Nanoscale Magnetization and Current Imaging using Time-Resolved Scanning-Probe Magneto-Thermal Microscopy

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Primary CNF Tools Used: JEOL 9500, GCA 5x stepper

Abstract:

High resolution, time-resolved magnetic microscopy is crucial for understanding novel magnetic phenomenon such as skyrmions, spin waves, and domain walls. Currently, achieving 10-100 nanometer spatial resolution with 10-100 picosecond temporal resolution is beyond the reach of table-top techniques. We have developed a time-resolved near-field magnetic microscope-based on magneto-thermal interaction, which achieved a spatial resolution on the scale of 100 nm and a temporal resolution below 100 ps. Our results suggest a new approach to nanoscale spatiotemporal magnetic microscopy in an accessible, table-top form to aid in the development of high-speed magnetic devices.

Summary of Research:

Our group has previously developed time-resolved magneto-thermal microscopy for magnetic imaging [1-3]. We apply a pulsed laser to create thermal gradient ∇T. The local magnetization M subjected to ∇T generates an electric field E_{ANE} through the anomalous Nernst effect [Figure 1]. This technique can be used to image both local static and dynamic magnetization, as well as an applied current density [4]. In this work, we extend magneto-thermal microscopy to nanoscale resolution with near-field light. We use a gold-coated cantilever glued on tuning fork as our probe, controlled by atomic force microscopy. We shine a laser on the tip apex, and the near-field enhancement of the electric field at the tip [5-6] heats the sample as a nanoscale heat source [Figure 1]. The heating length scale is comparable to the tip radius, below 100 nm.

We first study a 5 μm × 15 μm CoFeB/Hf/Pt sample fabricated using photolithography with the GCA 5× stepper. We demonstrate magnetic imaging of near-field scanning probe with a multi-domain state. Figure 2(a) shows a far-field image taken using a focused light to confirm the magnetic state. Figures 2(b-d) show topography, far-field and near-field images, acquired simultaneously with the scanning probe. The near-field image resembles the far-field image, but with higher resolution. We note that the smallest feature of the near-field image is ~ 455 nm in this sample, which is below the optical diffraction limit of the set-up. That feature is likely the actual domain wall width rather than being limited by the instrument resolution.

To probe instrument resolution further, we measure in current imaging mode and use a new sample designed with a sharp current density feature. The sample is a thin-film heterostructure composed of 5 nm $Ni_{81}Fe_{19}$/2 nm Ru, then patterned into a 2 μm-diameter disk with two 150 nm necks using JEOL 9500 e-beam lithography. Figure 3 shows topography and near-field current density images taken with the near-field scanning probe. By taking linecuts through two necks, as shown in Figure3(a) inset, we compare signals between focused light far-field and scanning probe near-field microscopy. The scanning near-field image has higher resolution than the far-field image, and by fitting to a model, we demonstrate a spatial resolution on the scale of 100 nm. We note that the resolution here is only an upper bound. We expect a resolution of 50 nm using magneto-thermal microscopy with sharp, high-endurance tips.

We now turn our attention to characterizing the temporal resolution of our instrument. In the measurements, we electrically mix the voltage pulses generated from the sample with reference voltage pulses that are synchronized with the laser but have a controllable delay τ. Figure 4(a) and (b) show the mixed output signal as a function of the delay τ, which can be understood as the temporal convolution signal of the two pulses. The convolved signal widths are roughly 100 ps, similar to the reference pulse width. Therefore, the voltage pulses generated by the near-field thermal excitations must be shorter than 100 ps, demonstrating a time-resolved nano-probe. The picosecond temporal

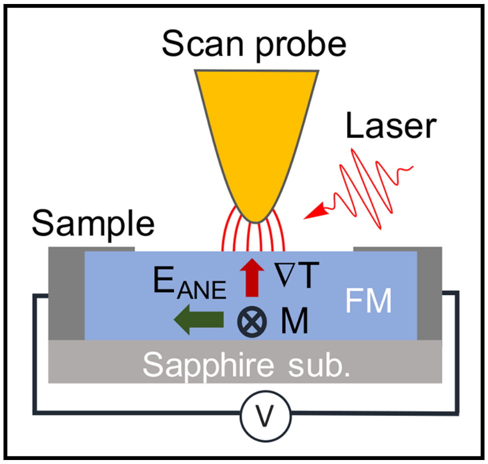

Figure 1: Schematic of scanning near-field magneto-thermal microscopy setup, illustrating laser, sample, scan probe, and near-field interaction.

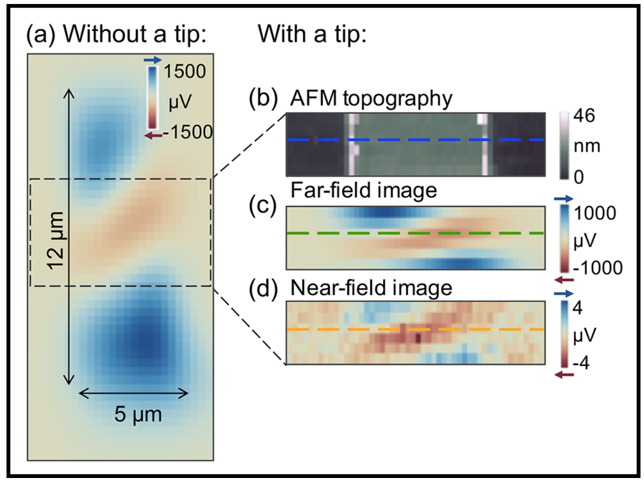

Figure 2: Magnetic multi-domain imaging. (a) Magnetic far-field images of a multi-domain state. With a scanning probe tip, (b) topography, (c) far-field and (d) near-field images acquired simultaneously.

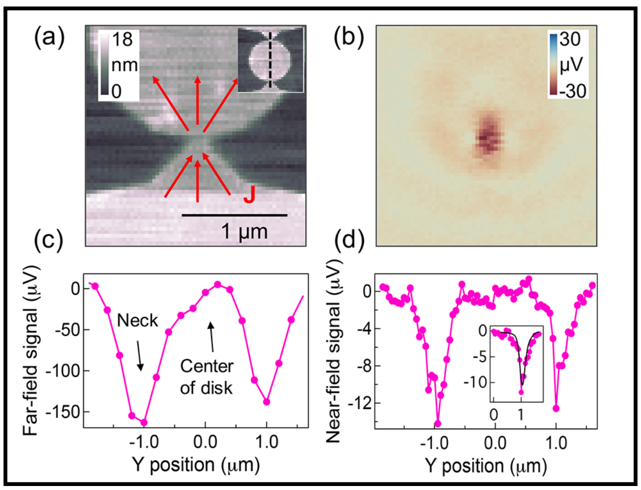

Figure 3: Current imaging and spatial resolution. (a) Topography and (b) current density images. Line cuts of (c) far-field and (d) near-field signals for resolution comparison. (d) The inset shows the simulated fit to the data.

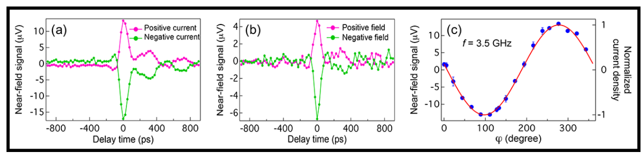

Figure 4: Time-domain measurements of the near-field voltage pulses produced by (a) current density and (b) magnetization as a function of the pulse delay τ. (c) Stroboscopic measurements of microwave current as a function of phase ψ.

resolution enables us to probe a stroboscopic section of the gigahertz frequency cycle. We demonstrate the stroboscopic capability of the scanning probe by measuring a 3.5 GHz microwave current at the nano-constriction. We phase-lock the laser and microwave current such that the thermal pulses constantly probe the current at the same phase ψ. Figure 4(c) shows normalized microwave current density as a function of ψ, showing the phase-sensitive response.

Conclusions and Future Steps:

We have developed a time-resolved scanning near-field magneto-thermal microscopy for magnetic and current imaging. We demonstrated 100 nm scale spatial resolution and picosecond temporal resolution. Next step, we will apply this instrument to study the dynamics of nanoscale spin textures, e.g. magnetic skyrmions.

This work is published in Nano Letters in Ref. [7].

References:

[1] J. M. Bartell, D.H. Ngai, et al., Nat. Commun. 6, 8460 (2015).
[2] J. M. Bartell, et al., Phys. Rev. Appl. 7, 044004 (2017).
[3] I. Gray, et al., Phys. Rev. Mater. 3, 124407 (2019).
[4] F. Guo, et al., Phys. Rev. Appl. 4, 044004 (2015).
[5] J. C. Karsch, et al., APL Photonics 2, 086103 (2017).
[6] L. Meng, et al., Optics Express, 11, 13804, (2015).
[7] C. Zhang, et al., Nano Lett. 21, 4966 (2021).