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Ellipsometric and magneto-optic properties of sputtered dysprosium-iron multilayers

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Ellipsometric and magneto-optical properties of Dy (3.5 Å thick) and Fe (2.5–12.5 Å thick) multilayers were investigated over the spectral range from 3000 to 8000 Å in magnetic fields to 0.21 T. In this range of layer thickness the magnetic anisotropy is vertical. Kerr rotations, were found to be weakly spectrally dependent, and as large as 0.06°. The magnetically driven change of ellipticity of reflected light was as large as 0.13, depending on sample and wavelength. Ellipsometric analysis of layer thickness was performed assuming a multilayer geometry. In addition, the optical constants were determined assuming the multilayer was a homogeneous layer with "effective" properties.

I. INTRODUCTION

The purpose of this work was to investigate the spectrally dependent magneto-optical properties of rare-earth/transition-metal multilayered structures, and also to determine the multilayer thicknesses and effective optical properties of these structures using variable angle of incidence spectroscopic ellipsometry (VASE).[1,2] A series of atomically thin rare-earth/transition-metal multilayers were studied in an effort to be able to control both the magnetic and the magneto-optic properties. This paper reports on our first results: four samples in the DyFe system.

II. EXPERIMENT

The multilayers were prepared in the same multiple-gun sputtering system described in a companion paper.[3] Quartz substrates were held on a water-cooled, stepper-motor controlled rotating table which was positioned inside a vacuum chamber with a base pressure of 2×10^{-7} Torr. As the sample spun on the table overhead, the Dy was deposited from an rf sputtering gun, and Fe was deposited with a dc sputtering gun. Thicknesses were determined by the length of time the substrate was held above the corresponding target.

The VASE system[2] uses a rotating analyzer with 72 data points digitized per revolution. With up to 300 revolution averaging, a greatly enhanced signal-to-noise ratio can be achieved when needed. A Marquardt regression analysis[1] with thicknesses as variables was performed on a VAX 11/780.

III. THEORY

The ellipsometric parameters ψ and Δ are defined from

$$\bar{\rho} = r_p/r_s = \tan\psi \exp(j\Delta), \tag{1}$$

where r_p and r_s the (complex) Fresnel reflection coefficients for light linearly polarized in the plane of incidence r_p, or perpendicular to the plane of incidence r_s.

The magneto-optic effects are analyzed as follows: Spectral data of ψ and Δ are taken for both a positive (+) and a negative (−) magnetic field applied in a polar Kerr orientation (perpendicular to the film surface). This defines a $\rho(+)$ and $\rho(-)$ similar to Eq. (1):

$$\rho(\pm) = r_p'/r_s'(\pm M), \tag{2}$$

where M is the magnetization of the sample. The primed quantities are defined by

$$r_p' = r_p + k_p E_s/E_p \tag{3}$$

and

$$r_s' = r_s + k_s E_p/E_s, \tag{4}$$

where E_s and E_p are the electric field amplitudes in the s and p orientations, and k_s and k_p are defined as the off-diagonal terms in the complex Fresenel reflection matrix and are equal in the Polar Kerr effect. The quantity

$$E_p/E_s = \cot\theta, \tag{5}$$

where θ is the azimuth of the polarizer from the p-plane.

The Kerr rotation is given by the real part of k_p/r_s found by analyzing Eqs. (1) through (5) above, resulting in

$$\frac{k_p}{r_s} = \frac{\rho(+)-\rho(-)}{\tan\theta\,[\rho(+)-\rho(-)] - \cot\theta}. \tag{6}$$

IV. RESULTS

Figures 1 and 2 are examples of the measured ψ and Δ data for zero magnetic field for one of the samples. Under a magnetic field of 0.21 T, ψ varied as much as 0.1° and Δ as much as 0.3°. Changes as small as 0.01° in ψ and 0.05° in Δ can be easily distinguished experimentally. Figures 3 and 4

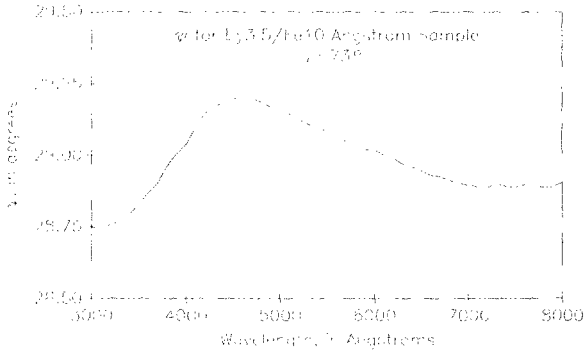

FIG. 1. ψ as a function of wavelength for all four samples in zero magnetic field.

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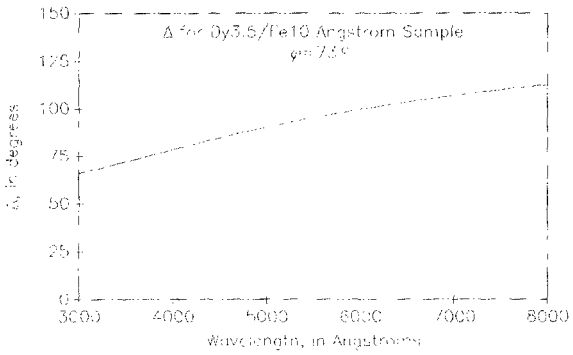

FIG. 2. Same as Fig. 1 but for Δ.

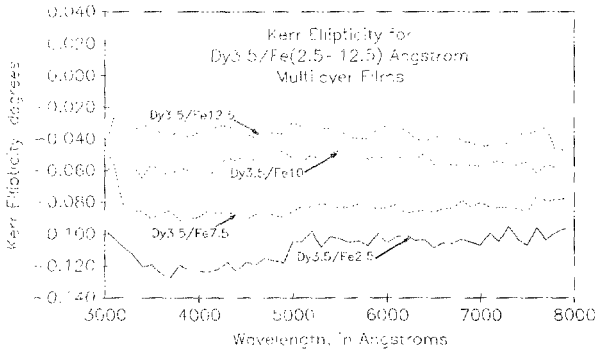

FIG. 4. Ellipticity $\zeta = \mathrm{Im}\{k_p/k_s\}$ as a function of wavelength.

show the Kerr rotation and ellipticity as functions of wavelength for all four samples.

In performing the ellipsometric analysis it was assumed that all Dy layers are of the same (unknown) thickness, and all the Fe layers are of the same (again, unknown) thickness. Additionally, it was assumed that the optical constants are those of pure bulk Dy and Fe films which were also measured using the same system. The nominal thicknesses of 3.5 Å for the Dy layers and 2.5–12.5 Å for the Fe layers solved ellipsometrically to negative thickness values. Clearly, this model does not fit the data.

Figures 5 and 6 show the real imaginary part, respectively, of the zero-field complex dielectric constant for the Dy/Fe stack, and compares the results with those for pure Dy and pure Fe bulk films. It is quite evident from Fig. 5 and 6 that the dielectric constants of the multilayer films are quantitatively and qualitatively different than their constituent bulk films, and are not simply interpolations between two bulk values.

V. DISCUSSION

The sputtered layers formed in our deposition system are totally amorphous, as determined from x-ray diffraction. The bulk film optical constants for Dy and Fe were also measured, and then used for the ellipsometric solutions. However, the individual layer thicknesses are so thin that it may not be appropriate to use bulk film values. The optical properties of these thin layers are likely being dominated by either interfacial effects or intermixing between layers.

Another difficulty we encountered is a lack of knowledge of the (spectrally dependent) optical constants of iron oxide (Fe was the top layer of the stack). Surely there is an oxide on top of the entire stack, and this will influence our results. To "simulate" the oxide we added 30 Å of diamond-like carbon (the index and extinction coefficients are in reasonable ranges for simulating Fe_2O_3). The addition of a 30-Å dielectric overlayer did not significantly alter the thickness values determined for the Dy and Fe layers, and therefore did not improve the fit of the model.

The question remains as to whether the optical constants of these multilayers depend on interactions at the Dy/Fe interfaces or whether there is enough interdiffusion between these atomically thin layers that the films are behaving as bulk DyFe alloys. This question is currently under further study.

The Kerr rotation and elipticity values found for the samples studied in this work are comparable to values found for amorphous DyFe alloys (nonmultilayer).[4] There were no sharp peaks found in the spectral data, in contrast to what reportedly occurs near a plasma edge,[5] or a sharp magneto-optically active electronic transition.[6,7]

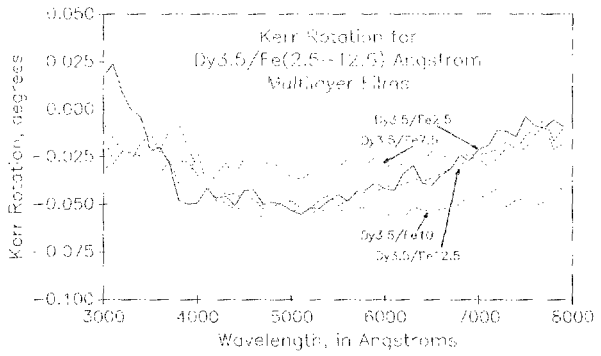

FIG. 3 Kerr rotation $\theta_k = \mathrm{Re}\{k_p/k_s\}$ as a function of wavelength.

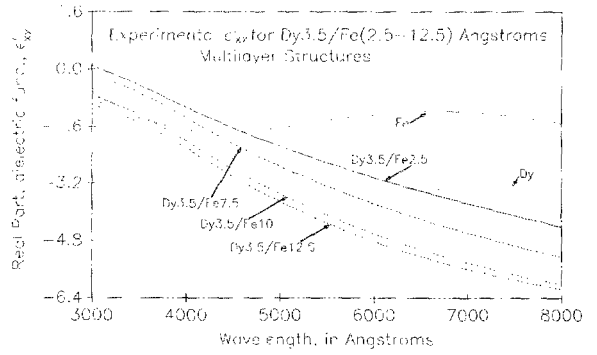

FIG. 5. Real part of the dielectric constant for the Dy/Fe multilayer stack, compared with values for bulk Fe and Dy films.

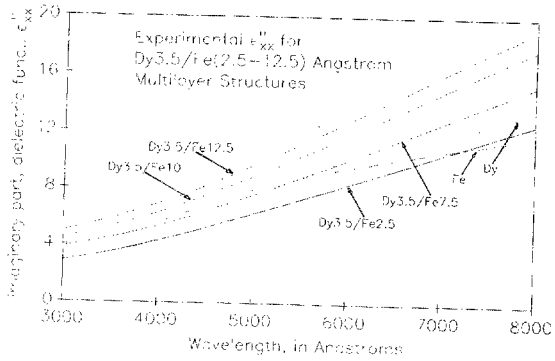

FIG. 6. Imaginary part of the dielectric constant for the Dy/Fe multilayer stack, compared with values for bulk Fe and Dy films.

ACKNOWLEDGMENTS

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