In-situ Microscopy Using Electromagnetic Field and Light as the Stimuli

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In-situ electron microscopy has gained a lot of attention in recent years. It provides a "live" view of materials or devices under study at various length scales. For example, by applying electric and magnetic fields on a ferroelectric and magnetic architecture under operation, one can directly observe how electric and magnetic domains switch and how anions/cations shift their positions and how spins change their configuration across a domain wall. In the study of photovoltaic, in-situ capabilities allow us to directly correlate light induced electric currents with local structural inhomogeneity and dynamics of p-n junctions and to improve their optoelectronic efficiency.

In this presentation we report our systematic study of magnetic reversal of permalloy islands in an square spin-ice geometry. In spin-ice the magnetic moments within a lattice obey "ice" rules analogous to the ice rule for solid water. It is a model system to investigate frustration, correlation, and shot/long range order-disorder process and has opened a new field of physics. Using in-situ Lorentz phase microscopy and electron holography we reveal the magnetic reversal process including nucleation, propagation, annihilation, and avalanche of magnetic charges, or emergent monopoles and the presence of flux channels similar to Dirac strings between the magnetic charge monopoles during the reversal (Fig.1). Real space imaging and statistical analyses suggest that positively and negatively charged monopoles always move together, connected by a common flux channel. The interaction between monopoles and flux channels is determined by local frustration and can explain monopole populations and various states of ordering. We also report our development of the Multimodal Optical Nanoprobe (MON, Fig.2), a TEM sample stage that enables simultaneous measurement of optical, optoelectronic, electric transport, mechanical and structural properties of samples inside any S/TEM without compromising the microscope's performance. It provides the only means currently available for the simultaneous in-situ correlation of optical, spectroscopic, electronic and structural properties of complex materials and devices at length scales ranging from hundreds of micrometers to angstroms. Of particular technological importance is the ability to investigate the site- or location-specific properties of engineered material interfaces such as the p-n junctions for photovoltaic applications. The development of the MON was recognized by the 2011 R&D 100 Award and the 2011 Innovation Award [1] and was recently awarded a US patent [2]. Applications using this system will be demonstrated [3].

References

[1] Y. Zhu, M. Milas, J.D. Rameau and M. Sfeir, and A. Danilov, 2011R&D100 Award (R&D Magazine), Multimodal Optical Nanoprobe for advanced electron microscopy", Innovation Award, Microscopy Today, Microscopy Society of America, 2011.
[2] M. Milas, Y. Zhu, and J.D. Rameau, "A Transmission Electron Microscope Sample Holder with Combined Piezo Controlled Electric Biasing and Optical Lighting Capabilities", U.S. Patent Application Publication, US-2010-0102248A1. The patent was awarded in April 2012.
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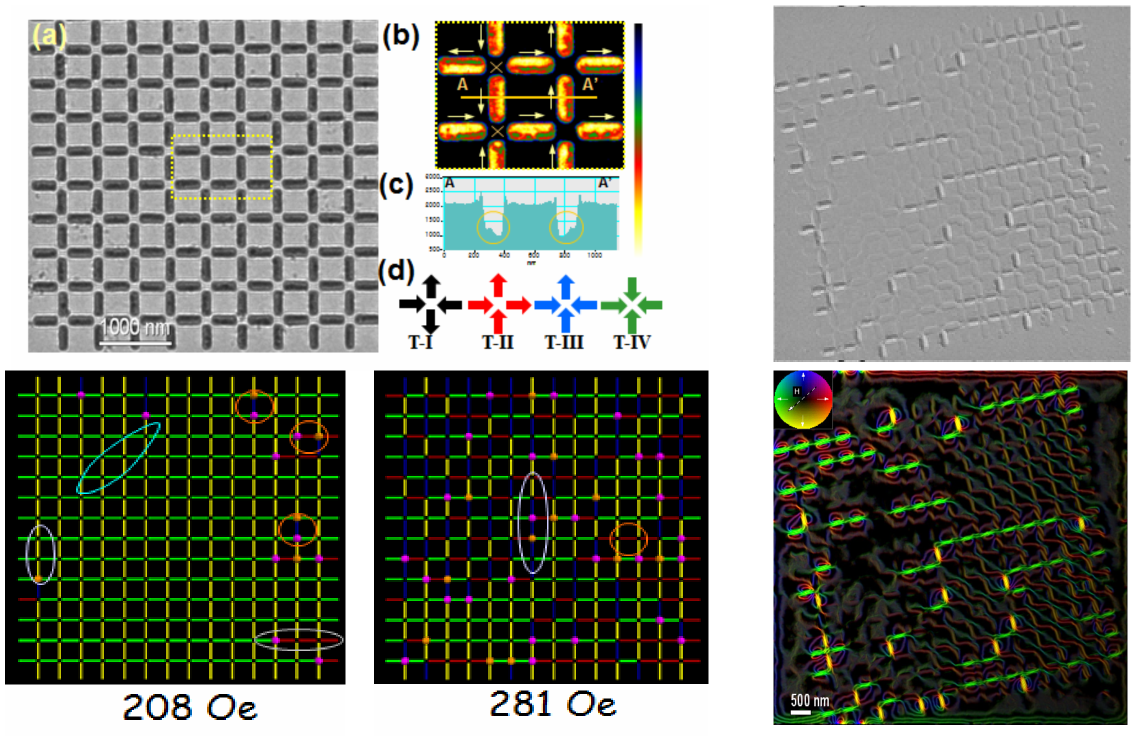

Fig.1 (a) The 420-permalloy-element artificial square spin-ice-array. (b-c) Color coded magnetic contrast with a line-scan profile. (d) The four possible topological vertex types of the system. Bottom left panels: experimental snapshots under two different magnetizations along the [11] direction. Right panels: difference intensity map (top) and phase contour map (bottom) of two Lorentz images showing the switching behavior.

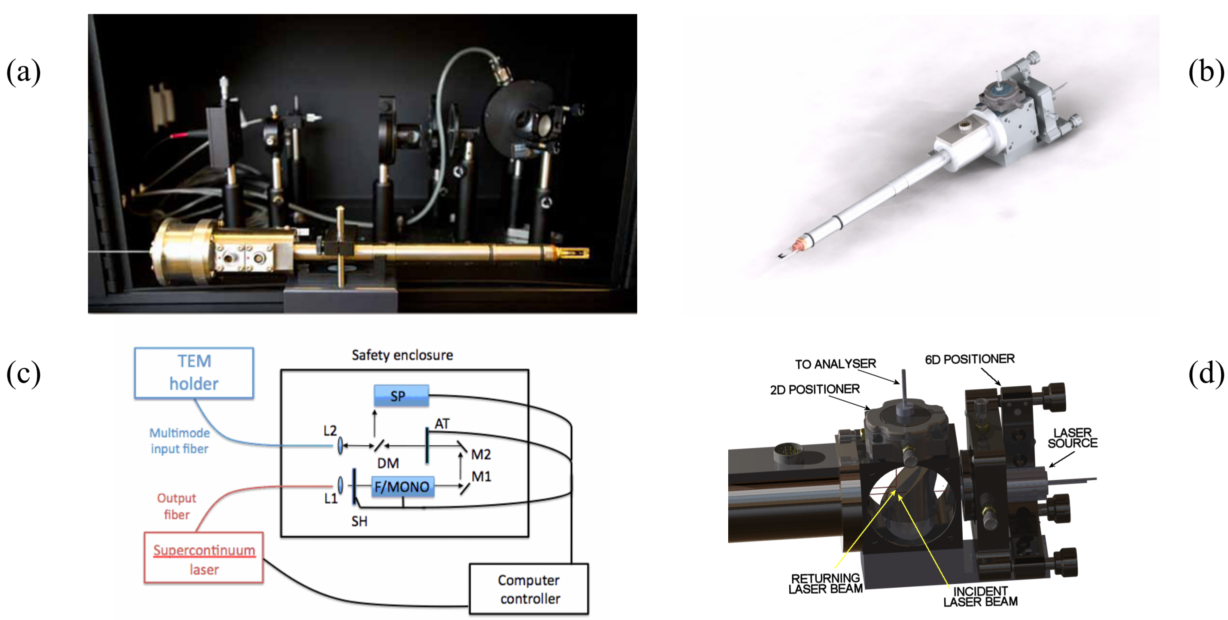

Fig. 2 (a) The Multimodal Optical Nanoprobe (MON) system for photon excitation, electric biasing, and optical spectroscopy in TEM. Its associated laser unit is shown in the background. (b) The MON with the external aligner. (c) The laser unit designed for various optical and spectroscopy modes. L1 and L2 are lenses, SH is a shutter, F/MONO is the filter/monochromator system to select bands or single wavelengths, M1 and M2 are steering mirrors, AT is a variable attenuator, DM is a dichroic mirror to separate the excitation and emission beams, SP is a compact spectrometer. (d) Open view of the external optical alignment module (see ref [2] for details).