



SURFACE NUCLEATION OF MAGNETIC TWIST IN ARTIFICIAL Fe/Gd MULTILAYERS

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ABSTRACT

Artificial magnetic multilayers can exhibit complex inhomogeneous magnetic structures wherein the magnetization varies throughout the thickness of the multilayer. Surfaces and interfaces can act as nucleation centers for such inhomogeneous states. We present direct evidence for nucleation of such state at the surfaces of Fe-terminated Fe/Gd multilayers. This surface nucleation was predicted more than a decade ago but its experimental confirmation has not been realized until now.

1. MOTIVATION

Symmetry breaking at surfaces and interfaces can induce novel magnetic states in artificial structures. Over a decade ago LePage and Camley[1] predicted the surface nucleation of an inhomogeneous magnetic state in ferrimagnetic multilayers terminated by the minority magnetic component. At nucleation the magnetization deviates from the applied field direction near the surface but remains field-aligned in the bulk. Experimental confirmation required showing the existence of a surface twist but its absence in the bulk. Most techniques, however, probe the surface or the bulk. Our novel approach[2] combines two well known properties of x-rays: (a) penetration depth tunability near the critical angle for total external reflection and (b) x-ray magnetic circular dichroism (XMCD) near absorption edges of magnetic elements.

2. EXPERIMENTAL

The $\text{Si}/\text{Nb}(100\text{\AA})/\text{Fe}(35\text{\AA})[\text{Gd}(50\text{\AA})/\text{Fe}(35\text{\AA})]_{15}/\text{Nb}(30\text{\AA})$ multilayer was sputter deposited. Fe and Gd magnetizations couple anti-parallel at Fe/Gd interfaces. Gd has larger bulk magnetization than Fe at low temperatures, where Fe is the minority component. However, the Gd magnetization (Curie Temp. 293K) decreases faster than Fe (Curie Temp. 1024K) and here they become equal at ≈ 110 K. Above this temperature Fe becomes the dominant component.

The experimental setup (Fig. 1) permits simultaneous measurements of specular reflectivity and x-ray magnetic circular dichroism, the latter in fluorescence geometry. The specularly reflected beam is used to determine the grazing incidence angle. This is important since the penetration depth of x-rays varies rapidly near the critical angle for total external reflection.

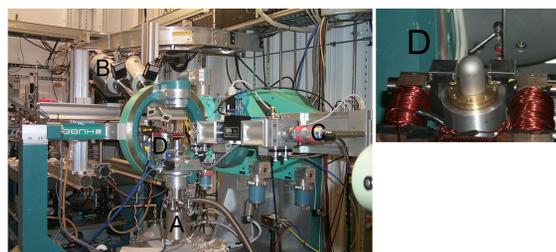


Fig. 1. Experimental setup for simultaneous measurement of specular reflectivity and XMCD in fluorescence geometry. (A) Displex refrigerator; (B) Ge detectors; (C) NaI detector; (D) Electromagnet.

3. RESULTS

XMCD measurements were performed by scanning the x-ray energy through Gd L_2 and Fe K absorption edges. At each energy point the absorption coefficient was measured for opposite helicities of circularly polarized x-rays (μ^+ , μ^-). The results are shown in Fig. 2.

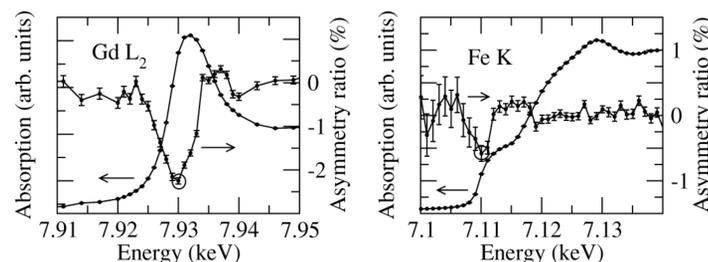


Fig. 2. Absorption $(\mu^+ + \mu^-)/2$ and asymmetry ratio $(\mu^+ - \mu^-)/(\mu^+ + \mu^-)$ near Gd L_2 and Fe K-edges measured at $T=20\text{K}$, $H=600$ Oe and $\theta=9.5^\circ$. Optimal energies used for element-specific hysteresis loops shown by circles.

Element specific hysteresis loops were carried out at 7.930 keV (Gd L_2 edge) and 7.110 keV (Fe K-edge). The x-ray energy is fixed and the asymmetry ratio is recorded as a function of applied magnetic field. For Gd layers ($E=7.930$ keV) surface and bulk sensitivity was achieved by tuning the x-ray incidence angle to $\theta=0.43^\circ$ and $\theta=9.5^\circ$, respectively. The grazing geometry probes the top 1-2 bilayers, while the higher angle probes the whole multilayer (Fig. 3). For Fe layers ($E=7.110$ keV), surface sensitivity at $\theta=0.43^\circ$ is reduced with the x-rays penetrating 4-5 bilayers (Fig. 3, left). Decreasing the incidence angle further was not practical due to the relatively high critical angle of the Nb cap at this energy.

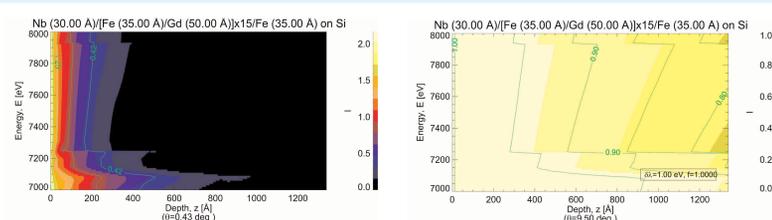


Fig. 3. Calculated x-ray intensity depth profiles for $\theta=0.43^\circ$ (left) and $\theta=9.5^\circ$ (right) incident angles and energies including Fe K and Gd L_2 edges. The calculations use Parratt's formalism with experimental optical constants and fitted structural parameters (Fig. 4).

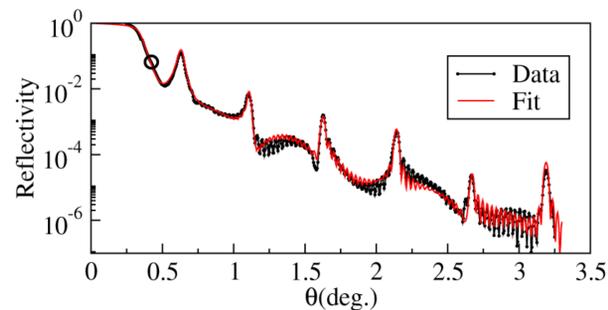


Fig. 4. Specular reflectivity data together with a Parratt's fit, modified to include roughness. The fitted layer thicknesses are $35.48(2)$ \AA and $49.38(2)$ \AA for Fe and Gd, respectively. The interfacial roughness at Fe/Gd interfaces is 3.7 \AA . The angle used for Gd surface sensitive loops is shown (circle).

REFERENCES:

- 1 J. LePage and R. Camley, Phys. Rev. Lett. **65**, 1152 (1990).
- 2 D. Haskel, G. Srajer, Y. Choi, D. Lee, J. Lang, J. Meersschaut, J. Jiang, and S. Bader, Phys. Rev. B **67**, 180406(R) (2003).

3. RESULTS (CONT'D.)

Element-specific hysteresis loops at different temperatures and incidence angles are shown in Fig. 5. XMCD measures the projection of magnetic moment along the x-ray beam (field) direction, so a "flat" hysteresis loop indicates moments aligned with the field at all field values. At $T=70\text{K}$ and $T=90\text{K}$, however, the grazing incidence ($\theta=0.43^\circ$) hysteresis loops become "tilted," indicating a decrease in magnetic moment along the beam/field direction with increased applied field. Since the $\theta=9.5^\circ$ bulk loops remain mostly flat, the magnetic moments twist away from the field direction only in the top part of the multilayer and not in its interior. This is the "surface twisted" state. At $T=110\text{K}$ the $\theta=9.5^\circ$ bulk loops show significant tilting; the twist now propagates throughout the multilayer. At $T=200\text{K}$ a flat hysteresis loop is recovered, where Fe is field-aligned and Gd anti-parallel.

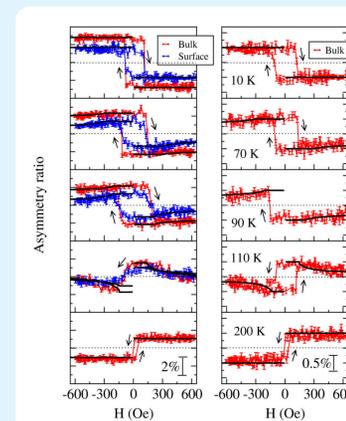


Fig. 5. Gd (left) and Fe (right) hysteresis loops. The "flat" loops correspond to Gd (10K) and Fe dominant (200K) field-aligned configurations. The "tilted" loops correspond to magnetic twisted configurations where the magnetization deviates from the applied field direction in the surface alone (70, 90K) or also in the bulk (110K). The hysteresis jump is proportional to the saturation magnetization at each temperature, which changes for Gd but does not for Fe. The correlated change in sign at about 110K indicates the transition from Gd-dominant to Fe-dominant magnetizations. Solid lines are obtained from Landau-Lifshitz calculations of the magnetization profiles (Fig. 6).

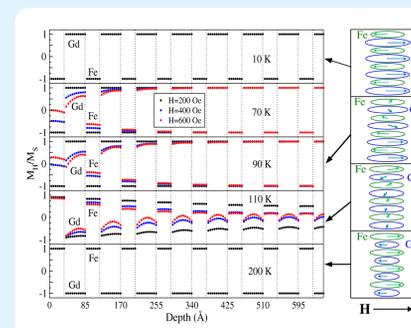


Fig. 6. Theoretical magnetization profiles shown for half of the multilayer structure; other half is mirror symmetric. Magnetization is normalized to saturation value at each temperature. The schematic diagram (right) represents the magnetization (intra-layer averaged) in the upper four bilayers at the different temperatures and $H=600$ Oe.

4. DISCUSSION & SUMMARY

Ferrimagnetic Fe/Gd multilayers exhibit collinear and "twisted" configurations. At low applied fields and temperatures exchange energy dominates over Zeeman energy and collinear structures are favored, Gd aligning with the field Fe constrained anti-parallel by interlayer exchange. At higher fields and temperatures twisted phases arise to minimize Zeeman energy losses in the Fe layers, which increase their projected moment along the field direction, but result in increased exchange energy (non-collinearity). Most of the exchange energy cost occurs within Gd layers, which have a much weaker intralayer coupling than Fe, while the Fe/Gd coupling at interfaces, also strong, remains collinear (Fig. 6). When the multilayer is terminated with Fe the transition into a twisted state nucleates at the surfaces. The energy barrier for a twist of the Fe sublattice towards the applied field direction is decreased at the surfaces due to the absence of Fe/Gd interlayer exchange coupling at the end sides of terminal Fe layers. Our results are the first direct confirmation of this long-ago predicted surface nucleation of an inhomogeneous state.[1] In addition, our method opens a way towards distinguishing surface from bulk states in inhomogeneous magnetic systems.²