X-Ray Imaging of Magnetic Normal Modes Driven by Spin Transfer Torque in Magnetic Nanopillar Devices

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Abstract:
We have fabricated CoFe/Cu/NiFe magnetic nanopillars with $100 \times 250 \text{ nm}^2$ elliptical cross section on top of a suspended silicon nitride membrane, designed for performing x-ray transmission microscopy of magnetic dynamics. We are now studying these devices to image the magnetic normal modes that can be excited by the spin transfer torque from a microwave-frequency current passing through the pillar.

Summary of Research:
A spin-polarized current passing through a ferromagnet can exert a torque on the ferromagnet that is strong enough to either reverse its magnetization or excite steady-state high-frequency (1-20 GHz) magnetization precession, depending on the device structure and applied magnetic field [1]. This spin-torque effect is under intensive study both because of its fundamental importance and because of its potential applications in magnetic random access memory (MRAM) and high speed signal processing. One of the critical outstanding issues in this field is the nature of the magnetization dynamics excited by the spin torque. Direct imaging [2,3] of the spatial and temporal dependence of the magnetic dynamic modes with high resolution x-ray transmission microscopy can offer unique understanding of this effect and would be a major advance in this field. X-ray transmission microscopy can selectively image a ferromagnetic element via x-ray magnetic circular dichroism (XMCD), by which the transmission of x-ray photons through a ferromagnetic material depends on the polarization of the photons and the magnetization direction of the ferromagnetic element.

![Device schematic: nanopillar device on top of a suspended silicon nitride membrane.](image1)

![Spin-transfer-driven ferromagnetic resonance spectra of one device.](image2)
We start with a Si substrate coated with 150 nm low stress (film tension < 200 MPa) SiN films on both sides, one of which will be made into suspended membrane to allow for x-ray transmission microscopy (Figure 1).

We deposit the metallic multilayers of the structure (in nm): \( \{ \text{Ta} 3 / \text{CuN} 20 \} _2 / \text{Ta} 3 / \text{Py} 40 / \text{Cu} 6 / \text{Co}_{80}\text{Fe}_{10} 15 / \text{Cu} 4 / \text{Ru} 4 \) (where Py is the magnetic alloy permalloy, \( \text{Ni}_{81}\text{Fe}_{19} \)) in a sputtering system. E-beam lithography and ion milling are then used to define pillars with elliptical cross section of 100 × 250 nm² (Figure 2). Multiple steps of photolithography and ion milling are used to make the contact leads, and silicon oxide is deposited by electron-beam evaporation to provide electrical isolation between top and bottom leads. To form the suspended nitride membrane, the Si substrate is etched anisotropically in heated KOH solution, using photolithographically-patterned silicon nitride on the back side of the substrate as the etch mask.

The XMCD experiments are carried out at the full-field soft x-ray transmission microscope (XM-1) and the scanning transmission x-ray microscope (STXM) at the Advanced Light Source of Lawrence Berkeley National Laboratory. Both microscopes have a spatial resolution of 15 nm and temporal resolution of 70 ps. The x-ray is incident at 30° from the normal direction of the device plane (Figure 1), and its energy is tuned to the characteristic Co \( L_3 \) resonance absorption edge. These experiment conditions allow detection of the in-plane component of the magnetization of the 15 nm thin CoFe layer in the nanopillar. A magnetic field is applied in the device plane along the short axis of the ellipse.

Figure 2 shows the electrical characterization of the spin-transfer-driven ferromagnetic resonance [4] spectrum of one sample as a function of microwave current frequency, \( f \), and magnetic field, \( H \). For x-ray studies, we excite the sample into a particular resonance mode with appropriate values of \( f \) and \( H \) (for example, point A around 2.5 GHz in Figure 2), and use x-ray microscope to image the spatial configuration of the magnetization at 8 different phases (phase 1 to 8) evenly spaced throughout one oscillation cycle. Magnetic contrast images are shown in Figure 3. Figure 3a (b, c, d) corresponds to the contrast between phase 1 (2, 3, 4) and phase 5 (6, 7, 8).

The contrast images show that the magnetic precession is not uniform within the nanopillar -- the lower edge precesses at a different phase and amplitude than the center of the device. We are currently working on imaging the resonance modes at higher frequencies and comparing with micromagnetic simulations to understand the mode structure in these 15 nm CoFe devices. We are also planning to investigate samples with thinner (5 nm) magnetic layer in which the results can be directly compared to previous electrical studies of spin-transfer-driven magnetic dynamics.

References: