Vector Magneto-Optical Generalized Ellipsometry on Slanted Columnar Thin Films

UNIVERSITY OF NEBRASKA-LINCOLN

D. Schmidt*, C. Briley, E. Schubert, and M. Schubert

Department of Electrical Engineering and Center for Nanohybrid Functional Materials, University of Nebraska-Lincoln, U.S.A.

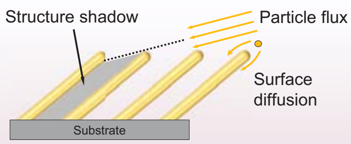
*schmidt@huskers.unl.edu http://ellipsometry.unl.edu http://cnfm.unl.edu

Our Message

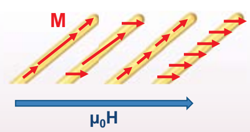
- Glancing angle deposition is utilized to grow magnetic slanted columnar thin films (SCTFs), which then are passivated with a thin conformal Al_2O_3 layer by means of atomic layer deposition (ALD).
- An anisotropic Bruggeman EMA approach is employed to analyze Mueller matrix ellipsometry spectra and to determine monoclinic optical and structural properties as well as fractions of multiple film constituents at 0 T.
- Vector magneto-optical generalized ellipsometry (VMOGE) is an excellent approach to investigate magneto-optical and magnetization properties of complex anisotropic nanostructures.
- Slanted columnar thin films exhibit highly anisotropic magneto-optical and magnetization properties due to geometry, size, coupling, and confinement effects.

Ferromagnetic Nanostructures

Glancing Angle Deposition



An incoming collimated particle flux at glancing angle results in self-organized, coherently aligned slanted columnar thin films due to geometrical shadowing, and limited surface adatom mobility. Subsequently, the nanostructure was passivated by atomic layer deposition of Al_2O_3 to prevent oxidation.



How do magnetic domains align and how do they switch

Magneto-Optical Characterization

Dielectric Tensor

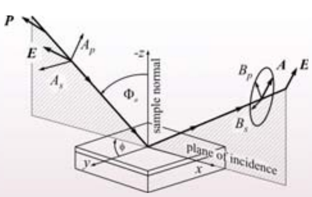
$$\varepsilon = \begin{pmatrix} \varepsilon_{\mathrm{eff},a} & \varepsilon^{\mathrm{P}}_{xy} & -\varepsilon^{\mathrm{T}}_{xz} \\ -\varepsilon^{\mathrm{P}}_{xy} & \varepsilon_{\mathrm{eff},b} & \varepsilon^{\mathrm{L}}_{yz} \\ \varepsilon^{\mathrm{T}}_{xz} & -\varepsilon^{\mathrm{L}}_{yz} & \varepsilon_{\mathrm{eff},c} \end{pmatrix}$$

Off-diagonal parts account for magneto-optical activity

Dielectric tensor of a magnetized biaxial SCTF with polar, transversal, and longitudinal magneto-optical elements

Experimental Techniques

Mueller Matrix Ellipsometry



Ellipsometry measures the polarization state change of an electromagnetic wave upon reflection off a sample surface.

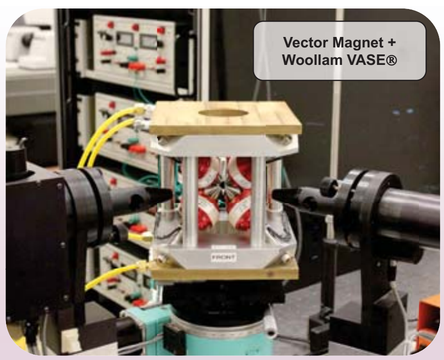
If the sample is anisotropic, spectroscopic Mueller matrix ellipsometry allows for determination of complete sets of optical constants.

The 4×4 real-valued Mueller matrix connects the incident and emergent Stokes vector components

$$\begin{bmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{bmatrix}_{\mathrm{out}} = \begin{pmatrix} M_{11} & M_{12} & M_{13} & M_{14} \\ M_{21} & M_{22} & M_{23} & M_{24} \\ M_{31} & M_{32} & M_{33} & M_{34} \\ M_{41} & M_{42} & M_{43} & M_{44} \end{pmatrix} \begin{bmatrix} I_P + I_S \\ I_P - I_S \\ I_{45} - I_{-45} \\ I_{RC} - I_{LC} \end{bmatrix}_{\mathrm{in}}$$

D. Schmidt *et al.* Appl. Phys. Lett. **94**, 011914 (2009).

Vector Magneto-Optical Generalized Ellipsometry

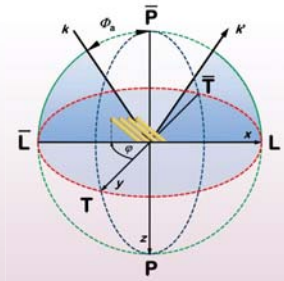


Vector Magnet

- four solenoid pairs along the space diagonals for arbitrary magnetic field directions with up to $\mu_0 H$ = 200 mT
- field homogeneity >99% within the probed sample area (1 mm³ in the magnet center)
- stray fields <4%

Woollam VASE®

- rotating analyzer ellipsometer with auto-retarder
- spectral range: 0.75 – 5 eV
- angle of incidence: 15°, 45°...90°
- equipped with focusing probes (beam size 1 mm)



Definition of VMOGE: **k** and **k'** denote the incident and emergent wave vectors, respectively, with an angle of incidence Φ_a. P, L, and T indicate polar, longitudinal, and transversal directions in accordance with traditional Kerr geometries

Results

Optical Model ($\mu_0 H$ = 0 T)

Scanning electron microscope image of an unpassivated NiFe SCTF and optical model equivalent

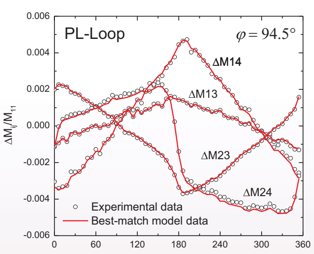
Spatially aligned, anisotropic inclusions with three major effective polarizabilities $\mathbf{P}_{\mathrm{eff},j}$ along principal axes j = **a**,**b**,**c** (based on Bruggeman)

$$\sum_{n=1}^{m} f \frac{\varepsilon_n - \varepsilon_{\mathrm{eff},j}}{\varepsilon_{\mathrm{eff},j} + L_j(\varepsilon_n - \varepsilon_{\mathrm{eff},j})} = 0$$

This model accounts for m = 3 different constituents ($Ni_{80}Fe_{20}$, Al_2O_3, air) with bulk-like optical constants ε_n. Depolarization factors L_j represent the biaxial film geometry. A projection matrix is applied to transform the virtual orthogonal basis into a monoclinic system.

Optical and structural properties determined prior to magneto-optical analysis

D. Schmidt *et al.* Appl. Phys. Lett. (in submission, 2011).



Point-by-point fit of magnetic field-induced difference data, $\Delta M_{ij}(\mu_0 H = 170\ \mathrm{mT}) - \Delta M_{ij}(\mu_0 H = 0\ \mathrm{T})$, normalized to M_{11} for an Al_2O_3 passivated $Ni_{80}Fe_{20}$ SCTF with respect to magnetic field orientation (Φ_a = 55°, λ = 500 nm)

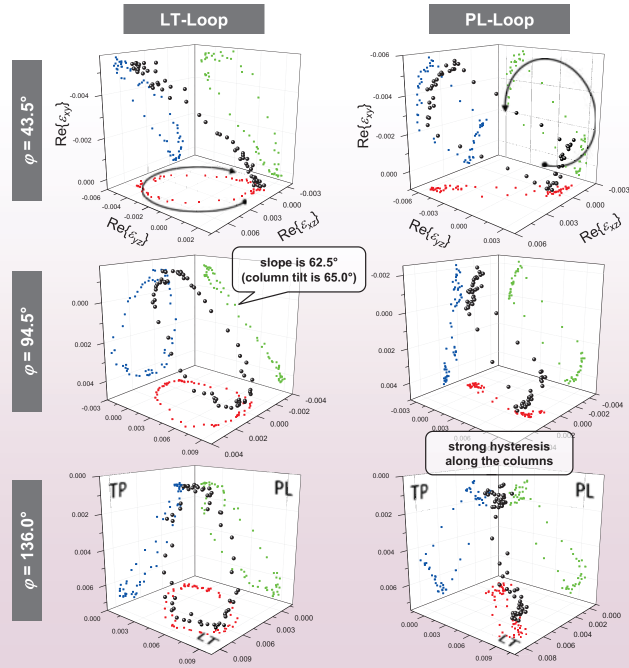
LT-Loop

strong out-of-plane component
magnetization ellipse depends on sample orientation
(long axis of ellipse is parallel to long axis of columns)

PL-Loop

strong hysteresis exclusively along columns
(no transversal component at φ = 94.5°)
magnetization only parallel to long axis of columns

→ three-dimensional magneto-optical parameter plots indicate sample magnetization!



2011 MRS Fall Meeting & Exhibit, Boston, MA, December 2011

Funding: NSF RII (EPS-1004094), CAREER (ECCS-0846329), MRSEC (DMR-0820521)