Comparison of time-resolved x-ray magnetic circular dichroism measurements in reflection and transmission for layer-specific precessional dynamics measurements

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We present experimental techniques to measure magnetization precession of individual layers in a "spin-valve" trilayer. Precessional motions of individual $Ni_{81}Fe_{19}$ and $Co_{93}Zr_7$ layers have been separated in $Ni_{81}Fe_{19}/Cu/Co_{93}Zr_7$ using ±45 ps time-resolved x-ray magnetic circular dichroism (tr-XMCD) at Fe and Co edges. We compare the efficacy of two experimental configurations in this paper. Pulsed-field tr-XMCD measurements in reflectivity are compared with resonant-field tr-XMCD measurements in transmission. Despite the order of magnitude larger angles of precession excited in pulsed-field reflectivity measurements, data quality is found to be superior in resonant-field transmission measurements. Relative roles of sample preparation and timing jitter in the different techniques are discussed.
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I. INTRODUCTION

The precessional dynamics of ferromagnetic layers in trilayer structures (FM1/NM/FM2) determines the gigahertz response in spin electronics. To date, it has not been possible to characterize the precession of buried magnetic layers directly. Soft x-ray-based techniques are appealing for this purpose due to the long penetration depths of ~1 keV photons, up to 800 nm in transition metals,[1] and the element specificity of absorption at $L_{2,3}$ edges.

Previously, we have shown that time-resolved x-ray magnetic circular dichroism (tr-XMCD) is useful to characterize *element-specific* precessional dynamics in an alloy of $Ni_{81}Fe_{19}$.[2] Coupled precession of Ni and Fe moments was verified within ±45 ps. In this work, we show the utility of this technique for measuring *layer-resolved* precessional dynamics in a $Ni_{81}Fe_{19}/Cu/Co_{93}Zr_7$ trilayer structure. Decoupled dynamics of different elemental moments, pertaining to different layers, of Ni (in FM1 = $Ni_{81}Fe_{19}$) and Co (in FM2 = $Co_{93}Zr_7$) were observed for the first time.

We compare the relative advantages of two experimental configurations for measurement. Pulsed-field, large-angle precession, analogous to pulsed inductive microwave magnetometry[3] (PIMM), was measured in reflectivity; resonant-field, small-angle precession, analogous to ferromagnetic resonance[4] (FMR), was measured in transmission. Hallmarks of decoupled precession are seen in both cases. Surprisingly, despite the much smaller cone angles excited in FMR-like time-resolved transmission measurements, we find that the quality of data measured using this technique is superior. Tr-XMCD measurements are compared with PIMM and FMR measurements on the same films. The ease of sample preparation for the transmission experiment likely contributes to the improved data quality seen here.

II. EXPERIMENT

Tr-XMCD measurements were carried out at Beamline 4-ID-C of the Advanced Photon Source (APS) in Argonne, IL. MCD spectra were obtained using helicity σ switching at the elliptical undulator. Reflected/transmitted intensity was read at a soft x-ray photodiode and normalized to an incident intensity at a reference grid. Time resolution was achieved through pump-probe techniques, where the repetition frequency of APS photon bunches is 88 MHz with rms bunch length σ_{ph}=25 ps, and a variable delay was applied between pump (rf field) and probe (APS photon bunch). $Ni_{81}Fe_{19}$ (25 nm)/Cu (20 nm)/$Co_{93}Zr_7$ (25 nm)/Cu (5 nm) thin-film samples were deposited using UHV magnetron sputtering from alloy targets at a base pressure of 4×10^{-9} Torr.

For reflectivity measurements, the experimental configuration can be found in our previous work.[2] The MCD signal was obtained in reflectivity at near grazing incidence for fixed applied field H_B. Fast transition magnetic-field pulses (<100 ps rise/fall time) were synchronized with variable delay to APS x-ray photon bunches.

The reflectivity sample was deposited on a coplanar waveguide (CPW), fabricated on GaAs, with 250 nm Cu thermally evaporated as center conductor and ground planes. 5 μm SU8 photoresist was spin coated between the film and CPW to serve as an insulating layer. In order to localize the reflected signal to the active region of the CPW, a 100 nm Ti layer was thermally evaporated on the top of the film and lifted off, leaving a patterned window 4×60 μm^2 centered

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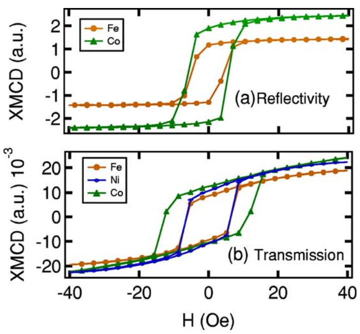

FIG. 1. (Color online) (a) Element-specific hysteresis loops measured by tr-XMCD in reflectivity. (b) Element-specific hysteresis loops measured by tr-XMCD in transmission.

along the narrowest part of the CPW center conductor. Anisotropy was induced along H_B using a 20 Oe deposition field.

For transmission measurements, the MCD signal was obtained at an incident angle of 38° from normal for fixed static applied field H_B. Due to the difficulty of fabricating a microwave CPW which is transparent to soft x rays, we have developed a different means to excite precession in transmission experiments.

The transmission sample was deposited onto a supported Si_3N_4 membrane window (1.0 mm square and 100 nm thick). This sample was placed in the center of a hollow microwave resonator.[5] Uniform precession of the magnetization was excited at 2.3 GHz by a continuous-wave low-power microwave field, synchronized with variable delay to APS x-ray photon bunches. Microwave absorption was measured *in situ* using standard lock-in techniques, detecting reflected power at the resonator.

III. RESULTS AND DISCUSSION

Calibration of the magnetization angles $\phi_{Ni_{81}Fe_{19}}$ and $\phi_{Co_{93}Zr_7}$ is shown in Fig. 1, where the saturation values of XMCD signals are taken to be ±90° for each element or layer.[2] The hysteresis loops were taken along the easy axis of the reflectivity sample while along an arbitrary direction of the transmission sample (no induced anisotropy present). Fe, Co, and Ni MCD signals at L_3 edges 707, 778, and 853 eV, respectively, are easily seen above background. The large transmission XMCD signals, consistent with our previous work,[6] are insensitive to alignment; reflectivity measurements have comparable signals but are highly sensitive to incident angle. We find that the coercivity of $Co_{93}Zr_7$ exceeds that of $Ni_{81}Fe_{19}$ in both cases, but the difference in coercivities is less pronounced for the reflectivity sample (ΔH_c=1.3 Oe compared with ΔH_c=6 Oe).

Reflectivity tr-XMCD measurements of magnetization precession for Fe and Co moments at different bias fields are presented in Fig. 2. XMCD signals were measured as a function of pump-probe delay and converted into time-dependent layer-specific magnetization angles $\phi_{Ni_{81}Fe_{19}}$ and $\phi_{Co_{93}Zr_7}$ for Fe and Co, respectively. Large rotational angles (up to ~20°) and precessional oscillations (up to ~5°) can be seen for both elements/layers. Cone angles diminish in amplitude and increase in frequency with increasing longitudinal bias $20 < H_B < 80$ Oe, as expected for pulsed measurements.[2]

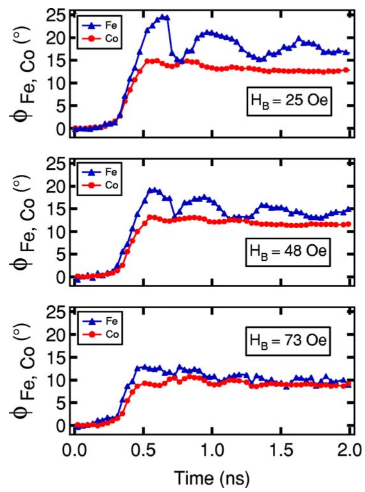

FIG. 2. (Color online) Reflectivity tr-XMCD measurements of Fe and Co magnetization angles at different bias fields.

The reflectivity tr-XMCD data (Fig. 2) have been converted into a "synthetic" PIMM signal for comparison with PIMM data, shown in Fig. 3. PIMM measures the flux change $d\Phi/dt$ through the CPW center-conductor,–ground-plane loop, scaled by a coupling constant η.[3] Tr-XMCD magnetization angles were converted to pseudo-PIMM data via the algorithm: $d\Phi/dt \propto [M_s^{Py}(d\phi_{Fe}/dt)+M_s^{Co}(d\phi_{Co}/dt)]$, using $B_s^{Py} \approx 0.9$ T and $B_s^{CoZr} \approx 1.4$ T. The obtained shape is insensitive to assumed relative variations of magnetization by 20%.

In the PIMM/tr-XMCD comparison, the amplitudes of the first and subsequent oscillations are in rough agreement, and the positions of several minima and maxima coincide. Nevertheless, fits of the data using coupled Landau-Lifshitz-Gilbert (LLG) precession models fail for tr-XMCD, whereas agreement between PIMM and simulation (not shown) is reasonable.

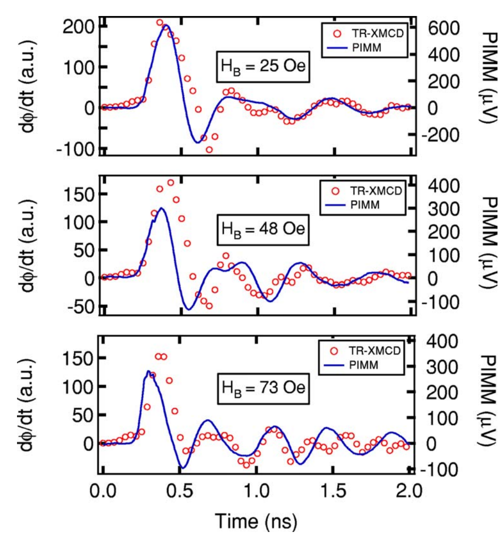

FIG. 3. (Color online) Traces of magnetization as a function of time, as determined by both reflectivity tr-XMCD and PIMM measurements. Solid lines are the PIMM data, while open circles are "synthetic" PIMM data from tr-XMCD data.

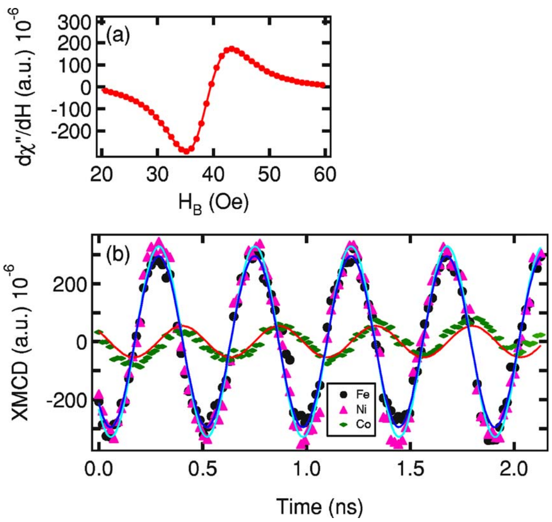

FIG. 4. (Color online) (a) In-plane FMR spectra of $Ni_{81}Fe_{19}/Cu/Co_{93}Zr_7$ measured *in situ* at 2.3 GHz. (b) Transmission tr-XMCD measurements of Fe, Ni, and Co magnetization precession at $Ni_{81}Fe_{19}$ branch resonance, 39 Oe at 2.3 GHz. Solid lines are sinusoidal fits.

Time-resolved transmission XMCD measurements of magnetization precession for $Ni_{81}Fe_{19}$ and $Co_{93}Zr_7$ are presented in Fig. 4(b). In these measurements, precession was excited using cw rf excitation at 2.3 GHz. The applied bias field H_B was matched to the FMR field H_{res} for $Ni_{81}Fe_{19}$, measured *in situ* and shown in Fig. 4(a). Transmission XMCD signals were taken as a function of delay time for Fe, Ni, and Co, respectively.

In Fig. 4(b), small-angle sinusoidal motion for both $\phi_{Ni_{81}Fe_{19}}$ and $\phi_{Co_{93}Zr_7}$ is clearly seen. Fe and Ni moments are found to precess together, as expected[2] within instrumental resolution. The motion of $\phi_{Co_{93}Zr_7}$ is $\sim 90°$ out of phase. The phase and amplitude behavior is qualitatively consistent with on- (off-) resonance excitation of FMR in uncoupled $Ni_{81}Fe_{19}(Co_{93}Zr_7)$ or the role of partial ferromagnetic coupling in a acousticlike mode; the assignment is not clear at the time of writing.

The improved performance in the FMR-like transmission measurement is rather surprising due to the smaller motions excited compared with the pulsed-field reflectivity measurement. We believe that much of the difference can be attributed to the relative ease of sample preparation for transmission. Tr-XMCD measurement in reflectivity, in our configuration, requires deposition over the CPW center conductor. We did not observe dynamics in samples where the trilayer was deposited directly onto the 250 nm Cu. The 5 μm SU8 layer, necessary perhaps to avoid current shunting through the trilayer Cu spacer, has non-negligible roughness when spun onto the CPW. We believe that this process step, necessary for our reflectivity measurements, induces inhomogeneous topological (Neel) coupling between the two FM films, causing the tr-XMCD data to deviate from single-domain behavior. For transmission measurements, in contrast, samples are deposited on a very flat Si_3N_4 supported membrane window, avoiding the difficulty of planarizing the CPW.

IV. CONCLUSION

We have compared time-resolved XMCD measurements in reflection and transmission to characterize layer-specific precessional dynamics in $Ni_{81}Fe_{19}/Cu/Co_{93}Zr_7$. Decoupled precessional dynamics was observed using both techniques.

ACKNOWLEDGMENTS

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