4-15-1991

Optical and magneto-optical characterization of TbFeCo thin films in trilayer structures

William A. McGahan
University of Nebraska - Lincoln

Ping He
University of Nebraska - Lincoln

Liang-Yao Chen
University of Nebraska - Lincoln

Sal Bonafede
University of Nebraska - Lincoln

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

See next page for additional authors

Optical and magneto-optical characterization of TbFeCo thin films in trilayer structures

William A. McGahan, Ping He, Liang-Yao Chen, Sal Bonafede, and John A. Woollam
Center for Microelectronic and Optical Materials Research and Departments of Electrical Engineering and Physics, University of Nebraska-Lincoln, Lincoln, Nebraska 68588-0511

F. Sequeda,[a] T. McDaniel, and H. Do
IBM Storage Systems Products Division, San Jose, California 95193

A series of TbFeCo films ranging in thickness from 100 to 800 Å have been deposited in trilayer structures on silicon wafer substrates, with Si_3N_4 being employed as the dielectric material. These films have been characterized both optically and magneto-optically by variable angle of incidence spectroscopic ellipsometry, normal angle of incidence reflectometry, and normal angle of incidence Kerr spectroscopy. From these measurements, the optical constants n and k have been determined for the TbFeCo films, as well as the magneto-optical constants $Q1$ and $Q2$. Results are presented that demonstrate the lack of dependence of these constants on the thickness of the TbFeCo film, and which can be used for calculating the expected optical and magneto-optical response of any multilayer structure containing similar TbFeCo films.

I. INTRODUCTION

Of all materials currently of interest for magneto-optical storage systems, the family of TbFeCo amorphous alloys is perhaps the most promising.[1,2] This work was motivated by the desire to obtain accurate values of both the optical and magneto-optical constants of thin films of TbFeCo deposited in trilayer structures containing dielectric films of Si_3N_4. The other primary purpose of this study was to determine the dependence (if any) of the optical and magneto-optical constants of the TbFeCo layers on the film thickness. Previous results from the Dy/Co compositionally modulated alloys suggested the possibility of variation in optical and magneto-optical properties from thick-film values when thicknesses of less than ~300 Å are used.[3] As film thicknesses of the order of 100–800 Å are often desired for optimal recording structures, TbFeCo films spanning this range were studied in order to evaluate the dependence of the optical and magneto-optical response of the films on the thickness. Finally, this work was motivated by the desire to demonstrate the accurate characterization of magneto-optic thin films deposited in relatively complicated multilayer systems using readily available reflection mode experimental techniques, whereas this approach has been applied previously only to simpler systems.[4,5]

II. SAMPLE PREPARATION

Amorphous TbFeCo films were prepared by nonbiased dc magnetron sputtering techniques using commercially available alloy targets in an in-line sputtering system. The composition of the films, as determined by x-ray flourescence, was 20.33% Tb, 71.7% Fe, 7.96% Co. Trilayer structures were fabricated on silicon wafer substrates ($Si/Si_3N_4/TbFeCo/Si_3N_4$). The nominal thickness of the bottom Si_3N_4 layer (between the silicon substrate and the TbFeCo film) was 400 Å while the top Si_3N_4 layer was nominally 260 Å thick for all samples. The nominal TbFeCo thickness was varied by 100-Å increments from 100 to 800 Å. All samples were found through Kerr loop measurements to have square hysteresis loops in the perpendicular orientation, with room-temperature coercivities ranging from 3.7 kOe for the thinnest TbFeCo layer to 7.5 kOe for the thickest. Additionally, three films of Si_3N_4, ranging from 200 to 800 Å thick, were prepared on silicon substrates for determination of the Si_3N_4 optical constants.

III. EXPERIMENTAL PROCEDURE

The samples were characterized optically by variable angle of incidence spectroscopic ellipsometry (VASE), which was performed over the spectral range 3000–8000 Å and at three angles of incidence: 60°, 65°, and 70°.[6,7] In addition, the intensity reflectance of each sample was measured at normal incidence over the spectral range 3800–7500 Å. The samples were magneto-optically characterized

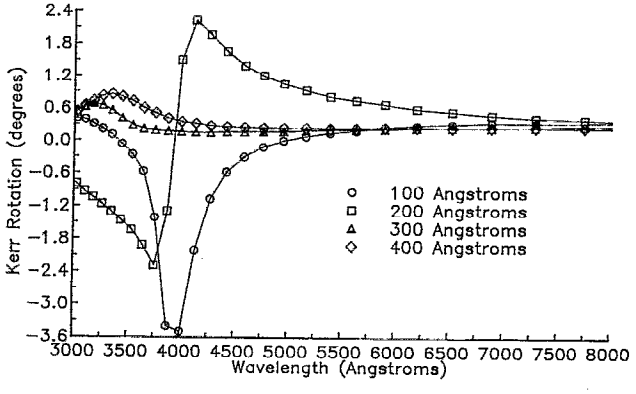

FIG. 1. Polar Kerr rotation measured at normal incidence for four TbFeCo films.

[a]On assignment from IBM Almaden Research Center.

0021-8979/91/084568-03$03.00

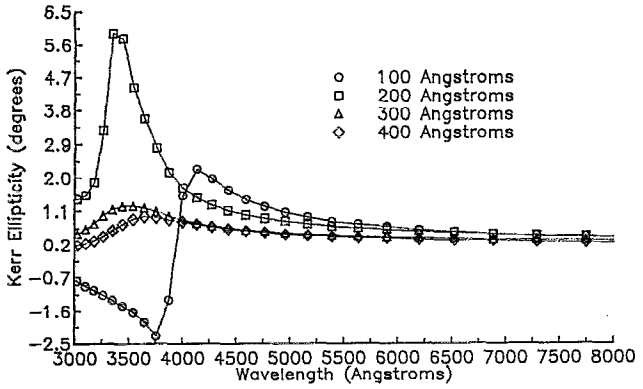

FIG. 2. Polar Kerr ellipticity measured at normal incidence for four TbFeCo films.

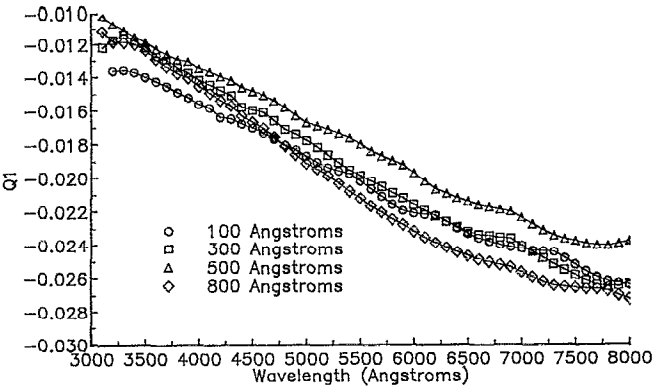

FIG. 4. Real part of the Voigt parameter $Q1$, found from simultaneous analysis of ellipsometric, reflectance, and Kerr data. Data are shown for four different TbFeCo layer thicknesses.

by measurement of the polar Kerr rotation and ellipticity at normal incidence over the spectral range 3000–8000 Å.[8] Experimental Kerr data are shown in Figs. 1–3, as a function of TbFeCo layer thickness. Spectra are shown for the first four layer thicknesses only, as both the Kerr parameters (as well as the reflectance) were found to be insensitive to increasing TbFeCo layer thickness for thicknesses in excess of ~400 Å.

In order to improve the accuracy of the analysis the silicon substrate and Si_3N_4 optical constants were measured by independent experiments. First, a silicon substrate was characterized ellipsometrically, and the thickness of the native oxide on a typical wafer was determined to be 23 Å. Then, three samples of thin films (200–800 Å) of Si_3N_4 were characterized ellipsometrically in order to determine the index of refraction of the Si_3N_4 over the spectral range 3000–8000 Å. Given this information, nonlinear regression was used to determine the optical and magneto-optical constants of the TbFeCo layer in the trilayer structures, as well as the thickness of the top dielectric layer (and the storage and bottom dielectric layers when possible). This analysis was performed by using the Levenberg–Marquardt algorithm to find the values of the unknown parameters that minimized the mean-square error between the experimental data points and their calculated values. For this calculation, the 4×4 characteristic matrix formulation[9] was used to determine both the optical and magneto-optical response of the four-layer system ($Si/SiO_2/Si_3N_4/TbFeCo/Si_3N_4$). In this model, we assume that the complex index of refraction is given by $\tilde{n}\equiv n+i|k|$. The Voigt parameter is defined as the constant of proportionality between the diagonal and off-diagonal elements of the permittivity tensor for a magneto-optic material, so that the permittivity tensor has the form

$$[\tilde{\epsilon}]=\begin{bmatrix}\tilde{\epsilon} & -i\tilde{Q}\tilde{\epsilon} & 0\\ i\tilde{Q}\tilde{\epsilon} & \tilde{\epsilon} & 0\\ 0 & 0 & \tilde{\epsilon}\end{bmatrix}, \tag{1}$$

where $\tilde{\epsilon}$, the isotropic dielectric constant, is equal to the square of the (complex) index of refraction.

The end point of this model calculation is the pseudo-Jones matrix for the multilayer system, whose elements are $\tilde{R}_p$ and $\tilde{R}_s$, the optical pseudo-Fresnel coefficients that describe the reflection of p- and s-polarized light from the structure, respectively, and $\tilde{K}$, the off-diagonal pseudo-

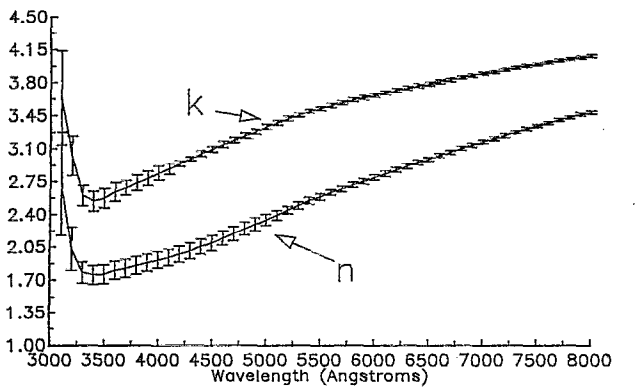

FIG. 3. Index of refraction n and extinction coefficient for the TbFeCo films, found from simultaneous analysis of ellipsometric, reflectance, and Kerr data. Error bars represent spread of values for the entire range of layer thicknesses, not experimental error or statistical uncertainty.

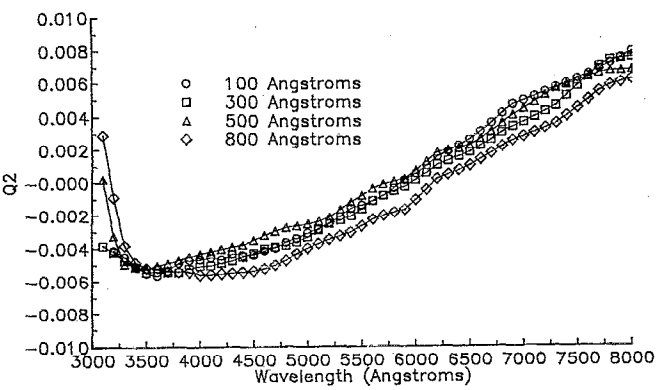

FIG. 5. Imaginary part of the Voigt parameter $Q2$, found from simultaneous analysis of ellipsometric, reflectance, and Kerr data. Data are shown for four different TbFeCo layer thicknesses.

Fresnel coefficient that determines the mixing of the p- and s-polarized components of the incident beam upon reflection, and hence the magneto-optic activity of the sample. These coefficients can be calculated provided the optical and magneto-optical constants of each layer, as well as its thickness, are given, and the angle of incidence is known. Once the pseudo-Jones matrix has been found, the various experimental quantities can be calculated:

Reflectance:

$$R=|\tilde{R}_p|^2=|\tilde{R}_s|^2, \tag{2}$$

Kerr effect:

$$\theta_k+i\eta_k=\tilde{K}/\tilde{R}_s=-\tilde{K}/\tilde{R}_p, \tag{3}$$

ellipsometric parameters:

$$\tan\psi=\sqrt{\frac{1+\alpha}{1-\alpha}}\,|\tan P|, \tag{4}$$

$$\cos\Delta=\pm\beta\left(\sqrt{1-\alpha^2}\right)^{-1}\left(+\ \text{if}\ P>0\right),$$

where θ_k is the Kerr rotation, η_k is the Kerr ellipticity, P is the polarizer azimuthal angle in the ellipsometer with respect to the plane of incidence (p plane), and α and β are given by

$$\alpha=\frac{|R_p|^2\cos^2P-|R_s|^2\sin^2P+2[\mathrm{Re}(\tilde{R}_p\tilde{K}^*)-\mathrm{Re}(\tilde{R}_s\tilde{K}^*)]\sin P\cos P}{|R_p|^2\cos^2P+|\tilde{R}_s|^2\sin^2P+2[\mathrm{Re}(\tilde{R}_p\tilde{K}^*)+\mathrm{Re}(\tilde{R}_s\tilde{K}^*)]\sin P\cos P}, \tag{5}$$

$$\beta=2\,\frac{\mathrm{Re}(\tilde{R}_p\tilde{K}^*)\cos^2P+\mathrm{Re}(\tilde{R}_s\tilde{K}^*)\sin^2P+\mathrm{Re}(\tilde{R}_p\tilde{R}_s^*)\sin P\cos P}{|\tilde{R}_p|^2\cos^2P+|\tilde{R}_s|^2\sin^2P+2[\mathrm{Re}(\tilde{R}_p\tilde{K}^*)+\mathrm{Re}(\tilde{R}_s\tilde{K}^*)]\sin P\cos P}. \tag{6}$$

Note that the ellipsometric parameters ψ and Δ are then functions of the magneto-optic quantity $\tilde{K}$ as well as the optical coefficients $\tilde{R}_p$ and $\tilde{R}_s$. As a result, even in the absence of an applied field the remanent magnetization of the sample will cause a polar Kerr effect, and hence will effect the values of the ellipsometric parameters.

The analysis of these trilayer structures is not possible with only VASE and Kerr data, as the parameter correlation between the TbFeCo optical constants and the top dielectric layer thickness prevents an unambiguous simultaneous determination of these parameters.[5] The inclusion of reflectance data in the fit was found to reduce this correlation so that the top dielectric thickness and TbFeCo constants could be simultaneously determined for each sample.

IV. RESULTS AND CONCLUSIONS

The optical constants of the TbFeCo layer, shown in Figs. 4 and 5, were found not to vary with layer thickness. The vertical bars in both figures indicate the range of values determined for all samples, i.e., the values of the optical constants of all TbFeCo layers lie within the vertical bars. There appears to be small variations in the magneto-optical constants $Q1$ and $Q2$, as can be seen in Figs. 5 and 6; however, this variation is not systematic in that there is no distinct trend with increasing or decreasing layer thickness, and is considerably larger than the statistical uncertainties of these parameters as found from the regression analysis. As a result, this variation cannot be attributed to varying layer thicknesses or to experimental error.

The major contribution of this work is to provide spectra of both optical and magneto-optical constants for TbFeCo thin films, thus permitting predictive performance modeling calculations to be made for any structure involving similar TbFeCo thin films. Additionally, a powerful analysis technique has been demonstrated whereby readily available reflection mode techniques (ellipsometry, reflectometry, and Kerr spectrometry) can be used to accurately characterize individual magneto-optic films in relatively complicated multilayer structures. We have also shown that the magneto-optic activity of the sample in the remanent state (assuming a square loop material) can be accounted for in the modeling of ellipsometric data in order to provide the most accurate possible optical constants for the layer(s) of interest. Finally, we have demonstrated the lack of systematic thickness dependence of the optical and magneto-optical constants of TbFeCo thin films over the thickness range 100–800 Å.

ACKNOWLEDGMENT

The research at the University of Nebraska was supported by National Science Foundation Grant No. CMR8918889.

[1] D. S. Bloomberg and G. N. N. Connell, in *Magnetic Recording*, edited by C. D. Mee and E. D. Daniel (McGraw-Hill, NY, 1988), Vol. II, Chap. 6, p. 305.
[2] S. L. Grove and W. A. Challener, Proc. Jpn. J. Appl. Phys. **28**, Suppl. 28-3, 51 (1989).
[3] W. A. McGahan, P. He, L. Y. Chen, and J. A. Woollam (these Proceedings).
[4] W. A. McGahan, L. Y. Chen, J. A. Woollam, F. Sequeda, and H. Do, Appl. Phys. Lett. (to be published).
[5] G. A. N. Connell, Appl. Opt. **22**, 3155, 1983.
[6] J. A. Woollam, P. G. Snyder, and M. C. Rost, Mater. Res. Soc. Proc. **93**, 203 (1987).
[7] P. G. Snyder, M. C. Rost, G. H. Bu-Abbud, J. A. Woollam, and S. A. Alterovitz, J. Appl. Phys. **60**, 3293 (1986).
[8] L. Y. Chen and J. A. Woollam, SPIE **1166**, 267 (1989).
[9] W. A. McGahan and J. A. Woollam, Appl. Phys. Comm. **8**, 1 (1989).