May 1990

# Enhancement of magneto-optical Kerr effects

Liang-Yao Chen
*University of Nebraska - Lincoln*

William A. McGahan
*University of Nebraska - Lincoln*

Z.S. Shan
*University of Nebraska - Lincoln*

David J. Sellmyer
*University of Nebraska-Lincoln*, dsellmyer@unl.edu

John A. Woollam
*University of Nebraska-Lincoln*, jwoollam1@unl.edu

Chen, Liang-Yao; McGahan, William A.; Shan, Z.S.; Sellmyer, David J.; and Woollam, John A., "Enhancement of magneto-optical Kerr effects" (1990). *David Sellmyer Publications*. 125.
https://digitalcommons.unl.edu/physicssellmyer/125

# Enhancement of magneto-optical Kerr effects

Liang-Yao Chen, William A. McGahan, Z. S. Shan, D. J. Sellmyer, and John A. Woollam
*Departments of Electrical Engineering and Physics, University of Nebraska, Lincoln, Nebraska 68588-0511*

A general expression for the magneto-optical polar Kerr effect is given for a bilayered configuration in which the optical constants of the two media differ. The equation shows that a giant enhancement of the Kerr effect in magneto-optical/metallic bilayers can be expected if the dielectric constants of the two materials are low or are matched well to the other. An explicit equation is also given to calculate the spectral enhancement due to a dielectric overcoating on magnetic substrates. An example is given for SiO-coated Dy/Co compositionally modulated alloys, yielding a good comparison to the experimental results in both the transparent and absorbing spectral regions of SiO.

## I. INTRODUCTION

Recently, new mechanisms have been presented to explain giant enhancements of the magneto-optical Kerr effect (MOKE) observed by different authors for a single magneto-optic or a magneto-optic/metallic bilayer film system.[1–6] Feil and Haas have shown that a resonance-shaped MOKE spectra can be induced by the plasma resonance.[1] Katayama *et al.* reported that for a Fe/Cu bilayer, the enhancement of $\theta_k$ is a result of the plasma absorption of nonmagnetic copper.[2] Reim and Weller gave results for TbFeCo/Cu bilayers with an expression showing that if the nonmagnetic reflector has a low refractive index, an enhancement of $\theta_k$ can be expected.[3] Previously,[4–6] we have used both ellipsometric and MOKE data to show that the resonant enhancement of $\theta_k$ for a bilayer has an optical origin. In this paper we further study this problem, and give an analytical expression showing that although MOKE is fundamentally related to magnetic behavior, the optical properties of the magneto-optic/metallic bilayer play an equally important role in determining its value. A giant enhancement of the MOKE for such a system can be associated with the plasma edge of the metal, but can also be expected if both of the dielectric constants of the two materials are low or are well matched to each other.

In addition, we present an explicit equation which can be easily used to calculate the spectral enhancement of the Kerr rotation due to a dielectric coating in a two-layer sample. A comparison between the calculated and experimental results for SiO-coated Dy/Co compositionally modulated alloys has been made with good results in both the transparent and absorbing spectra regions of SiO.

## II. THEORY

### A. Two-medium system

For a ferromagnetic material, we assume that the magnetization $M$ is in the $z$ direction and that a linearly polarized wave at normal angle of incidence propagates and vibrates along the $z$ and $x$ axes, respectively. The linearly polarized electric field $E_x$ can be decomposed into two circularly polarized fields, right $E_r$ and left $E_l$, i.e., $E_x = E_r + E_l$. The reflected field $E'$ is

$$E' = E'_r + E'_l = \tilde{\gamma}_+ E_r + \tilde{\gamma}_- E_l, \tag{1}$$

where $\tilde{\gamma}_+$ and $\tilde{\gamma}_-$ are the reflection coefficients for the right and left circularly polarized light, respectively. Now consider a two-medium system, i.e., a medium $A$ and a medium $B$ with the complex refractive index $\tilde{n}_a$ and $\tilde{n}_\pm$, respectively, in contact each other. Taking the first-order approximation for $Q$ (Voigt parameter), $\tilde{n}_\pm = \tilde{n}_b\,(1 \mp Q/2)$,[5,7] and assuming the light is incident from medium $A$ to medium $B$, $\tilde{\gamma}_\pm$ will be given by

$$\tilde{\gamma}_\pm = \gamma_\pm e^{i\delta_\pm} = \frac{\tilde{n}_a - \tilde{n}_\pm}{\tilde{n}_a + \tilde{n}_\pm} = \tilde{\gamma}\tilde{\rho}_\pm, \tag{2}$$

where $\tilde{\gamma}$ is the ordinary reflection coefficient with zero magnetization,

$$\tilde{\gamma} = \gamma e^{i\varphi} = \frac{\tilde{n}_a - \tilde{n}_b}{\tilde{n}_a + \tilde{n}_b} \tag{3}$$

and $\tilde{\rho}_\pm$ is a complex quantity related to the pure MOKE, and can be determined from

$$\tilde{\rho}_\pm = \tilde{\gamma}_\pm/\tilde{\gamma} = \rho_\pm e^{i\theta_\pm} \simeq 1 + \epsilon_\pm + i\theta_\pm, \tag{4}$$

where $\epsilon_\pm$ and $\theta_\pm$ are small quantities related to $Q$. The ellipticity $\epsilon_k$ and rotation angle $\theta_k$ are

$$\epsilon_k = -\frac{\gamma_+ - \gamma_-}{\gamma_+ + \gamma_-} = -\frac{\rho_+ - \rho_-}{\rho_+ + \rho_-} \simeq -\epsilon_+, \tag{5}$$

$$\theta_k = -\frac{\delta_+ - \delta_-}{2} = -\frac{\theta_+ - \theta_-}{2} = -\theta_+. \tag{6}$$

Therefore, the complex Kerr function $\tilde{\phi}_k$ is

$$\tilde{\phi}_k = \epsilon_k + i\theta_k = -\eta\cdot Q = -\frac{Q\sqrt{\tilde{\epsilon}_a\tilde{\epsilon}_b}}{\tilde{\epsilon}_a - \tilde{\epsilon}_b}. \tag{7}$$

If medium $A$ is air, $\tilde{\epsilon}_a = 1$ and $\tilde{\epsilon}_b = \tilde{\epsilon}$, Eq. (7) is the same as that derived by other authors,[1,8]

$$\tilde{\phi}_{k0} = -\frac{Q\sqrt{\tilde{\epsilon}}}{1 - \tilde{\epsilon}}. \tag{8}$$

From Eqs. (7) and (8), the Kerr function $\tilde{\phi}_K$ can be enhanced either by improving the material $Q$, or by having a large optical $\eta$ value. The latter is best fulfilled by making an optical match between the two media, i.e., by making $(\tilde{\epsilon}_a - \tilde{\epsilon}_b)$ small. Plasma effects can be introduced to explain the Kerr rotation enhancement in a special case ($\tilde{\epsilon}_a = 1$) of the more general condition of a close match between the

0021-8979/90/095337-03$03.00

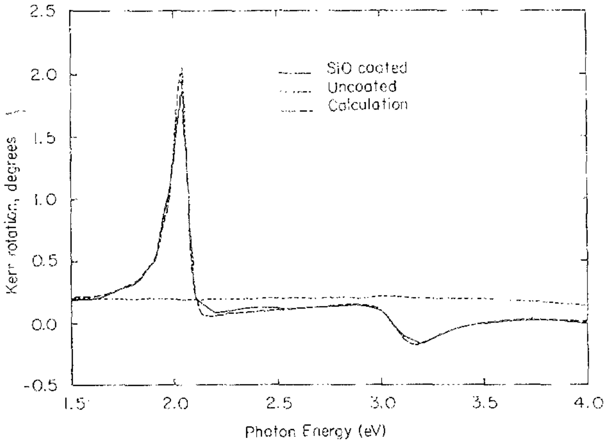

FIG. 1. Experimental and calculated Kerr rotation spectra for the bare and SiO-coated Dy/Co samples.

optical constants of the two media at the interface, viz., $\tilde{\epsilon}_a \approx \tilde{\epsilon}_b$.

## B. Dielectric coated systems

Assume that the complex indices of refraction of the ambient atmosphere, dielectric film (with layer thickness $d$), and magnetic substrate are $\tilde{n}_1$, $\tilde{n}_2$, and $\tilde{n}_3$, respectively. From Eq. (1), $\tilde{\gamma}'_\pm$ for the film overcoating system is

$$\tilde{\gamma}'_\pm = \gamma'_\pm e^{i\delta'_\pm} = \frac{\tilde{\gamma}_1 + \tilde{\gamma}_\pm e^{i\beta}}{1 + \tilde{\gamma}_1 \tilde{\gamma}_\pm e^{i\beta}}, \tag{9}$$

where at the wavelength $\lambda$, $\beta = 4\pi \tilde{n}_2 d/\lambda$, and

$$\tilde{\gamma}_1 = \gamma_1 e^{i\varphi_1} = \frac{\tilde{n}_1 - \tilde{n}_2}{\tilde{n}_1 + \tilde{n}_2}, \tag{10}$$

$$\tilde{\gamma}_\pm = \tilde{\gamma}_2 \tilde{\rho}_\pm,$$

and

$$\tilde{\gamma}_2 = \gamma_2 e^{i\varphi_2} = \frac{\tilde{n}_2 - \tilde{n}_3}{\tilde{n}_2 + \tilde{n}_3}. \tag{11}$$

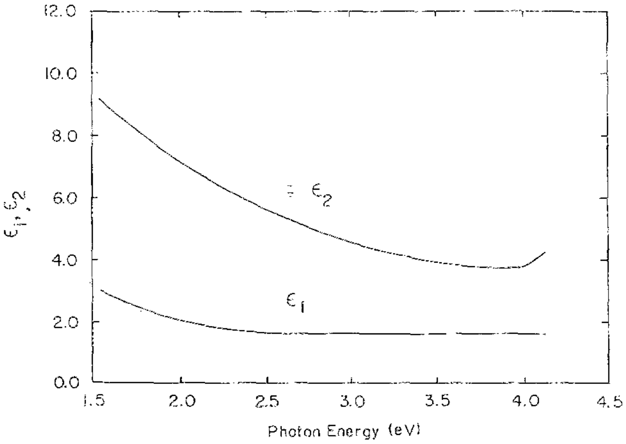

FIG. 2. Ellipsometrically measured complex dielectric function of the bare Dy/Co sample.

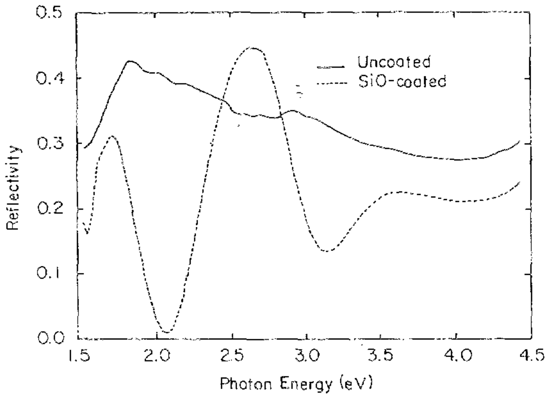

FIG. 3. Reflectivity measured at normal angle of incidence for bare and SiO-coated Dy/Co samples.

Using the result as $d = 0$, and noticing that $\epsilon_\pm = \mp \epsilon_k$ and $\theta_\pm = \mp \theta_k$, yields

$$\tilde{\gamma}'_\pm = \frac{\tilde{\gamma}_1 (1 - \tilde{\gamma}_1 \tilde{\gamma}^0_\pm) + (\tilde{\gamma}^0_\pm - \tilde{\gamma}_1) e^{i\beta}}{(1 - \tilde{\gamma}_1 \tilde{\gamma}^0_+) + \tilde{\gamma}_1 (\tilde{\gamma}^0_\pm - \tilde{\gamma}_1) e^{i\beta}}, \tag{12}$$

where

$$\tilde{\gamma}^0_\pm = \left( \frac{\tilde{n}_1 - \tilde{n}_3}{\tilde{n}_1 + \tilde{n}_3} \right) (1 \mp \epsilon^0_k) e^{i \mp \theta^0_k}. \tag{13}$$

## III. EXPERIMENT AND RESULTS

SiO-coated Dy/Co samples have been prepared with 1445-Å-thick compositionally modulated magnetic Dy/Co multilayer films. The Dy/Co with nominal Dy and Co layer thickness of 7 and 5 Å, respectively, were sputtered onto the silver or quartz substrates.[9] Afterwards, approximately 2000-Å-thick SiO layers were sputtered onto the top of some of the Dy/Co samples. Thus there were two sets of Dy/Co samples with similar magneto-optical properties, but one set with, another set without, an SiO coating. Both the polar Kerr rotation and reflectivity measurements at a normal angle of incidence, as well as the spectroscopic ellipsometry measurements at three angles of incidence (60°, 65°, and 70°) were made for all samples in the 1.5–4.5-eV photon-energy

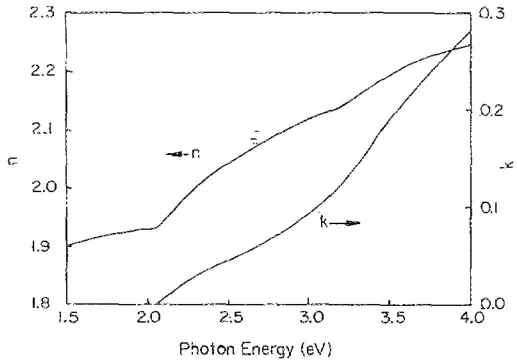

FIG. 4. Complex index of refraction of SiO obtained by fitting from the experimental Kerr rotation data.

TABLE I. Thickness $d$ of the SiO film, obtained from data analyses.

| | | | Interference analysis | |
|---|---|---|---|---|
| | Kerr analysis | Ellipsometric analysis | $\lambda = 6093$ Å<br>$\tilde{n}_2 = 1.93 + i0.0$<br>$\tilde{n}_3 = 2.120 + i1.651$<br>$\theta_k = 0.19$, $m = 3$ | $\lambda = 3875$ Å<br>$\tilde{n}_2 = 2.14 + i0.12$<br>$\tilde{n} = 1.683 + i1.250$<br>$\theta_k = 0.19$, $m = 5$ |
| $d$(Å) = | 2092 | 2020 | 2051 | 2025 |

region. The results of the Kerr rotation, and the complex dielectric function, as well as the reflection coefficient spectra for the bare and SiO-coated Dy/Co samples, are shown in Figs. 1–3, respectively.

The Kerr rotation for the SiO-coated sample can be calculated from Eq. (12). In the calculation, $\tilde{n}_1 = 1$ for air and $\theta_k^0$ and $\tilde{n}_3$ are taken from Figs. 1 and 2. The measured $\epsilon_k^0$ was found to be much smaller than $\theta_k^0$, thus $\epsilon_k^0 \simeq 0$ in Eq. (13). We determined $\tilde{n}_2$, with a value of $d$ found from a fit to the Kerr rotation data first at several critical photon energies, such as at peak positions. The remainder of the $\tilde{n}_2$ spectra were then approximated using a cubic spline interpolation method. The resulting $\tilde{n}_2$ spectra for SiO are shown in Fig. 4. The film thickness obtained was 2092 Å, close to the 2020-Å value obtained from the ellipsometric analysis using $\tilde{n}_2 \simeq 2$ in the transparent spectral region of SiO. The calculated Kerr rotation spectra for SiO-coated samples was found to be in good agreement with the experimental data, as see in Fig. 1.

The thickness $d$ also can be solved from the reflectivity minimum condition,

$$d = (\lambda / 4\pi n_2)(m\pi + \varphi_1 - \varphi_2 - \theta_k). \tag{14}$$

We use Eq. (14) to calculate $d$ at two reflectivity minima, 6093 and 3875 Å, where the Kerr rotation is enhanced. Results are shown in table I with a comparison to those obtained from the Kerr and ellipsometric analyses. The values of $d$ calculated at 6093 Å, where the peak is sharper and the bandwidth is narrower, is probably better than that at 3875 Å where the film is absorbing. The slight differences between experimental and calculated results for $d$ might be due partly to experimental error, or from ignoring the influence of the denominator in Eq. (9).

## ACKNOWLEDGMENTS

The authors are grateful to Professor S. S. Jaswal and Professor R. Kirby for helpful discussions. This work is supported by National Science Foundation (NSF) Grant No. DMR 8605367.

[1] H. Feil and C. Haas, Phys. Rev. Lett. **58**, 65 (1987).

[2] T. Katayama, Y. Suzuki, H. Awano, Y. Nishihara, and N. Koshizuka, Phys. Rev. Lett. **60**, 1426 (1988).

[3] W. Reim and D. Weller, Appl. Phys. Lett. **53**, 2453 (1988).

[4] L. Y. Chen, W. A. McGahan, Z. S. Shan, D. J. Sellmyer, and J. A. Woollam, Mater. Res. Soc. Symp. Proc. **150**, 109 (1989).

[5] W. A. McGahan, L. Y. Chen, Z. S.Shan, D. J. Sellmyer, and J. A. Woollam, Appl. Phys. Lett. **55**, 2479 (1989).

[6] W. A. McGahan and J. A. Woollam, Appl. Phys. Commun. **9**, 1 (1989).

[7] A. V. Sokolov, *Optical Properties of Metals* (American Elsevier, New York, 1967), part II.

[8] P. N. Argyres, Phys. Rev. **97**, 334 (1955).

[9] Z. S. Shan, D. J. Sellmyer, S. S. Jaswal, Y. J. Wang, and J. X. Shen, Phys. Rev. Lett. **63**, 499 (1989).