Direct Observation of Surface-driven Twisted Magnetic State in a Gd/Fe Multilayer

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Introduction

The ability to separate, in a measurement, the "surface" region from the "bulk" region in magnetic nanostructures is critical to assessing the role that termination layers play in stabilizing a certain magnetic structure. Most techniques exclusively probe either the surface or the bulk region, so determinations of surface and bulk magnetic states cannot be done simultaneously. Here we show that x-ray magnetic circular dichroism (XMCD) in the hard x-ray regime can be used to probe both of these regions by tuning the x-ray incidence angle. The predicted [1] nucleation of a noncollinear ("twisted") magnetic phase at the surface of a multilayer is directly observed.

Methods and Materials

Postulated Phase Diagram

The magnetic phase diagram of ferrimagnetic Gd/Fe multilayers exhibits collinear and twisted configurations that result from a delicate balance between inter/intralayer exchange and Zeeman energies (Fig. 1). At very low applied fields, exchange dominates, and collinear structures are favored. The layers with the largest magnetization align with the field, and the minority component is constrained to be antiparallel by interlayer exchange. Gd dominates the magnetization at low temperatures (T_{Curie} of ≈300K), leading to the Gd || H phase, while Fe dominates at higher temperatures (T_{Curie} of ≈1000K), leading to the Fe || H phase. At higher fields, a twisted phase arises to minimize Zeeman energy losses in the antiparallel minority component, increasing its projected moment along the field direction. Since temperature reduces the Gd moment faster than the Fe moment, the field needed to induce such a twist decreases with temperature.

When the multilayer is terminated with the minority component (here Fe is minority at low temperature), a transition into a surface twisted phase is predicted to occur at a much lower field than that required to induce a bulk twist [1]. This is because the top layer is constrained only by exchange from the bottom, while the bulk layers are constrained on both sides. Here we present the most clear evidence yet that shows the existence of this phase.

Experiment

Surface sensitivity with hard x-rays was achieved by decreasing the incidence angle to near (but above) the critical angle for total external reflection from the multilayer structure. Since the x-ray penetration depth changes very quickly with incidence angle, it is critical to assure that this angle is correctly determined. We used the multilayer's first Bragg peak to calibrate this angle. Our setup allows for simultaneous measurements of the multilayer's reflectivity and XMCD in fluorescence geometry. Element-specific hysteresis loops were carried out at 7.930 keV (Gd L_2 edge) and 7.110 keV (Fe K edge). At these energies, the XMCD signals for each element are maximized (Fig. 2).

Surface and bulk sensitivity were achieved at the Gd L_2 edge by tuning the incidence angle to $\theta = 0.43^o$ and $\theta = 9.5^o$, respectively. The grazing incidence geometry probes the top one to two bilayers, while the higher incidence angle probes the whole multilayer. At the Fe K edge (7.110 keV), the total absorption coefficient is low, and surface sensitivity is greatly reduced. The grazing incidence geometry at this energy probes about four to five bilayers.

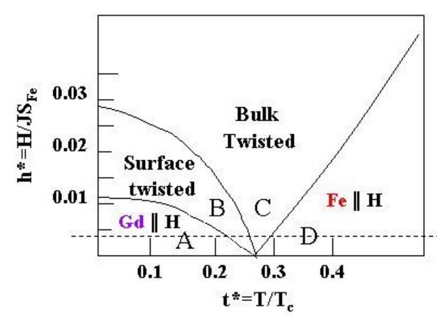

FIG. 1. Calculated phase diagram for an Fe-terminated Gd/Fe multilayer as function of reduced magnetic field and temperature [1].

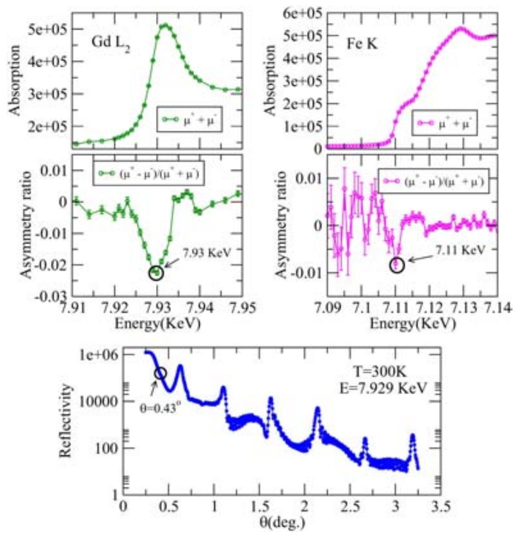

FIG. 2. Top: Absorption spectra ($\mu^+ + \mu^-$) and asymmetry ratios ($\mu^+ - \mu^-$)/($\mu^+ + \mu^-$) obtained at the Gd L_2 (left) and Fe K (right) edges. μ^+ and μ^- are the measured absorption coefficients for incoming left and right circularly polarized x-rays, respectively. Bottom: specular reflectivity from the Si/Nb (100 Å)/Fe (35 Å)[Gd (50 Å) Fe (35 Å)]$_{15}$/Nb (30 Å) multilayer. The incident angle used for the surface sensitive measurements is shown.

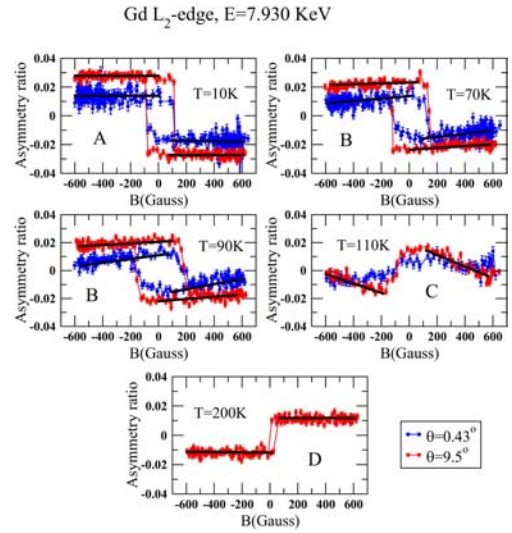

FIG. 3. Gd element-specific hysteresis loops. The sequential transition Gd-aligned → surface-twisted → bulk-twisted → Fe-aligned is observed with increased temperature. The labels A-D correspond to those in Fig 1. The reduction in hysteresis "jump" with temperature is due to the reduction in the Gd moment. The relative change in the sign of the loops between 10 and 200K is due to the transition from Gd-aligned to Fe-aligned phases.

Results

Figures 3 and 4 show element-specific hysteresis loops of Gd and Fe layers at different temperatures and different incidence angles. The loops are obtained by measuring the asymmetry ratio at each applied field value. The XMCD signal is proportional to the projection of the magnetic moment along the x-ray beam (field) direction. A square hysteresis loop indicates the moment is aligned with the field, independent of the field strength. This is the case at T = 10K, where the multilayer is in the Gd-aligned state. At T = 70K and T = 90K, however, the grazing incidence ($\theta = 0.43^o$) hysteresis loop becomes "tilted," indicating that the component of the magnetic moment along the beam/field direction decreases with increased applied field. Since the $\theta = 9.5^o$ hysteresis loop remains nearly square, the twist of the magnetic moments away from the field direction occurs only in the top part of the multilayer and not in its interior. This is the surface-twisted state.

As temperature is increased further (T = 110K), the twist propagates inside the multilayer, and now the $\theta = 9.5^o$ hysteresis loop also shows significant tilting. At T = 110K, the hysteresis loop already changed sign, indicating that Fe already dominates the magnetization at this temperature. A further increase in temperature (200K) again leads to a square hysteresis loop, and the multilayer is in the Fe-aligned phase.

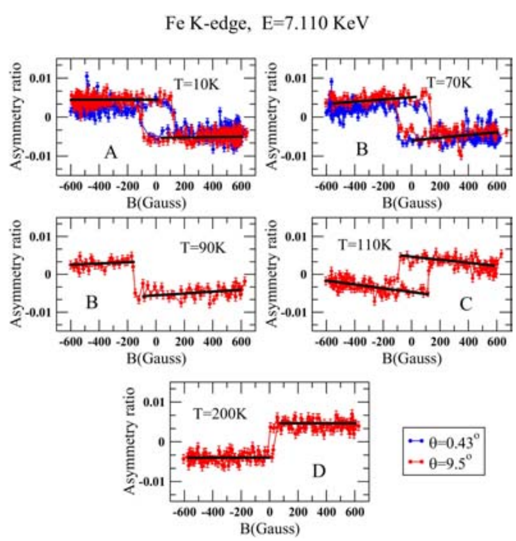

FIG. 4. Fe element-specific hysteresis loops. The labels A-D correspond to those in Fig. 1.

Discussion

Element-specific hysteresis loops were obtained from surface and bulk regions of a Gd/Fe multilayer. The surface nucleation of a twisted phase was directly observed, in agreement with the predictions by LePage and Camley [1].

Acknowledgments

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Reference

[1] LePage and Camley, Phys. Rev. Lett. **65,** 1152 (1990).