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Sub-micron mapping of GHz magnetic susceptibility using scanning transmission x-ray microscopy

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We report submicron imaging (~0.75 μm resolution) of complex magnetic susceptibility in a micron-size ferromagnetic heterostructure using time-resolved scanning transmission x-ray microscopy. The real and imaginary parts of the susceptibility are extracted from the phase and amplitude of the small-angle (~20') rotational response of the local magnetization under microwave excitation. Frequency-dependent response patterns were observed in an incompletely saturated bilayer element. The technique is extensible to higher frequencies (to ~10 GHz), better spatial resolution, and layer-specific measurement. © 2012 American Institute of Physics.

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High frequency (>1 GHz) magnetization dynamics of patterned magnetic heterostructures are of interest for a wide variety of applications, including high data-rate magnetic information storage, on-chip power conversion, and emerging applications in microwave signal processing. The dynamical response can be described completely by the complex, frequency-dependent susceptibility $\hat{\chi}(\omega)$, for arbitrary applied field pulses, if the magnetization response is linear. Pump-probe magneto-optical imaging techniques have been used to image $\hat{\chi}(\omega)$ in symmetric and nearly uniformly magnetized micron-size structures, with a best resolution of ~300 nm.

Soft x-ray microscopies have compelling advantages for imaging the magnetization response in device-relevant structures: superior spatial resolution (to 15 nm), relevant temporal resolution (~30 ps), and the capability to image individual magnetic layers buried ~1 μm below electrical leads. However, dynamic imaging through x-ray techniques has been limited, to date, to the characterization of gyrotropic vortex motion, behavior which generates high contrast in x-ray magnetic circular dichroism (XMCD). It has not been clear that the phase-sensitive small-angle dynamics characterized in time-resolved (TR) XMCD, from which $\hat{\chi}(\omega)$ can be inferred, could be imaged in x-ray microscopy. This would be useful to characterize the majority of devices, or device-relevant structures, which are biased close to a uniform magnetization state. Photo-electron emission microscope (PEEM) measurements have succeeded in characterizing the phase-resolved response, but only at a few discrete points, at the expense of large spatial averages (>4 μm), in a flux-closed square element.

In this paper, we show that scanning transmission x-ray microscopy (STXM) can be used to image phase-sensitive small-angle dynamics with submicron resolution. We have imaged the susceptibility $\hat{\chi}(\omega)$ at frequencies of 0.5–4 GHz in an incompletely saturated 7.5 μm × 30 μm elliptical CoZrTa(15 nm)/nonmagnetic (NM)(5 nm)/CoZrTa(15 nm) bilayer element, with a sensitivity of ~10° at a spatial resolution of 0.75 μm. The phase and amplitude of the response are consistent with diversity of local resonance fields, but with a greater fraction being in resonance near 2 GHz. The technique, which is extensible to much finer spatial resolution, will enable imaging of susceptibility in submicron structures, making it possible to characterize layer-resolved magnetic eigenmodes in individual nanometer-scale structures.

A ferromagnetic (FM)/NM/FM sandwich structure, Ta(3 nm)/Co91Zr5Ta4.5(15 nm)/SiO2(2 nm)/Ta(3 nm)/Co91Zr5Ta4.5(15 nm)/SiO2(10 nm), was sputtered on a 200 nm Si3N4 membrane, and patterned into 7.5 μm × 30 μm elliptical elements with photolithography and lift-off process. The bottom 3 nm Ta layer is a seed layer to improve adhesion and homogeneity of the film. The top SiO2 layer protects the metallic film from oxidation. The SiO2(2 nm)/Ta(3 nm) bilayer in the middle serves as a 5 nm NM spacer layer. The FM layers Co91Zr5Ta4.5(15 nm) were dc magnetron sputtered at optimized conditions to achieve soft magnetic properties (coercive field $H_c < 1$ Oe), with power 250 W, Ar pressure 1.2 mTorr, and deposition rate 3.8 Å/s. An external magnetic field of 50 Oe was applied along the long axis of the elliptical element during deposition. The induced anisotropy field $H_K$ was measured to be 20 Oe in unpatterned films. For further details on the deposition system, see Ref. 18.

We carried out the STXM measurements at the Canadian Light Source (CLS), soft x-ray spectromicroscopy beamline 10ID-1 (SM, minimum x-ray spot size 30 nm), with x-ray photon energy set to the Co L2 edge at 779 eV for maximal XMCD signal. To enhance the final contrast, we take two images under the same conditions, with x-rays of left- and right-circular polarization (CL and CR), respectively, subtract the two images(CR-CL) and convert the difference into optical density (OD),

$$OD = \log_{10}(I_0/I_1),$$

where $I_0$ is the intensity of the incident x-ray before passing through the thin-film stack, and $I_1$ is the intensity of the transmitted x-ray. We took the average of the difference image (CR-CL) contrast over a large area on the bare membrane as $I_0$. 

10 GHz), better spatial resolution, and layer-specific measurement. © 2012 American Institute of Physics.
For time-resolved measurements, we implemented the same “pump-and-probe” methodology for TR-XMCD experiments as described in Ref. 15. The x-ray bunch length is 35 ps and the bunch frequency is 500 MHz. The bunch clock signal is sent through a comb generator and then filtered to give a desired harmonic of 0.5 GHz, providing the rf excitation signal. For frequencies of 0.5 GHz, 2 GHz, and 4 GHz, we kept the input rf power to the CPW constant at 1 W (+30 dBm) by adjusting the attenuators in the rf circuit and confirming the power value using an rf power meter, measured at the input to the STXM chamber. The delay line defines the relative position of the “probe” versus the “pump,” and we chose the sampling rate to be 25 points per period for all three frequencies. For each image in the time series, we take an averaging window of 5 × 5 pixels (0.75 μm × 0.75 μm square), scan it over the 227 × 100 pixels (34 μm × 15 μm) image area at 1-pixel step. At each step, the averaged contrast over the window area is plotted against the delay time and fitted with a sinusoidal function, yielding both the amplitude of the local magnetization change as well as its phase compared with the driving rf signal. The offset from zero of the sinusoidal function refers to the local static contrast, as observed in the biased element in Fig. 1(b). Fig. 1(c) demonstrates the contrast as a function of time over the period (500 ps) of the 2 GHz excitation, in representative areas in the biased element. While the domain configuration displays no obvious shift, contrast plotted here in areas A, B, and C shows clear oscillatory behavior with different amplitudes, phases, and offsets. The background area BG sits on the bare Si3N4 membrane and shows close to zero optical density and no sinusoidal variation. We performed this analysis for the element under 0.5, 2, and 4 GHz excitations. Even though the excitation power is fixed, the element responds with larger oscillation amplitude at 2 GHz, while at 4 GHz (not shown) the response is considerably weaker and shows much more variance in the fitted parameter.

Next, we describe our method for extracting precessional amplitude of the incompletely saturated element. Assuming the magnetization lies in-plane (x’y’-plane) and no domain wall propagation takes place under the excitation, we interpret the dynamic response of the biased element as rotation of the local magnetization. We extracted the precessional amplitude of in-plane magnetization rotation ϕ from the fitted functions as illustrated in Fig. 2(a). At each location, the normalized magnetization \( \mathbf{m} \) forms an angle \( \theta \) with the \( x' \)-axis. The observed static magnetization contrast is proportional to the projection of \( \mathbf{m} \) onto the \( x' \)-axis, \cos \theta. This is also the offset of the fitted sine wave. The maximum contrast occurring in the elements corresponds to \( \mathbf{m} \) parallel with the \( x' \)-axis. Under rf excitation, \( \mathbf{m} \) oscillates at an angle \( \varphi \). In the small-angle limit of precession, the full range of precessional motion \( \text{arc} l \), equal to \( \varphi \) in value, projects onto the \( x' \)-axis as \( \Delta = l \sin \theta \). The observed low-amplitude change in local contrast is thus related to the rotation angle \( \varphi \) as shown in the right panel of Fig. 2(a).

The diagram of the experimental setup is shown in Fig. 1(a). The sample was mounted on a custom-designed coplanar waveguide (CPW), with a hole (100 μm diameter) in the center conductor allowing for x-ray transmission in the z-direction. The long axis of the elliptical element is arranged parallel with the center conductor, in the y-axis. The sample plane is tilted 30° away from the x-axis to visualize the in-plane magnetization. In order to obtain a domain configuration other than the flux-closed remanence state and avoid the stochastic motion of domain walls under excitation,20 a static magnetic field of approximately 20 Oe was applied horizontally with a homemade electromagnet, with copper wire wound round an iron nail to fit into the compact vacuum chamber. The tip of the nail was positioned as close to the sample as possible, providing a concentrated magnetic flux over the element under investigation. Fig. 1(b) compares the domain structure of the element at the demagnetized state and after the external dc field was applied.
resonance. At 0.5 GHz, these areas concentrate at the domain edges while at 2 GHz the major area within the domains gives larger rotation angles. It is likely that at those locations where the magnetization sees a more abrupt change, the local exchange field acts against the bias field, leading to a smaller effective field and thus lower resonant frequency. We eliminated the analysis for 4 GHz, since the observed response was very small and noisy, as expected for driving frequencies above resonance.

Finally, we demonstrate the mapping of local susceptibility (real part and imaginary part)

$$\chi(\omega) = \frac{M e^{i(\omega t - \delta)}}{H_0 e^{i(\omega t)}} = \frac{M}{H_0} \cos \delta - j \frac{M}{H_0} \sin \delta = \chi' - j \chi''$$

at 0.5 GHz and 2 GHz in Fig. 3, derived from the amplitude and phase $\delta$ of the sine fit. The saturation magnetization of Co$_{91.5}$Zr$_{4.0}$Ta$_{4.5}$ film is 17 kG, measured by ferromagnetic resonance (FMR), which corresponds to the optical density contrast of 11 in the element. The amplitude of the sine fit at each pixel is therefore converted to $\Delta M$. The rf magnetic field amplitude on the CPW (400 $\mu$m center conductor width, 50 $\Omega$ impedance, +30 dBm rf power) is estimated to be 1.24 Oe. In the comparison between susceptibility maps $\chi(\omega)$ at $\omega = 0.5$ and 2 GHz, we see that the higher frequency map is closer to the FMR condition, with a large and mostly imaginary susceptibility.

We have demonstrated submicron (<0.75 $\mu$m) imaging of complex GHz susceptibility $\tilde{\chi}(\omega)$, accessing small-to-medium-angle (~10°) magnetization dynamics, using scanning transmission x-ray microscopy. The technique is extensible to finer spatial resolution in submicron structures and layer-specific imaging in compositionally distinct layers, without expected reduction in contrast, and is compatible with lock-in techniques to enhance contrast. We expect that the technique will enable, for example, the study of eigenmodes in submicron device structures, possible to date only for micron-size elements.

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FIG. 2. (a) Sample plane $x'y'$: illustration of converting contrast variation ($\Delta$) to magnetization rotation angle ($\alpha$); (b) magnetization rotation angle and phase in the element under 0.5 GHz and 2 GHz excitations; the two phase maps in the lower panel share the same scale bar.

FIG. 3. Real and imaginary parts of the complex susceptibility, 0.5 GHz and 2 GHz.


17See supplementary material at \texttt{http://dx.doi.org/10.1063/1.4765663} for realtime illustrations for both 0.5 GHz and 2 GHz.