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Abstract

We have applied the technique of variable angle of incidence spectroscopic ellipsometry (VASE) to the analysis of multilayered magneto-optic structures. With this instrument we measure the complete pseudodielectric tensor (diagonal and off-diagonal elements) for the sample of interest at variable angles of incidence. We have also developed computer software to perform a best-fit analysis of the measured data, providing optical constants, Voigt parameters, and layer thicknesses for the individual layers in the sample. Additionally, given an estimate of the material parameters, this software will provide an estimate of the optimum spectral range and angles of incidence for accurate characterization of the sample. An example of the above is given for a series of thicknesses of Dy/Co compositionally modulated multilayers deposited on a thick silver layer and subsequently overcoated with a thick layer of SiO. Results confirm the predicted optimum range of accuracy for this material system and effectively delineate the useful spectral range of this technique.

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I. INTRODUCTION

Variable angle of incidence magneto-optic ellipsometry (VASMOE) has been useful in the study of bulk magnetic media,[1,2] but was severely limited in its application to multilayers by the lack of regression analysis capability. In this paper we describe software analogous to that used for VASE[3] to perform a best fit analysis of VASMOE data. We propose this technique as a powerful tool which takes advantage of the additional information provided by multiple angles of incidence to characterize magnetic layers within multilayered structures. We present the fundamental points of the theory, as well as a brief demonstrative example.

II. THEORY

For a given multilayered magneto-optic structure, the pseudo-Fresnel coefficients (in reflection) are defined by

$$\mathbf{E}^r = \begin{bmatrix} r_p & k_s \\ k_p & r_s \end{bmatrix} \mathbf{E}^i, \tag{1}$$

where $\mathbf{E}^r$ and $\mathbf{E}^i$ represent the reflected and incident electric field vectors (expressed as p- and s-plane components) and r_p,r_s,k_p, and k_s are the pseudo-Fresnel coefficients. The measured quantities in VASMOE are

$$\rho^{\pm} = \tan \psi \pm e^{i\Delta \pm}, \tag{2}$$

where the $+$, $-$ indicate up and down directed magnetization. Since the quantities in (2) are functions of the psuedo-Fresnel coefficients and the (known) polarizer angle, we wish to calculate for a given model the psuedo-Fresnel coefficients r_p,$r_s k_p k_s$. To this end we solve Maxwell's equations in a general magnetic film having a dielectric tensor of the form[5-8]

$$[\epsilon] = \begin{bmatrix} \epsilon_{xx} & -\epsilon_{xy} & 0 \\ \epsilon_{xy} & \epsilon_{xx} & 0 \\ 0 & 0 & \epsilon_{zz} \end{bmatrix} \equiv \begin{bmatrix} \epsilon_{xx} & i\tilde{Q}\epsilon_{xx} & 0 \\ i\tilde{Q}\epsilon_{xx} & \epsilon_{xx} & 0 \\ 0 & 0 & \epsilon_{xx} \end{bmatrix}. \tag{3}$$

By taking advantage of the continuity of tangential field components at the interfaces, we form the characteristic transfer matrix for each layer in the model:

$$\begin{bmatrix} E_{bx} \\ H_{by} \\ E_{by} \\ H_{bx} \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & C_{14} \\ C_{21} & C_{22} & C_{23} & C_{24} \\ C_{31} & C_{32} & C_{33} & C_{34} \\ C_{41} & C_{42} & C_{43} & C_{44} \end{bmatrix} \begin{bmatrix} E_{fx} \\ H_{fy} \\ E_{fy} \\ H_{fx} \end{bmatrix}, \tag{4}$$

where the subscripts f and b denote the front and back surfaces of a given layer, respectively. The total characteristic matrix for the structure is then given by the product of the individual layer matrices:

$$[C]_T = [C]_1 [C]_2 [C]_3 \cdots [C]_{\text{substrate}}. \tag{5}$$

From this result we calculate the reflection pseudo-Fresnel coefficients.[3] Note that this formulation is valid at any angle of incidence such that $0 \leqslant \phi \leqslant 90°$.

III. PROCEDURE

The nominal structure of the samples are shown as insets in Figs. 1 and 2. We initially calculate as an example the sensitivity of the differential parameters:

$$\delta\psi = \psi^+ - \psi^-, \tag{6}$$

$$\delta\Delta = \Delta^+ - \Delta^-, \tag{7}$$

to the Voigt parameter of the DyCo layer, as we wish to most accurately determine this parameter. Sensitivity to all other parameters are easily calculated as well. Figures 1 shows the results of this calculation for a 1444-Å layer of Dy/Co on silver with a 2092-Å SiO overcoat. Note the complete lack of sensitivity from 3000 to 5000 Å, where the SiO region is absorbing and the probe beam does not reach the magnetic layer. Maximum sensitivity occurs from ~5000 to 6000 Å, a region in which the SiO layer exhibits quarter-wavelength behavior. As this corresponds to a minimum in the reflectance, we also expect a lower signal to noise ratio in this region for the VASMOE. Best results are expected in the 6000–8000 Å region, where the SiO is transparent and the sensitivity is still well above the noise level of the instrument.

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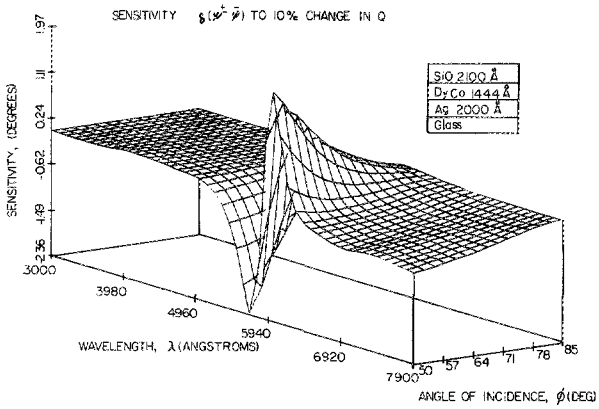

FIG. 1. Calculated change in the measured parameter for a 10% change in the complex Voigt parameter Q.

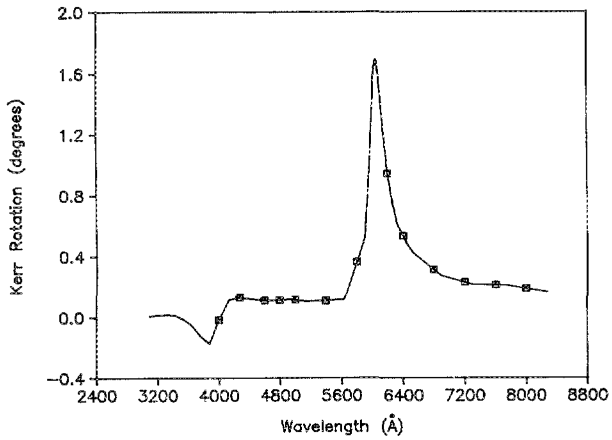

FIG. 2. Kerr rotation at normal incidence for 1444-Å CMA thickness. Solid line is measured; symbols are calculated points from best-fit optical and magneto-optical constants.

Analysis of VASMOE data for the sample described was carried out using a program implementing the Marquardt–Levenberg algorithm to find the optical and magneto-optical constants of the magnetic layer. For this example, data at 60°, 65°, and 70° angle of incidence were used as well as normal incidence Kerr rotation data. Figure 2 shows a typical fit to the experimentally measured Kerr rotation. Furthermore, the covariance matrix, sensitivity correlation matrix, and 90% confidence limits were calculated for the best-fit parameters. Results for this example were found to confirm the predicted lack of sensitivity at the lower wavelengths, as the mean square error for the fit model versus experimental data was not sensitive to changes in the DyCo optical or magneto-optical constants. At wavelengths above 5000 Å the optical and magneto-optical constants for the DyCo layer were determined for five CMA thicknesses.

IV. CONCLUSIONS

In this paper we have discussed a computer program which performs a best fit regression analysis of measured variable angle spectroscopic magneto-optic ellipsometry data. When performed in a spectral region where the measured quantities are sensitive to the unknown parameters of the model, VASMOE coupled with the newly developed analysis software provides a powerful tool for the analysis of multilayered structures. These samples may consist of magnetic and nonmagnetic, absorbing or nonabsorbing layers. These best fit analyses can provide optical constants, Voigt parameters, and layer thicknesses for the individual layers in the sample. The software also provides a complete multivariate statistical analysis of the fits, as well as three dimensional plots of sensitivity to any unknown parameter versus wavelength and angle of incidence.

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