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Determination of the interfacial magneto-optical effects in Co/Pt multilayer structures

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In this letter, we present results of a study of the magneto-optical Kerr response in Co/Pt superlattices by solving for optical constants and Voigt parameters of constituent layers in the structure. The absolute values of the Voigt parameters of Co/Pt interfaces were found to be about twice as large as for the Co layer in the superlattice. Furthermore, using the determined optical constants and Voigt parameters, we can generate the Kerr rotations and ellipticities for Co/Pt superlattices or sandwich structures with continuously changed layer thicknesses and different repeat numbers. Comparison of these theoretical results to the experimental magneto-optical responses for selected structures exhibits strong consistency. © *1997 American Institute of Physics.* [S0003-6951(97)00824-3]

Magneto-optical (MO) recording media have been studied intensively in the last two decades and have been industrialized using TbFeCo as recording media. The future for MO memory is to increase the memory density by reading at short wavelength.[1,2] Co or Fe based multilayer structures are the most promising MO media with good blue response, with Co/Pt structures being the best.[3] To fully understand the electromagnetic properties of MO media, a matrix $\tilde{\epsilon}$ describing dielectric tensors must be known,[4] given by

$$\tilde{\epsilon}=\begin{pmatrix} \tilde{\epsilon}_{xx} & -i\tilde{\epsilon}_{xx}\tilde{Q} & 0 \\ i\tilde{\epsilon}_{xx}\tilde{Q} & \tilde{\epsilon}_{xx} & 0 \\ 0 & 0 & \tilde{\epsilon}_{zz} \end{pmatrix}, \tag{1}$$

where $\tilde{Q}$ is the Voigt parameter and $\tilde{Q}=Q_1+jQ_2=-i\tilde{\epsilon}_{xy}/\tilde{\epsilon}_{xx}$, and dielectric function $\tilde{\epsilon}_{xx}=\tilde{\epsilon}_{xx1}+j\tilde{\epsilon}_{xx2}=\tilde{n}^{2}$. Here, complex optical constants are $\tilde{n}=n+jk$, where n and k are the index of refraction and extinction coefficients, respectively.

Electromagnetically, the electric field of the reflected and incident light beam are related by a Jones matrix given by

$$\mathbf{J}=\begin{pmatrix} R_x & K_y \\ K_x & R_y \end{pmatrix}, \tag{2}$$

where R_x, R_y, K_x, and K_y are functions of the optical constants and the Voigt parameter of the media, the angle of incident beam, and film thicknesses. Also $\mathbf{E}^r=\mathbf{J}\cdot\mathbf{E}^i$ with r and i referring to ''reflected'' and ''incident'' radiation. MO Kerr rotation θ_K and ellipticity η_K are defined as: $\theta_K=\mathrm{Re}(K_x/R_x)$ and $\eta_K=\mathrm{Im}(K_x/R_x)$. Therefore, the magneto-optical responses are directly related to the dielectric properties (Voigt parameters and optical constants) of the recording media, or vice versa.

In recent years, much has been done to investigate MO polar Kerr properties of metallic multilayer structures by finding the Voigt parameters for the media.[3] However, these results are not complete due to the fact that the multilayers are treated as entire films. Thus, the solved Voigt parameters are ''pseudo'' for the entire recording media, rather than for the individual layers.

In this letter, we will introduce a comprehensive study of the Kerr rotation and ellipticity for Co/Pt multilayer thin films by determining the Voigt parameter and optical constants of each constituent layer in the structures. The theory applied here was developed by P. He and W. McGahan, based on the original work by Lissberger and others.[4–6] Here, instead of using a Jones matrix for the entire structure, a characteristic matrix $\mathbf{C}_m$ is used for the mth individual layer as a function of the complex index $\tilde{n}_m$, the Voigt function $\tilde{Q}_m$, and layer thickness d_m. The entire structure is characterized by the matrix $\mathbf{C}=\mathbf{C}_\mathbf{O}\mathbf{C}_\mathbf{1}\mathbf{C}_\mathbf{2}\ldots\mathbf{C}_m$, and $\mathbf{E}_{\text{top}}=\mathbf{C}\cdot\mathbf{E}_{\text{Bottom}}$. Referring to Eq. (2), the coefficients R_x and K_x relate to vectors in matrix $\mathbf{C}$ as: $R_x=(1/2)\times(C^R_{21}/C^R_{11}+C^L_{21}/C^L_{11})$, and $K_x=(1/2)\times(C^R_{21}/C^R_{11}-C^L_{21}/C^L_{11})$, where R and L denote right-hand and left-hand circular polarizations, respectively. Combining this with Eq. (2), the Kerr rotation and ellipticity can be simulated in terms of the Voigt parameter and optical constants of each individual layer.

The Co/Pt multilayer films were dc sputter deposited on silicon. The deposition rate for Pt and Co are calibrated using *in situ* spectroscopic ellipsometry. *In situ* ellipsometry is a precise real-time method to determine the growth rate simultaneously with the optical constants of the monitored materials. Therefore, the optical constants for Pt and Co layers in the superlattice and the deposition rate of Pt and Co in the superlattice were predetermined and fixed during the magneto-optical analysis discussed in this letter.

A modified *ex situ* spectroscopic ellipsometer was used to take MO data on the Co/Pt multilayer films, with a spectral range from 300 to 1000 nm. The average noise level of the Kerr data was about 0.02°. The experimental data for three samples are shown in Fig. 1 as dotted lines, and the three samples are denoted as samples 1–3.

For samples 1 and 2 which have the same layer thicknesses but different repeat periods of 10 and 20, regression fits were made assuming that the Voigt parameter $\tilde{Q}$ comes entirely from the magnetic Co layer, and is the same in both samples. The fitting results were excellent. However, if the data for sample 3 (with a different Co layer thickness) were added to the regression, common $\tilde{Q}$ values for all three samples were not found. For comparison, we generated Kerr

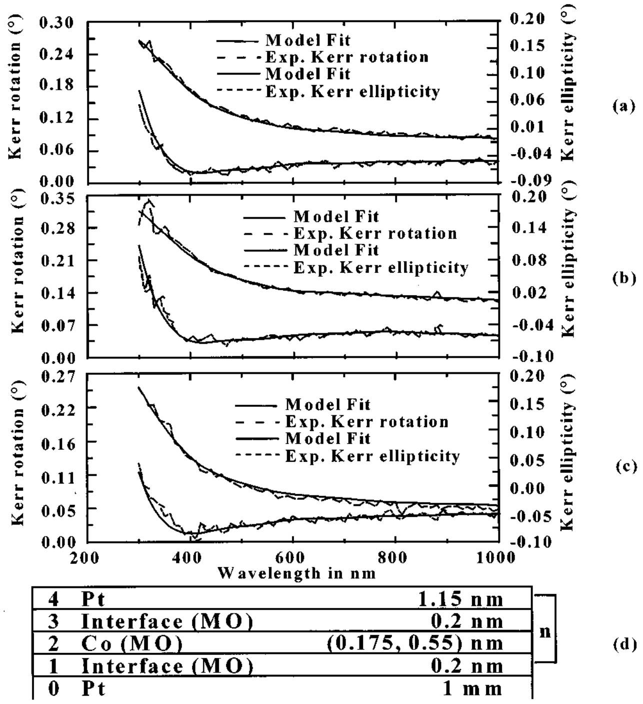

FIG. 1. Experimental data and regression fits for three Co/Pt samples assuming $\tilde{Q}$ in the bulk, defined as $\tilde{Q}_B$, is the same for all samples and $\tilde{Q}$ in the monolayer thick interface $\tilde{Q}_I$ is the same for all samples. Figs. 1(a), 1(b), and 1(c) correspond to samples 1, 2, and 3, respectively. (a) Experimental data and regression fits for sample 1: [Pt(1.35 nm)/Co(0.375 nm)]$_{20}$/Pt/Si. (b) For sample. 2: [Pt(1.35 nm)/Co(0.375 nm)]$_{10}$/Pt/Si. (c) For sample 3: [Pt(1.35 nm)/Co(0.75 nm)]$_{20}$/Pt/Si. (d) The model for the regression fits.

rotation and ellipticity data for sample 3 using the Q_1 and Q_2 values obtained from the fit for the first two samples, and the resulting generated Kerr responses were larger than the experimental responses. The conclusion is that the averaged $\tilde{Q}$ values for thinner Co layers in Co/Pt superlattices are greater than those for thicker Co layers. This suggests that the magnetic layer can be divided into two regions, the central film ''bulk'' region and the interfacial regions, as shown in Fig. 1(d). Thus, there exists an optically thick Pt underlayer, an interfacial Co–Pt mixed layer, the bulk Co layer, a top interface layer, and a top Pt coverlayer. The thickness of the interface layer was assumed to be 0.2 nm. The Bruggeman effective media approximation was used to optically model the interface, with a Pt to Co ratio of 1:1.[7]

Excellent regression fits were obtained using the model described above, as shown as solid lines in Fig. 1. For all 3 samples, a common $\tilde{Q}_B$ for the center bulk Co region as well as a common $\tilde{Q}_I$ for the interface regions were found as shown in Fig. 2. Using these $\tilde{Q}_B$ and $\tilde{Q}_I$, we generated the Kerr rotation and ellipticity data for five new samples of Co/Pt multilayers with various thicknesses and repeat numbers. Excellent matches were obtained when predictions were compared to measurements, and the result for sample [Pt(0.93 nm)/Co(0.375 nm)]$_{20}$/Pt/Si is shown in Fig. 3(a). A Pt/Co/Pt sandwich structure was also made to verify the correctness of this analysis. The structure consists of a Pt underlayer and a Pt coverlayer with a single layer of Co in between. For the two samples made, the thicknesses of Co layers were 3 and 1.5 nm, which assumed 0.2 nm interfacial regions. We used the same $\tilde{Q}_B$ and $\tilde{Q}_I$ determined from the regression fit in Fig. 1 to generate the corresponding Kerr rotations and ellipticities, then compared them to the experimental data. In view of the small scale of the Kerr responses from the sandwich structures, the matches between the experimental and generated data are exceptional, and confirm our initial results for the Voigt parameters. The experimental and generated Kerr data for sandwich structure Pt(3 nm)/Co(1.5 nm)/Pt(60 nm)/Si are shown in Fig. 3(b).

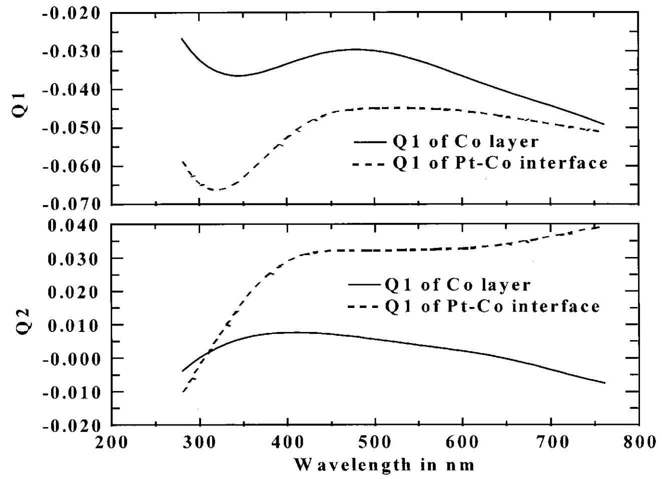

FIG. 2. Voigt parameters $\tilde{Q}_B$ and $\tilde{Q}_I$ determined from the regression fits in Fig. 1.

In summary, the magneto-optical Kerr rotation and ellipticity for a multilayer system were analyzed by solving for the optical constants and Voigt parameters of the individual layers instead of for the entire structure. This allows us to predict the MO response for any given multilayer structure using these same materials. In addition, the magneto-optical figure of merit can also be predicted once the optical constants and Voigt parameters of constituent materials are determined.

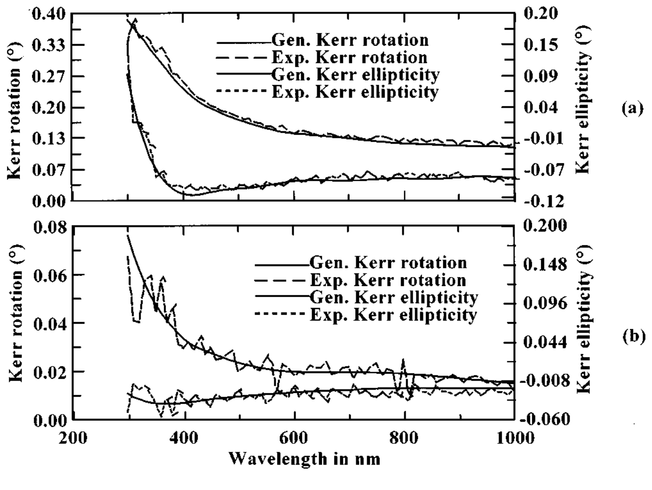

FIG. 3. Generated Kerr data for (a) Co/Pt multilayer sample [Pt(0.93 nm)/Co(0.375 nm)]$_{20}$/Pt/Si and (b) sandwich structure Pt(3 nm)/Co(1.5 nm)/Pt(60 nm)/Si, using $\tilde{Q}_B$ values for the Co bulk region and $\tilde{Q}_I$ for the Co–Pt interface determined from the regression fits in Fig. 1.

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