advantageous particularly in systems where in-plane and out-of-plane states of magnetization are involved in the reversal process. The feasibility of the method is demonstrated at the spin-reorientation transition in Co/Au(1 1 1) films. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

Moog and Bader have demonstrated that the magneto-optical Kerr effect (MOKE) is very well suited for the study of thin film magnetism [1]. Since this pioneering experiment MOKE has become a very important technique for the investigation of magnetism in monolayer films [2,3]. Three main experimental geometries are known, i.e. the polar, longitudinal and transverse Kerr effects. They are classified with respect to the orientation of the magnetization to the light scattering plane. Usually, the polar Kerr signal is one order of magnitude larger than the longitudinal signal [3]. Hence, a small perpendicular component can cause considerable polar contribution in the Kerr signal in longitudinal geometry. Particularly, in the spin-reorientation transition when the magnetization changes between perpendicular and in-plane orientations at least two components of magnetization can be involved in the reversal process due to a field sweep. The mixing of the two components will get even worse if the external field is slightly misaligned. Then, within the spin-reorientation the longitudinal, and polar Kerr signals are mixed with a field-dependent strength. This makes the quantitative data analysis difficult. Hysteresis loops revealing such a mixture have only qualitatively been discussed in Ref. [4]. To overcome this problem Yang and Scheinfein suggested to measure the exact polar signal in normal incidence geometry [5]. Up to now the deconvolution of mixed longitudinal and polar signals has not been addressed. In this paper we propose a new method to separate

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longitudinal and polar Kerr signals and demonstrate the feasibility of the proposed procedure.

2. Principle

In first-order approximation the Kerr signal is a function of the direction cosine between the propagation vector of the incident light $\boldsymbol{k}$ and the direction of the magnetization M, i.e. $\boldsymbol{k} \cdot \boldsymbol{M}$ [3].[1] In polar geometry the angles between k and M are exactly the same for inverted geometries (see Fig. 1a). Hence, the polar Kerr signal is an even function of the incident angle. Exactly the same hysteresis loops will be obtained in both geometries. On the contrary (see Fig. 1b), in the longitudinal geometry the two angles between $\boldsymbol{k}$ and $\boldsymbol{M}$ are supplementary angles in the reversed experiments. This means that the longitudinal signal is an odd function of the incident angle. It will change sign if the incident and scattered beams are exchanged. These basic symmetry properties are used to disentangle the mixed Kerr signals which may occur with a general geometry (neither strictly polar nor strictly longitudinal).

A phenomenological description of the magneto-optical Kerr effect can be given by utilizing the Fresnel coefficients of reflectivity. The Fresnel reflection coefficients r_{ps}, r_{ss} are given in Table 1 [5–8]. The first and the second subscripts indicate the polarization of the scattered light and the incident light, respectively. For the sake of simplicity a single interface nonmagnetic/magnetic has been assumed for deducing the formulae corresponding to a semi-infinite sample (bulk). For ultrathin films the effect of the substrate has to be considered. Similar formulae with the same characteristic features are obtained in first-order approximation [5–8]. The quotient of the coefficients r_{ps}, r_{ss} is the Kerr signal. The real/imaginary part represents the Kerr rotation/ellipticity, respectively. For s-polarized incident light the ratio of the longitudinal signal to the polar signal is proportional to $-\tan\theta_1$ (the ratio is $\tan\theta_1$ for p-polarized light). It is an odd function of the incident angle θ_0. This proves that both geometries are of different symmetry with respect to θ_0. Utilizing the reflection coefficients from Table 1 we can calculate the Kerr signals which reveal the above-mentioned symmetries. Particularly, for s-polarized light one can derive from Table 1 the ellipticities for $\pm\theta_0$:

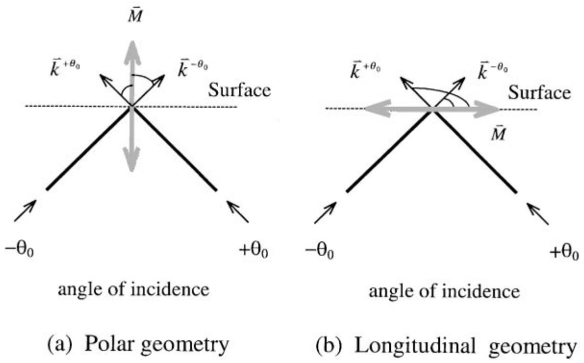

Fig. 1. Sketch of the experimental set-up for the polar and longitudinal Kerr effects. (a) In polar geometry the angles between k and M are exactly the same and $\boldsymbol{k} \cdot \boldsymbol{M}$ is equal for $\pm\theta_0$. (b) In longitudinal geometry the angles between $\boldsymbol{k}$ and $\boldsymbol{M}$ are supplementary angles for the light coming from the right- or left-hand side and $\boldsymbol{k} \cdot \boldsymbol{M}$ changes sign when the direction of incidence is reversed.

$$\varepsilon^{\pm\theta_0} = \varepsilon^{\mathrm{P}} \pm \varepsilon^{\mathrm{L}} \tag{1}$$

with $\varepsilon^{+\theta_0}$, $\varepsilon^{-\theta_0}$ the Kerr ellipticities for the respective angles of incidence, and ε^{P}, ε^{L} the ellipticities for the polar and longitudinal Kerr effects.

Hence, by two measurements of the Kerr signal in reversed geometries, one can obtain the sum and difference of the polar and longitudinal Kerr signals, respectively. This allows one to determine the individual contributions: by taking the sum of both signals one obtains twice the polar Kerr ellipticity, by taking the difference one obtains twice the longitudinal Kerr ellipticity. This procedure is thus very well suited to separate the response of the longitudinal and polar Kerr effects.

[1] In the classical model, Kerr effect can be understood as the change of the electric field vector by the Lorentz force $\boldsymbol{f} = \boldsymbol{E} \times \boldsymbol{M}$ due to the magnetization of material. The contribution to the Kerr signal is proportional to $\cos(\boldsymbol{k} \cdot \boldsymbol{M})$.

Table 1
The Fresnel coefficients for s-polarized light for a single nonmagnetic/magnetic interface. The complex index of refraction for both materials are n_0 and n_1. θ_0 and θ_1 are the angles of incidence and reflection of the light with respect to the interface normal

	r_{ss}	r_{ps}
Polar	$\frac{n_0 \cos\theta_0 - n_1 \cos\theta_1}{n_0 \cos\theta_0 + n_1 \cos\theta_1}$	$\frac{i n_0 n_1 \cos\theta_0\, Q}{(n_1 \cos\theta_0 + n_0 \cos\theta_1)(n_0 \cos\theta_0 + n_1 \cos\theta_1)}$
Longitudinal	$\frac{n_0 \cos\theta_0 - n_1 \cos\theta_1}{n_0 \cos\theta_0 + n_1 \cos\theta_1}$	$\frac{- i n_0 n_1 \cos\theta_0 \tan\theta_1\, Q}{(n_1 \cos\theta_0 + n_0 \cos\theta_1)(n_0 \cos\theta_0 + n_1 \cos\theta_1)}$
Transverse	$\frac{n_0 \cos\theta_0 - n_1 \cos\theta_1}{n_0 \cos\theta_0 + n_1 \cos\theta_1}$	0

3. Experiment

Co on Au(1 1 1) has been chosen to demonstrate the feasibility of the above-sketched method. Due to the spin-reorientation transition a mixing of different magnetization states can appear [9]. The Co films were grown at room temperature under UHV conditions by means of e-beam evaporation onto an Au(1 1 1) single crystal. The rate of deposition was 0.4 ML/min. The Au(1 1 1) crystal was cleaned by Ar ion etching and annealing at 900 K for half an hour. The reconstruction of Au was clearly seen in the low-energy electron diffraction (LEED) pattern. After growth, the film has been annealed at 510 K for 10 min in order to stabilize the magnetic properties, stop the Au diffusion and smooth the sample surface [10]. The thicknesses were tuned to fit the region close to the spin-reorientation transition.

S-polarized light was used to minimize signals caused by the transverse Kerr effect (see Table 1). Transverse signals can be caused by some small remnants of p-polarization. The amount of p-polarization can be estimated from optical calibration measurements. The extinction ratios have been determined in crossed polarizer geometry to investigate the effects of the windows. Values of 10^{-5} and 10^{-6} are found for the extinction ratio with and without windows, respectively.[2] The values are quite low for the reflection at a metal surface which indicates that the state of polarization must be very close to s-polarization.[3] If we assume that the extinction of 10^{-6} is solely determined by a slight misalignment of the polarization of the incoming light (worst case) we will obtain 1.5 mrad as the tilting angle. Due to birefringence of the windows the light is elliptically polarized and the extinction ratio is worse when windows are implemented. If we assign, in the same way as above, the increase in intensity due to birefringence to misalignment of the incident light we will get 3.5 mrad as the angle of deviation. For the magnetic measurements a quarter-wavelength plate is implemented to eliminate the window effects and to increase the sensitivity [12]. With the quarter wavelength plate again an extinction value of 10^{-6} is obtained. In spite of that high extinction ratio a total misalignment of 5 mrad, the sum of both uncertainties, is assumed as a conservative estimate. We have calculated the amount of ellipticity that is created due to the transverse Kerr effect caused by the estimated misalignment. Utilizing the formulae given by Zak and co-workers [13], the Voigt constant from Ref. [14] and tabulated values for the index of refraction [15] we find for our experimental settings 2.2% of longitudinal signal in saturation as an

[2] Glan-Thompson polarizer are used with an extinction ratio of 10^{-7}.

[3] In textbooks it is shown that only for s- or p-polarization a high extinction ratio will be found when the light is reflected at a metal surface and the angle of incidence is not too close to 0° or 90° (see Ref. [11]).

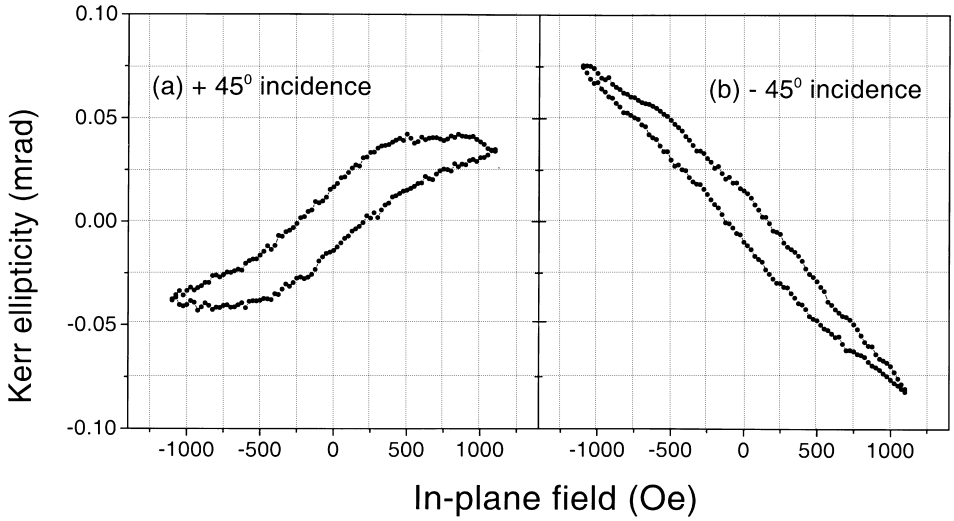

Fig. 2. Kerr ellipticities for a Co film on Au(1 1 1) at a thickness close to the spin-reorientation transition. The field is applied within the film and the light scattering plane. S-polarized light is impinging along $+45°$ (a) and $-45°$ (b), respectively.

upper limit for the uncertainty.[4] It should be pointed out that after exchanging the two optical parts the same value of extinction within a factor of 1.5 is achieved.

In order to keep the light spot at the same place on the sample, an additional laser has been used to mark the position while the light source and detector are interchanged. The positions where the light goes through the windows have also been marked. The optics, i.e. laser and polarizer as well as the analyzer components, are fixed to separate rigid supports which are tightly attached to the windows of the UHV chamber. The combination of marking the positions and the geometry of the experiment reduces the uncertainty of the incident angle on reversing the geometry to less than 1°. As the sensitivity of the polar and longitudinal Kerr effect is constant around 45° such small changes in the angle of incidence can be neglected [13].

4. Experimental results

The hysteresis loops obtained for an angle of incidence of $\pm 45°$ are plotted in Figs. 2a and b. The magnetic field was applied parallel to the film plane and the scattering plane of the light. A slight misorientation of 1–2° with respect to the surface plane could not be eliminated. The signals in the two measurements are quite different, depending on the relative orientation of the light and the external field. The two loops are inverted and the shape and magnitude are strongly different. If the magnetization was solely in the plane a pure longitudinal Kerr signal with two identical but reversed loops would be found.

Following the procedure sketched above we have calculated the point-by-point difference and sum of the two curves. The results, divided by two, are

[4] Following Zak, the Fresnel coefficients r_{pp}, r_{ss} and r_{ps}, in longitudinal geometry, and the change of reflectivity Δr_{pp} in transverse geometry at 2 eV were calculated for an angle of incidence of 45°. The sample is 5 ML Co/Au which is very close to the film thickness in the measurement. We obtained 139 μrad ellipticity for s-polarized light in longitudinal geometry. Assuming $\alpha = 5$ mrad as the angle of deviation from pure s-polarization and $\delta = 8.7$ mrad as the orientation of the analyzer we can calculate the ellipticity that is caused by the small amount of p-polarization. From the imaginary part of $\Delta r_{pp}(\delta + \alpha) \sin\alpha \cos\delta / (r_{ss} \cos\alpha \sin\delta + r_{pp} \sin\alpha \cos\delta)$ we obtain 3 μrad.

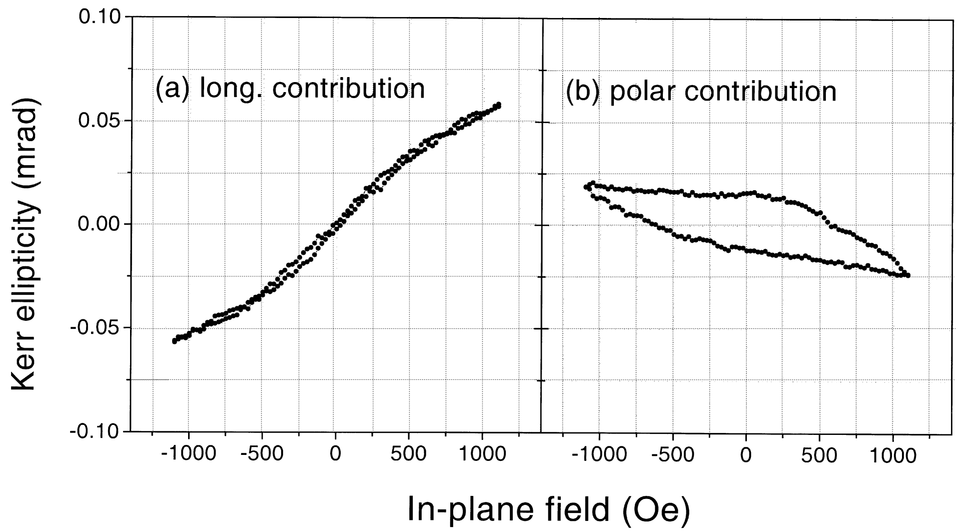

Fig. 3. Longitudinal and polar Kerr signals calculated from the data given in Fig. 2. (a) is $\frac{1}{2}$ of the difference and (b) is $\frac{1}{2}$ of the sum of the curves in Fig. 2. (For more details see text.)

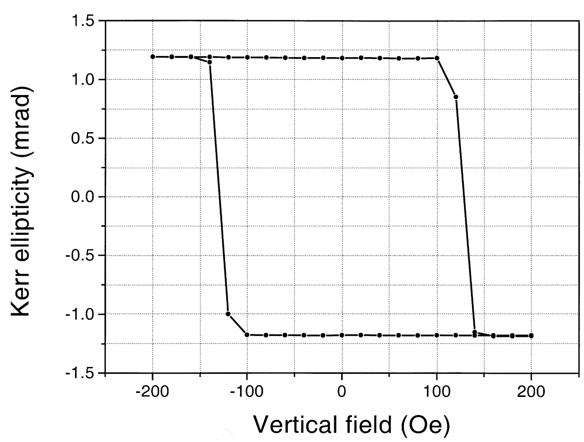

Fig. 4. Hysteresis loop obtained in a vertical field with the same film used for taking the data shown in Fig. 3. The angle of incidence is 15°.

shown in Figs. 3a (difference) and b (sum) which are the hystereses of the in-plane and polar Kerr signals, respectively. We have investigated the thickness dependence of the longitudinal signal in saturation for in-plane magnetization. From that dependence we extrapolate to the film thickness under investigation (roughly 5 ML). A Kerr ellipticity of 140 $\pm$ 5 μrad for the longitudinal signal in saturation is determined from this extrapolation, which is close the calculated value of 139 μrad (see foot note 4). Taking the above uncertainty analysis we obtain a maximal transverse signal of 3 μrad. Hence, Fig. 3a gives the longitudinal Kerr signal, i.e. the in-plane magnetization component along the field direction, exhibiting a hard axis loop. The vertical component (Fig. 3b), however shows a hysteresis. Apparently the field that is effective along the surface normal cannot saturate the film. Comparing Figs. 2 and 3 it is obvious that a polar signal that is caused by a slight misalignment of the field can change the hysteresis obtained in a longitudinal Kerr set-up. This demonstrates that it is necessary to separate the two Kerr contributions, particularly when performing experiments with systems close to a spin-reorientation transition. The polar loop shown in Fig. 4 was achieved when a field in the vertical direction was applied. The magnetization curve exhibits a square-like easy axis loop with a small coercivity (about 125 Oe) which proves that the easy axis is perpendicular to the film plane. The full signal is about 50 times larger than in Fig. 3b which demonstrates that the plot Fig. 3b is a minor loop.

In the longitudinal geometry the Kerr signal is expected to reverse sign when the experiment is

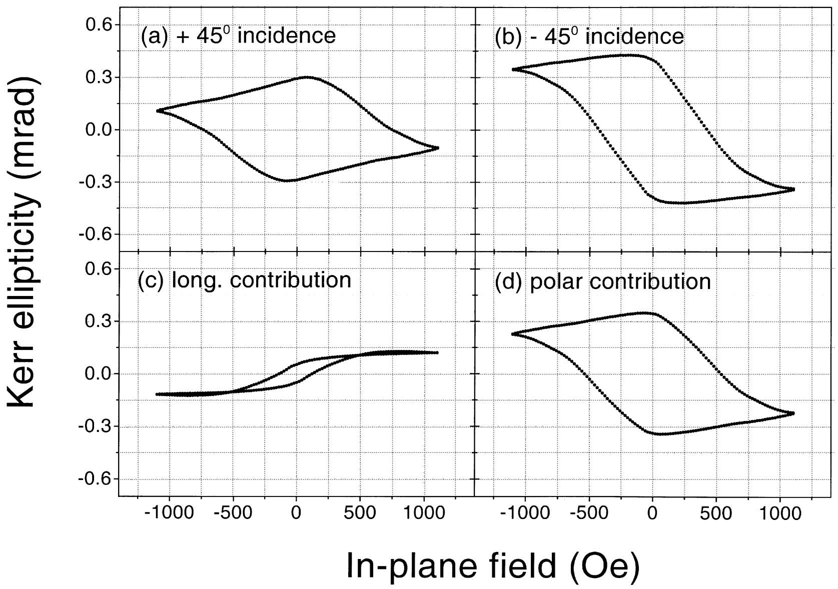

Fig. 5. Kerr ellipticities for a Co film on Au(1 1 1) at a thickness closer to the spin-reorientation transition than in the case of Fig. 3. The field is applied within the light scattering plane and the film plane. S-polarized light is impinging along $+45°$ (a) and $-45°$ (b). The calculated Kerr signals are the longitudinal contribution (c) and the polar contribution (d).

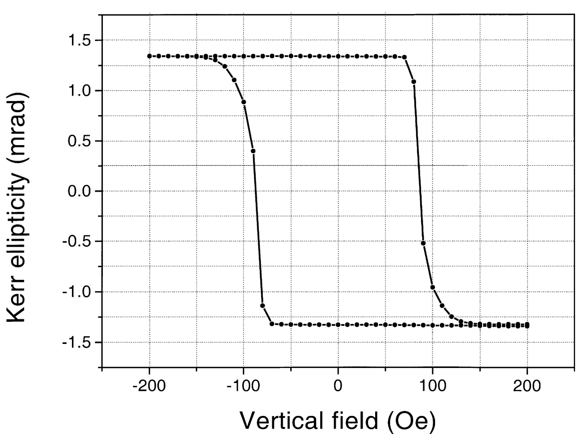

Fig. 6. Hysteresis loop obtained in a vertical field. The same film was used as for Fig. 5. The angle of incidence is 15°.

performed in the inverted geometry. In Fig. 5 the hysteresis for a Co thickness closer to the spin-reorientation transition is plotted. Both the signals with positive and negative angles of incidence show the same sign. This can be attributed to the large influence of the polar contribution. The magnetic perpendicular anisotropy is smaller in this case than before because the thickness is closer to the spin-reorientation value. Therefore, the misorientation of the external field causes a stronger signal in the polar Kerr effect, which in this case even dominates the total signal in a and b. The deconvoluted loops (c and d) show remanence in both in-plane and vertical directions while the longitudinal hysteresis again shows the correct sign. In pure vertical field a clearly easy axis appears in polar geometry (Fig. 6). More details will be given in a forthcoming paper [16].

Acknowledgements

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