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Journal of Magnetism and Magnetic Materials 205 (1999) 143–150

Journal of magnetism and magnetic materials

www.elsevier.com/locate/jmmm

Determination of the anisotropy field strength in ultra-thin magnetic films using longitudinal MOKE and a rotating field: the ROTMOKE method

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Received 7 May 1999; received in revised form 9 July 1999

Abstract

A new method for the determination of anisotropy field strength in specimens with uniaxial anisotropy is described. Longitudinal MOKE is used in combination with a rotating magnetic field. Due to sufficient large field strength, a Stoner–Wohlfarth-like magnetisation reversal process can be realised. By correcting higher-order MOKE terms, a highly accurate calculation of H_k is demonstrated on different Fe, NiFe and Co ultra thin films.

Keywords: Magneto-optical measurements; Anisotropy–uniaxial; Torque measurements; Second-order magneto-optical effect; Quadratic magneto-optical effect; QMOKE; Voigt effect; Ultrathin films

1. Introduction

Magnetic properties like anisotropy and coercivity field strength H_k and H_C and magnetostriction λ_s govern the applicability of ultra thin films in different systems for magnetoelectronics. One of the most powerful methods for studying these properties is the magneto-optical Kerr effect (MOKE) because of the high sensitivity down to sub-nm thickness. Problems arise when the anisotropy field strength has to be determined with high accuracy. Two problems complicate an exact determination of H_k by MOKE in many cases. These are asymmetries, often observed in hard axis loops [1–3] and non vanishing sample coercivity, which can be sometimes larger than the anisotropy field in thin films itself.

Whereas for thicker films the anisotropy can easily be determined by torquemetry, this method fails for very thin films and/or small areas, because the mechanical torque is too low for a quantitative measurement. We, therefore, propose a MOKE method, which allows the determination of the anisotropy field strength by realisation of a coherent magnetisation reversal (Stoner–Wohlfarth-like), avoiding hence all problems caused by hysteresis effects. This can be achieved by applying a sufficient large rotating field, which guarantees a true single domain behaviour of the specimen. To avoid the above mentioned asymmetries higher-order terms of the longitudinal Kerr effects have to be taken into account. As shown in Ref. [4], the only

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0304-8853/99/$ - see front matter
PII: S0304-8853(99)00526-0

important term in that sense is the Voigt or quadratic (QMOKE) effect [5–7]. This effect can be accurately separated by the proposed ROTMOKE method.

2. Sample preparation

Polycrystalline Fe and Co samples are DC Magnetron sputter deposited in a standard high vacuum system with a residual pressure p_0 lower than 10^{-7} Torr. The films are deposited at an Ar pressure of 4×10^{-3} Torr under influence of an in-plane field of about 100 Oe generated by permanent magnets. A 5 nm Ta layer was used as a buffer layer on the thermally oxidised Si wafer and a 3 nm Ta cap layer avoids oxidation of the layers. A 3 nm Cu layer on both sides of the magnetic films prevents interdiffusion with the Ta film. The Permalloy layers ($Ni_{81}Fe_{19}$) supplied by *bps* Alzenau/Germany were deposited in an EMERALD II system onto 5 nm Ta buffer and covered by a 5 nm Ta top layer.

3. Experimental MOKE set-up

The Kerr measurements are performed with p-polarised He–Ne-Laser (633 nm, 5 mW) by determination of the longitudinal Kerr rotation θ_k. We used crossed polariser/analyser geometry in combination with a Faraday compensator. The compensation of θ_k was done by a DC current. This compensation current was determined by applying an additional AC current with the frequency v. By means of a lock-in technique, the crossed polariser/analyser geometry was achieved at vanishing v component of the Kerr signal leaving only the $2v$ signal caused by the AC current itself. A detailed description of this measurement is given in Ref. [8]. The magnetic field was generated by Helmholtz coils. A transversal field was applied for careful orientation of the sample (easy and hard axis) with respect to the longitudinal magnetic field.

4. Experimental results and discussion

4.1. Longitudinal Kerr loops and sample orientation

To find out a proper geometrical adjustment of the magnetic easy and hard axis with respect to the applied field longitudinal Kerr loops are measured with longitudinally and transversely applied field. A vanishing transversal Kerr rotation loop as shown in Fig. 1 allows an adjustment of $\pm 0.5^\circ$ of the easy and hard axis of the specimen with respect to the X-axis (longitudinal axis) of the experimental set-up. This exact orientation is a basic condition for the separation procedure described below.

The measured hard and easy axis loops of a 4 nm Fe layer are displayed in Fig. 2a. Here due to many defects within the film a large coercivity can be recognised which suppresses the formation of a well

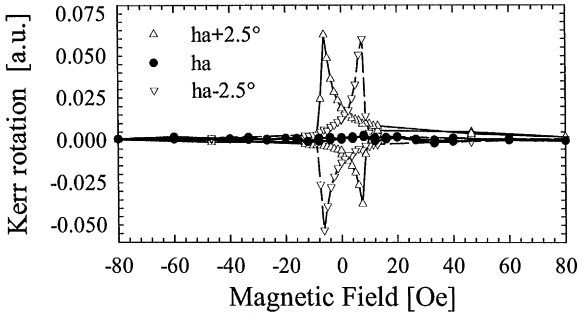

Fig. 1. Longitudinal Kerr loops of a 4 nm Fe specimen with a transversal applied field and different orientations of the hard axis (ha) with respect to the sensitivity direction of the MOKE set-up (X-axis).

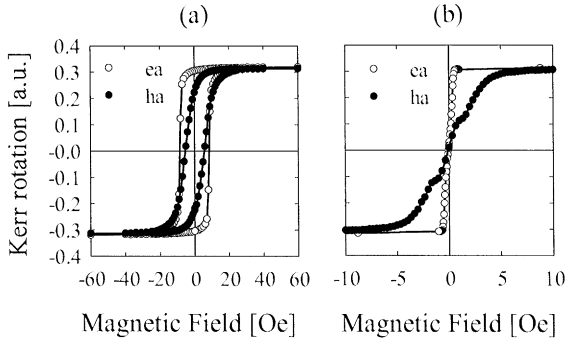

Fig. 2. (a) Hard axis (ha) and easy axis (ea) Kerr loop of a 4 nm Fe layer and (b) anhysteretic Kerr loops in ha and ea directions (details see text).

defined hysteresis-free hard- and a rectangular easy-axis loop. To distinguish between these both states MOKE loops are recorded where at every sequentially measured field strength additionally a transversal magnetic AC field with exponentially decreasing amplitude was applied immediately before determination of the Kerr rotation. The resulting curves are shown in Fig. 2b, which clearly indicate the easy and hard axis of the specimen. From the hard axis loop a rough estimation of H_k can be done resulting in a value for the LKL (longitudinal Kerr loop) $H_k^{LKL} = 3$ Oe which is much smaller than the coercivity of $H_C^{ea} = 8.5$ Oe.

4.2. Procedure for ROTMOKE: separation of QMOKE contributions due to the Voigt effect

For the case of a rotating field, which is able to secure a single domain state of the sample for any direction of the in-plane field, we can assume a Stoner–Wohlfarth like magnetisation reversal. Therefore, at least in fields much larger than H_k and H_C, the film should be in a single-domain state, allowing a simple mathematical description of the magnetisation rotation. A hysteresis-free behaviour at cw and ccw rotation of the magnetic field supports this model.

If there is only a uniform and uniaxial in-plane anisotropy, the energy density e is given by

$$e = \frac{E}{V} = -M_s H \cos(\alpha - \varphi) + K_u \sin^2 \varphi, \qquad (1)$$

where K_u is the uniaxial anisotropy, M_s the saturation magnetisation, V the volume of the magnetic layer, H the applied field strength, α the angle between easy (or hard) axis and the applied field, φ the angle between easy (or hard) axis and magnetisation. With the usual definition of $H_k = 2K_u/M_s$ a switching-free rotation should be obtained for $H > H_k$. Neglecting any hysteresis we can expect, that the magnetisation takes the equilibrium angle φ. This angle can be obtained by differentiating Eq. (1) resulting in

$$K_u \sin 2\varphi = HM_s \sin(\alpha - \varphi). \qquad (2)$$

With $H_k = 2K_u/M_s$ we obtain

$$\tfrac{1}{2}H_k \sin 2\varphi = H \sin(\alpha - \varphi). \qquad (3)$$

Hence, the only problem for the determination of H_k is to determine the angle φ at least for one angle α by using Eq. (3). As shown in Refs. [4,6] the longitudinal Kerr rotation θ_k can be described with a high accuracy by the equation:

$$\theta_k(M) = \theta^{sat} m_l + f m_l m_t, \qquad (4)$$

where θ^{sat} is the amplitude of the longitudinal Kerr rotation, m_l and m_t are the normalised longitudinal and transversal components of the magnetisation and f describes the contribution due to the quadratic Voigt effect.

Having in mind our careful orientation, we propose a simple method to separate the two contributions in Eq. (4). We use the fact that the linear and the quadratic terms have different signs in the corresponding quadrants of our rotating magnetic

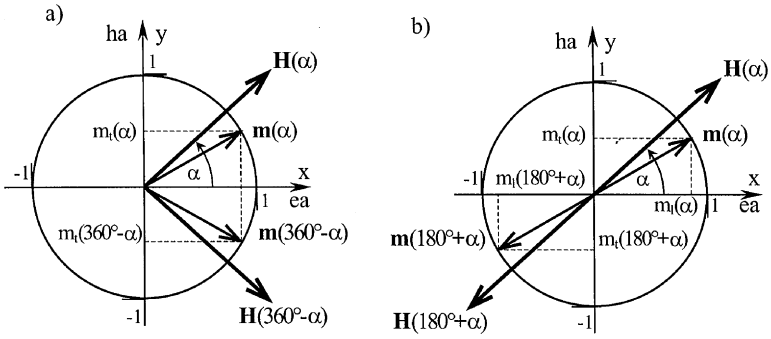

Fig. 3. Schematical picture of the directions of applied field $\boldsymbol{H}(\alpha)$ and normalised magnetisation $\boldsymbol{m}(\alpha)$, respectively. The components m_l and m_t of $\boldsymbol{m}$ for both symmetric states with respect to the X-axis are indicated in (a) for quadrant 1 and 4, and in (b) for quadrant 1 and 3.

field as explained in Figs. 3a and b:

$$m_l(\alpha) = m_l(360^\circ - \alpha),$$

$$m_l(\alpha) = -m_l(180^\circ + \alpha),$$

$$m_t(\alpha) = -m_t(360^\circ - \alpha),$$

$$m_t(\alpha) = -m_t(180^\circ + \alpha),$$

$$m_l m_t(\alpha) = -m_l m_t(360^\circ - \alpha),$$

$$m_l m_t(\alpha) = m_l m_t(180^\circ + \alpha).$$

From these equations the following relationship can be derived using the first and fourth quadrant:

$$\theta^{lin}(\alpha) = \tfrac{1}{2}[\theta(\alpha) + \theta(360^\circ - \alpha)] = \theta^{sat} m_l \quad (5)$$

allowing the separation of the second-order contribution from the measured signal. The remaining linear part $\theta^{lin}(\alpha)$ allows the easy determination of the angle φ by solving $m_l = \cos\varphi$.

A similar relationship can be given by using the first and the third quadrant:

$$\theta^{lin}(\alpha) = \tfrac{1}{2}[\theta(\alpha) - \theta(180^\circ + \alpha)] = \theta^{sat} m_l. \quad (6)$$

This relation gives an independent determination of the relation between α and φ. The influence of measuring and orientation error on both methods is discussed below.

4.3. Determination of the anisotropy field strength

Having in mind that the term

$$L(\alpha) = HVM_s \sin(\alpha - \varphi) \quad (7)$$

is a torque, which is usually determined by torquemetry [9], we are able to determine a related value by ROTMOKE by simultaneous determination of the two angles α and φ and using

$$l(\alpha) = H \sin(\alpha - \varphi) = \tfrac{1}{2} H_k \sin 2\varphi, \quad (8)$$

where $l(\alpha)$ is the ratio L/VM_s. H_k can therefore be identified as two times the amplitude of $l(\alpha(\varphi))$ versus α. A better way is the expansion of $l(\alpha(\varphi))$ over φ by using a fast Fourier transformation (fft). Here the different orders of the anisotropy energy with respect to φ can be directly derived. For the case of pure uniaxial anisotropy the integration of $l(\alpha(\varphi))$ over φ gives the ratio between uniaxial anisotropy energy K_u and saturation magnetisation M_s.

4.4. Experimental results

To get an impression of the power of the method we will illustrate the results which can be obtained by the new method on three different systems: (i) an magnetically soft Py ($Ni_{81}Fe_{19}$) film with uniaxial anisotropy, vanishing hard axis coercivity and rectangular easy axis loop, (ii) an Fe film with coercivity larger than anisotropy field strength and (iii) a system with very small magnetic layer thickness (0.8 nm Co).

4.4.1. Ta/4 nm Py/Ta sandwich with field-induced uniaxial anisotropy of the permalloy

Fig. 4 shows both the easy and hard axis loop of a 4 nm $Ni_{81}Fe_{19}$ film sandwiched between Ta buffer and Ta top layer. This specimen exhibits the typical behaviour of a well prepared permalloy film: a vanishing hard axis coercivity and a rectangular easy-axis loop allowing the determination of $H_k = (8.2 \pm 0.2)$ Oe. The coercive field strength in the easy axis direction is about $H_C = (3.5 \pm 0.2)$ Oe.

For those kinds of specimens the Kerr loops in well adjusted easy and hard axis direction are *not* influenced by QMOKE. For an easy axis reversal the m_t component can exist only during the switching of the magnetisation, whereas for the hard axis reversal due to careful orientation the second-order coefficient $m_l m_t$ vanishes due to the same part of domains rotating cw and ccw from the hard to one

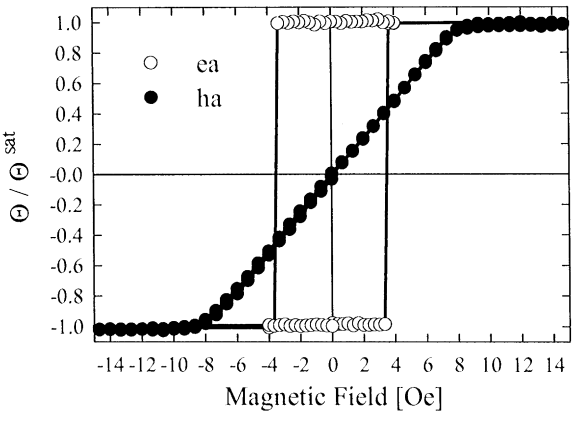

Fig. 4. Normalised Kerr rotation in hard axis (ha) and easy axis (ea) direction for a 4 nm Py film sandwiched between Ta.

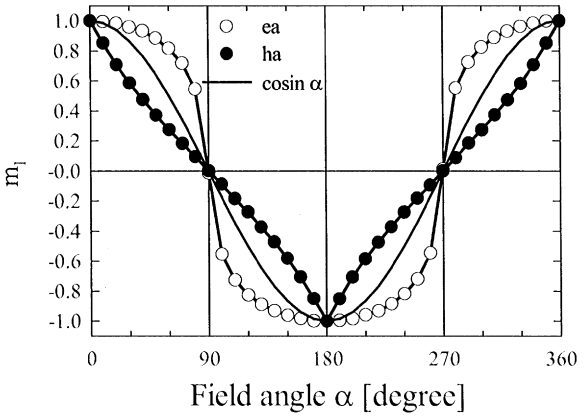

Fig. 5. Normalised longitudinal magnetisation component m_l as a function of angle of the applied field, $H = 10$ Oe, 4 nm Py.

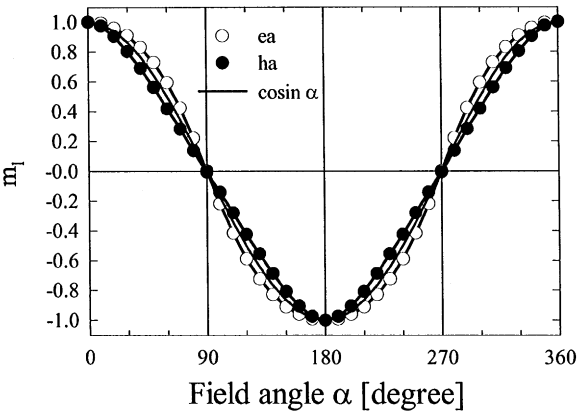

Fig. 7. Normalised longitudinal magnetisation component m_l as a function of angle of the applied field, $H = 40$ Oe, 4 nm Py.

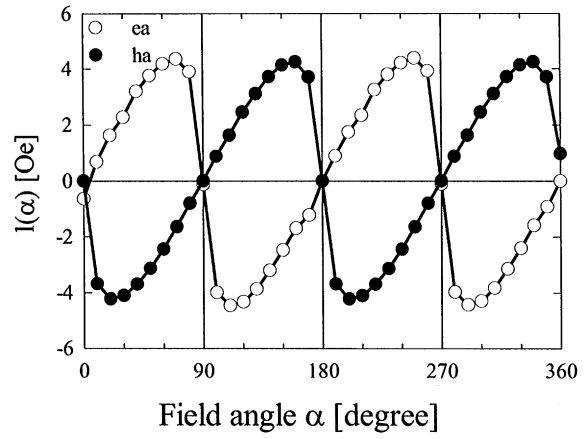

Fig. 6. Calculated normalised torque moment l(α) as a function of angle of the applied field, $H = 10$ Oe, 4 nm Py.

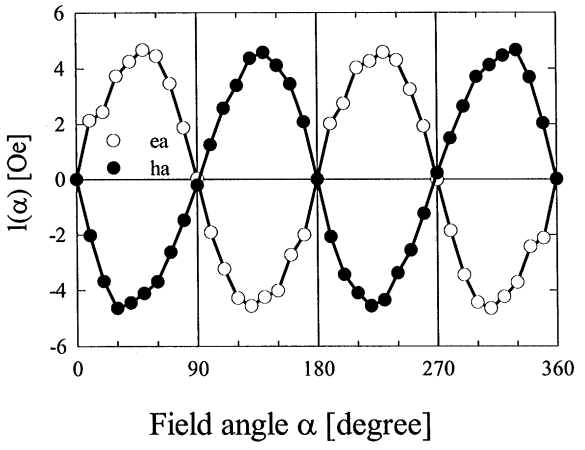

Fig. 8. Calculated normalised torque moment l(α) as a function of angle of the applied field, $H = 40$ Oe, 4 nm Py.

of the easy axis directions. In this way, the integral value of $m_l m_t$ vanishes. Fig. 5 displays the normalised Kerr rotation, corrected by the Eq. (5) in dependence on the field angle α for ea and ha orientation and a field strength of 1.2 H_k.

In Fig. 6 the calculated normalised torque curves clearly exhibit the expected ea and ha behaviour. As shown in Figs. 7 and 8, at field strength of five times H_k, the same general behaviour can be stated. If we further increase the magnetic field to ten times H_k, the difference between the cosine and the measured values get smaller and smaller causing remarkable scattering in the l(α) curves. Nevertheless, the fft yields a reliable value for H_k even for that high field region. The portion of QMOKE in this sample is 10% of the linear one.

4.4.2. Ta/Cu/Fe/Cu/Ta system

More interesting is the case where the coercive field strength H_C is large in comparison to H_k, complicating a reliable determination of the anisotropy field H_k as shown in Fig. 2a. Methods combining additional transversal or longitudinal AC fields with decreasing amplitude to achieve an anhysteretic loop are questionable. The deviation of the linear m_l versus H dependence in the hard axis

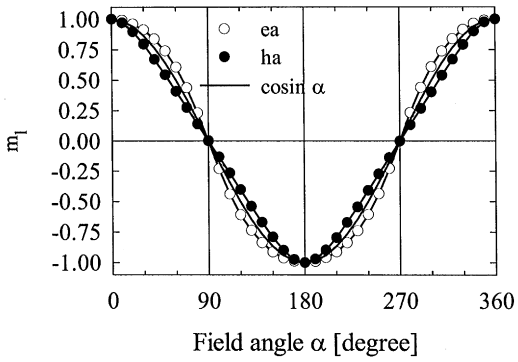

Fig. 9. Normalised longitudinal magnetisation component m_l as a function of angle of the applied field, $H = 20$ Oe, 4 nm Fe.

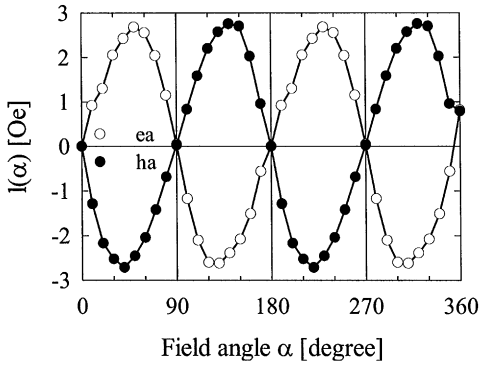

Fig. 10. Calculated normalised torque moment l(α) as a function of angle of the applied field $H = 20$ Oe, 4 nm Fe.

state, as can be recognised in Fig. 2b, is probably caused by the ill-defined magnetic state. For our new method, we expect that a rotating field generating a coherent magnetisation rotation is a much better choice for the determination of H_k. To study the influence of the coercivity on our measuring method we have performed the experiments in a large H range of the rotating field. Figs. 9 and 10 show a typical normalised Kerr curve and a reduced torque curve at intermediate field strength, respectively.

Our calculated H_k values are collected in Fig. 11. For the easy axis orientation we observe a very reasonable behaviour of H_k versus applied field. Starting with lower H_k values for field strength smaller than H_C there is a fast saturation of

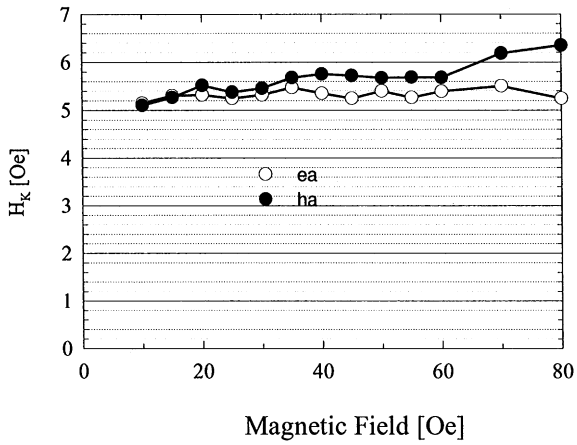

Fig. 11. The dependence of calculated H_k versus the applied field strength for ea and ha oriented parallel to the longitudinal direction of ROTMOKE experiment, specimen 4 nm Fe.

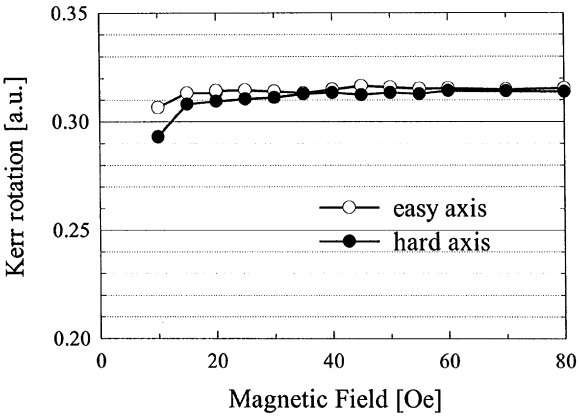

Fig. 12. The amplitude of the corrected Kerr rotation for ea and ha parallel to the longitudinal direction of ROTMOKE experiment, specimen 4 nm Fe.

$H_k = (5.3 \pm 0.1)$ Oe for ea orientation. The results measured in hard axis orientation are in general the same. Starting with a lower H_k for $H < H_C$ a saturation was achieved between 35 and 60 Oe. Surprisingly the H_k value is about (5.7 ± 0.1) Oe and therefore systematically larger than the value measured in ea orientation. The reason for this behaviour is not clear up to now. In Fig. 12, the amplitude of the corrected Kerr rotation is displayed for both cases of orientation. For field

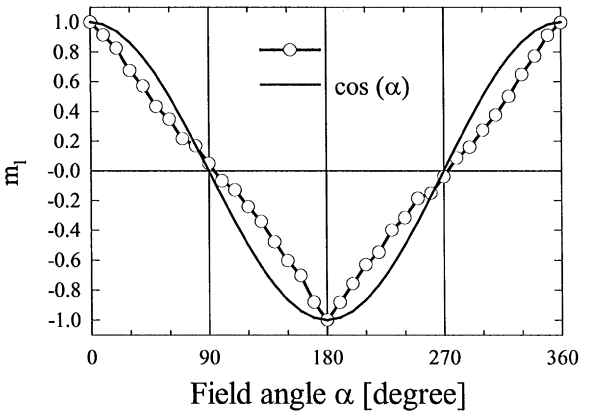

Fig. 13. Normalised longitudinal magnetisation component m_l as a function of angle of the applied field, $H = 20$ Oe, 0.8 nm Co film.

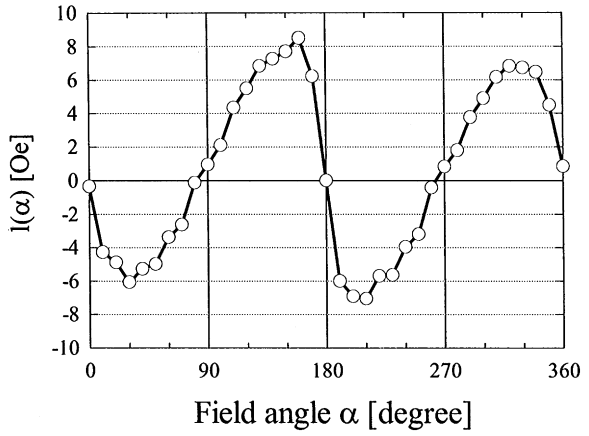

Fig. 14. Calculated normalised torque moment $l(\alpha)$ as a function of angle of the applied field, $H = 20$ Oe, 0.8 nm Co film.

strengths larger than 20 Oe we found constant amplitude with a small difference for ea and ha orientation. Summarising these results obtained on a high coercive specimen we get a value $H_k = (5.5 \pm 0.2)$ Oe which is only 65% of H_C.

4.4.3. Ta/Cu/Co/Cu/Ta system

For very thin films, the measuring errors may influence the Kerr rotation curve. Figs. 13 and 14 display the results obtained on a 0.8 nm thick Co film with $H_k = (13.5 \pm 1.5)$ Oe and $H_C = 2$ Oe. Due to low H_C in comparison to H_k, reliable result can be obtained for fields $\geqslant 15$ Oe. Here, the error increases but nevertheless H_k can be determined within $\pm 10\%$ accuracy.

5. Discussion

The proposed ROTMOKE method is a torque-like method for the determination of H_k. In contradiction to the usual torquemetry, where a mechanical torque is measured, which enables the determination of a *mean* anisotropy energy $VK_u = 1/2H_kVM_s$, the ROTMOKE makes use of the misalignment between the direction of applied field and the *mean* magnetisation direction. By using the Stoner–Wohlfarth model (SWM), the uniaxial *mean* anisotropy field strength can be derived. To fulfil the conditions of the SWM a hysteresis-free rotation has to be guaranteed. This can easily be verified by measuring the ROTMOKE curves with a cw and ccw rotating magnetic field. For all specimens presented here a hysteresis-free reversal was obtained. The second condition for extracting H_k from ROTMOKE curves needs the elimination of higher-order Kerr effects to get a pure linear relationship between corrected longitudinal Kerr rotation and longitudinal magnetisation component. As shown experimentally in Ref. [4], only quadratic contributions caused by the Voigt effects have to be separated. This quadratic contribution can be eliminated using symmetric configurations as shown in Figs. 3a and b. The separation procedure proposed here is based on a careful alignment of one of the distinguished axes (ea or ha) of the specimen with uniaxial anisotropy with the X-axis of the experimental set-up. As can easily be derived from Figs. 3a and b the influence of a misalignment of the ea (or ha) with respect to the X-axis is different for both methods represented by Eqs. (5) and (6). Using Eq. (5) (first and fourth quadrant, Fig. 3a) a misalignment leads to remarkable different values for $m_l(\alpha)$ and $m_t(\alpha)$ compared to the values at an angle of $360^\circ - \alpha$. In contradiction, using Eq. (6) (first and third quadrant, Fig. 3b) the values of $m_l(\alpha)$ and $m_t(\alpha)$ are not changed at the angle $180^\circ + \alpha$. Comparing the QMOKE contribution, e.g. the separated value of $m_l m_t$ versus angle α, for both separation methods, we have an additional

proof for the exact adjustment of our specimen during measurement. In all cases investigated, we found a perfect agreement of both criteria for the necessary adjustment of the specimen.

To calculate H_k the method needs a measurable deviation of the direction of the magnetisation φ from the direction of the applied field α. In dependence on the signal amplitude corresponding to the thickness of the magnetic film(s) and the specific Kerr rotation of the layer, this difference is sufficiently large for fields lower than 10 … 25 times H_k. Having in mind, that a minimum field is needed to guarantee a hysteresis-free rotation, which is in the most cases in the order of (1 … 3) H_k, there is a sufficiently large window for the determination of H_k. Within this window, the scattering of the calculated H_k is in the order of 2–5%, resulting in a trustworthy method for H_k determination. The observed differences of the estimated values for H_k in easy and hard axis orientation with respect to the sensitivity direction of our MOKE set-up in the order of 5% (see Fig. 11) are not clear up to now.

6. Conclusion

We have proposed a new method for the determination of the anisotropy field strength by means of a longitudinal MOKE experiment with rotating magnetic field, called ROTMOKE. The measuring conditions need a coherent rotation of the magnetisation during reversal. In this way, any effects caused by hysteresis can be avoided. Due to the proposed separation method based on a careful adjustment of the specimen with respect to the magnetic easy and hard axis, the quadratic or Voigt effects was separated from Kerr signal for the first time also for finite magnetic fields. This results in a separation of the linear Kerr signal, which can easily be interpreted in terms of the magnetisation direction in dependence on field strength and field angle and the QMOKE effect, which can be measured directly by the ROTMOKE method.

The use of the Stoner–Wohlfarth model allows the determination of the uniaxial anisotropy field of the films with high accuracy. One of the great advantages of this method is the fact, that this method can be applied also to specimen with a relatively large hard-axis coercivity $H_C^{ha}(H_C > H_k)$. Another advantage with respect to the usually applied torquemetry is the fact, that the determination of H_k is possible without knowing the value of the volume and magnetisation of the film necessary in the case of torquemetry. Especially for ultra thin films down to the sub-nm region, this is of great importance because of comparatively large uncertainty of the product of magnetisation times volume.

Acknowledgements

This project was financially supported by the Bundesminister für Bildung und Forschung (Grant No. 13N7089). Thanks to W. Maass (bps Alzenau/Germany) for supplying the Py samples and W. Schubert (IPHT) for the deposition of the Fe and Co films.

Note added in proof

A similar torque method was proposed by Gudeman [10] but without the very important correction of the higher-order magneto-optical effects.

References

[1] Q.-M. Zhong, A.S. Arrott, B. Heinrich, Z. Celinski, J. Appl. Phys. 67 (1990) 4448.
[2] Q.-M. Zhong, A.S. Arrott, B. Heinrich, Z. Celinski, J. Magn. Magn. Mater. 104–107 (1992) 1837.
[3] R.M. Osgood III, R.L. White, B.M. Clemens, IEEE Trans. Magn. 31 (1995) 3331.
[4] R. Mattheis, G. Quednau, Phys. Stat. Sol. (a) 172_2 (1999) R7.
[5] R.M. Osgood III, S.D. Bader, B.M. Clemens, R.L. White, H. Matsuyama, J. Magn. Magn. Mater. 182 (1998) 297.
[6] K. Postava, H. Jaffres, A. Schuhl, F. Nguyen Van Dau, M. Goiran, A.R. Fert, J. Magn. Magn. Mater. 172 (1997) 199.
[7] A. Hubert, R. Schäfer, Magnetic Domains, Springer, Berlin, 1998.
[8] H. Hornauer, T.M. Atmono, K. Röll, J. Magn. Magn. Mater. 83 (1990) 551.
[9] F.B. Humphrey, A.R. Johnston, Rev. Sci. Instrum. 34 (1963) 348.
[10] C.S. Gudeman, IEEE Trans. Magn. 26 (5) (1990) 2580.