# Local Photothermal Control of Phase Transitions for On-Demand Room-Temperature Rewritable Magnetic Patterning

**CNF Project Number: 2091-11**

**Principal Investigator(s): Gregory D. Fuchs[1], Darrell G. Schlom[2]**

**User(s): Isaiah Gray[1]**

*Affiliation(s): 1. School of Applied and Engineering Physics, 2. Materials Science and Engineering; Cornell University*

*Primary Source(s) of Research Funding: Cornell Center for Materials Research from the National Science Foundation MRSEC Program, Grant No. DMR-1719875*

*Contact: gdf9@cornell.edu, ig246@cornell.edu*

*Primary CNF Tools Used: GCA 5x stepper*

**Abstract:**

**The ability to make controlled patterns of magnetic structures within a nonmagnetic background provides the foundation of magnetic memory and logic devices, allows the creation of artificial spin-ice lattices, and enables the study of magnon propagation. Here, we report a novel approach for magnetic patterning that allows repeated creation and erasure of arbitrary shapes of thin-film ferromagnetic structures. This strategy is enabled by epitaxial $Fe_{0.52}Rh_{0.48}$ thin films designed so that both ferromagnetic and antiferromagnetic phases are stable at room temperature. Starting with the film in a uniform antiferromagnetic state, we demonstrate the ability to write arbitrary patterns of the ferromagnetic phase with submicron spatial resolution by local heating with a focused pulsed laser. The ferromagnetic patterns can be erased by cooling below room temperature and the material repeatedly re-patterned.**

## Summary of Research:

Local patterning of ferromagnetic regions forms the basis of magnetic logic and memory devices [1] as well as spin-wave devices such as magnon waveguides [2] and magnonic crystals [3]. Magnetic nanostructures are typically patterned with lithography and etching, which cannot be easily erased and repatterned. In this work [4] we present a platform for rewritable magnetic patterning, which is based on the 1st-order phase transition from antiferromagnet (AF) to ferromagnet (FM) in near 50/50 stoichiometric iron-rhodium (FeRh) [5].

Epitaxial FeRh films are grown on MgO(001) via molecular-beam epitaxy. Lower Rh concentration decreases the transition temperature $T_C$ [6]; we therefore tune the stoichiometry to $Fe_{0.52}Rh_{0.48}$ during growth, which sets $T_C \approx 430$ K such that both AF and FM phases are stable at room temperature.

In Figure 1 we show radial plots of magnetization $M$ as a function of magnetic field $H$ (clockwise) and temperature $T$ (radial). We plot $M(H,T)$ in both the cooling branch (Figure 1(a)) and the heating branch (1(b)) of the transition, which highlights the dissimilar $T_C$ in heating (AF to FM) and cooling (FM to AF).

Plots of $M(T)$ and resistance $R(T)$ at constant field in Figure 1(c) and 1(d) show that both AF and FM phases are stable at 293 K.

Having established room-temperature phase bistability, we pattern local FM regions using a laser focused to ~ 650 nm spot size at 10.8 mJ/cm$^2$ fluence, which locally heats the FeRh by 90K. This temperature increase induces the FM phase, which remains after the laser is turned off. We image the resulting patterns with the same laser at low (0.6 mJ/cm$^2$) fluence, using anomalous Nernst microscopy [7].

In this technique, the focused laser generates a local thermal gradient $\nabla T$, which induces an electric field $\boldsymbol{E}_{ANE}$ proportional to the moment: $\boldsymbol{E}_{ANE} = -N\mu_0 \nabla T \times \boldsymbol{M}$.

We raster scan the laser and measure the $\boldsymbol{E}_{ANE}$-induced voltage drop across the entire sample, which builds up a map of in-plane $\boldsymbol{M}$. By using low fluence, we image magnetic contrast without perturbing it.

Two examples of patterning and imaging are shown in Figure 2. In Figure 2(a) we show three anomalous Nernst effect (ANE) images at room temperature: one in the uniform AF phase before patterning, one after laser-writing FM patterns spelling out the authors' affiliation, and one after cooling the film below room temperature and warming back to room temperature. To subtract out artifacts from varying thermal conductivity and isolate the magnetic signal, each image presented is the

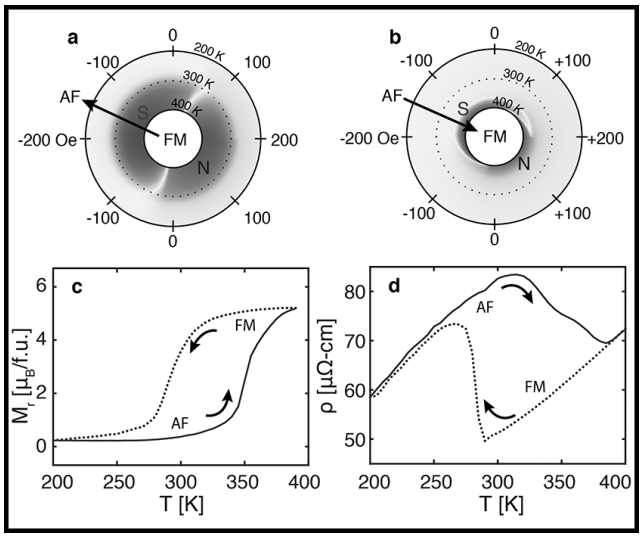


*Figure 1: (a,b) Magnetization* M *as a function of temperature* T *and magnetic field* H *in epitaxial* $Fe_{0.52}Rh_{0.48}$ *grown on MgO(001). The phase transition is observed in (a) the cooling branch and (b) the heating branch, showing the dissimilar transition temperatures between antiferromagnet to ferromagnet and vice versa. (c)* M*(*T*) and* R*(*T*) at fixed field show that both AF and FM phases are stable at room temperature.*

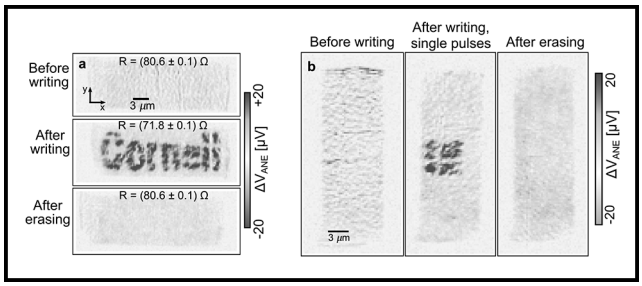


*Figure 2: Laser-writing ferromagnetic regions within an antiferromagnetic background and imaging the written regions using anomalous Nernst microscopy. (a) Imaging at room temperature in the AF phase, after laser-writing, and after erasing by cooling and warming back to room temperature. (b) Demonstrating ultrafast patterning by imaging a 5 μm square written using a single 3 ps laser pulse per pixel. (See pages vi-vii for full color version.)*

half-difference between raw ANE images acquired at 1 kOe magnetic field applied along opposite directions. Light red contrast represents uncompensated moments in the AF phase [8], while dark red represents FM moments. The images show that ferromagnetic regions can be patterned with submicron resolution, and that they are erased by cooling the sample below room temperature. Finally, in Figure 2(b) we demonstrate ultrafast magnetic patterning by writing a 5 × 5 μm square using a single 3 ps-wide laser pulse per pixel.

In summary, we demonstrate a platform for room-temperature rewritable magnetic patterning in bistable FeRh. Laser-written FM regions can be erased by cooling, and the film can be erased and rewritten many times with no measurable damage to the crystal structure. Our results could enable rapid prototyping of a variety of magnetic devices, including magnonic crystals and logic devices.

## References:


[1] S. N. Piramanayagam, T. C. Chong, Developments in Data Storage: Materials Perspective, Wiley, 2011.

[2] A. V. Chumak, et al., Nat. Phys. 11, 453 (2015).

[3] B. Lenk, H. Ulrichs, F. Garbs, and M. Müzenberg, Phys. Rep. 507, 107-136 (2011).

[4] A. B. Mei*, I. Gray*, et al., Adv. Mater. (accepted), arXiv:1906.07239 (2019).

[5] J. B. McKinnon, D. Melville, and E. W. Lee, J. Phys. C 3, S46 (1970).

[6] A. B. Mei, et al., Appl. Phys. Lett. 113, 082403 (2018).

[7] J. M. Bartell*, D. H. Ngai*, et al., Nat. Comm. 6, 8460 (2015).

[8] I. Gray, et al., Phys. Rev. Mater. 3, 124407 (2019).