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Direct Observation of Nanoscale Magnetization Reversal and Spin Dynamics using in-situ Lorentz Microscopy and Electron Holography

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In the forefront of spintronics research, transmission electron microscopy (TEM) is not only an essential tool for examining matter with high spatial resolution, but also associated with it is a rich variety of *in-situ* capabilities making quantitative investigation of the intriguing microscopic physical phenomena possible. This presentation covers TEM study of the controlled magnetization reversal and high frequency spin dynamics of patterned nanomagnets, which hold great promise for the development of next generation recording/memory technologies.

We first focus on the *in situ* studies of controlled magnetization reversal processes in a novel class of artificial nanomagnets: shape-engineered ferromagnetic/nonmagnetic/ferromagnetic trilayers. Using quantitative off-axis electron holography and associated phase retrieval algorithm, we were able to circumvent the projection problem in TEM, and identify in detail the sharply distinct reversal mechanisms within three different structures (asymmetric rings [1], ellipses [2], and combined disk-square elements [3]) in a layer-resolved fashion. The experimental observations are in good agreement with micromagnetic simulations using Landau-Lifshitz-Gilbert (LLG) Equation. From this, we systematically developed field-application recipes to produce different remanent magnetoresistive states, which can be directly employed as four fundamental states of magnetic building blocks [Fig. 1].

We then further explore the vortex core dynamics in high frequency regime, where spin angular momentum transfer between current and magnetization represents a radically new data-writing concept [4]. Here, by incorporating coaxial cable and coplanar wave guide, we designed and constructed a novel TEM stage to apply high frequency excitation stimulus to the magnetic nanosquare, and directly observed the current-excited resonant precession of vortex core with unprecedented spatial resolution [Fig. 2]. We systematically measured the shape and size of the precession orbits as a function of both frequency and current density, and fitted the experimental results with theoretical models based on LLG equation incorporated with the adiabatic spin-torque term. By doing this, we were able to quantify important physical parameters intrinsic to the underlying spin torque transfer process, such as damping coefficient and spin polarization ratio. For the first time, we have experimental proof that the vortex precession orbit is actually elliptical when it's off-resonance, with nm resolution [5].

References

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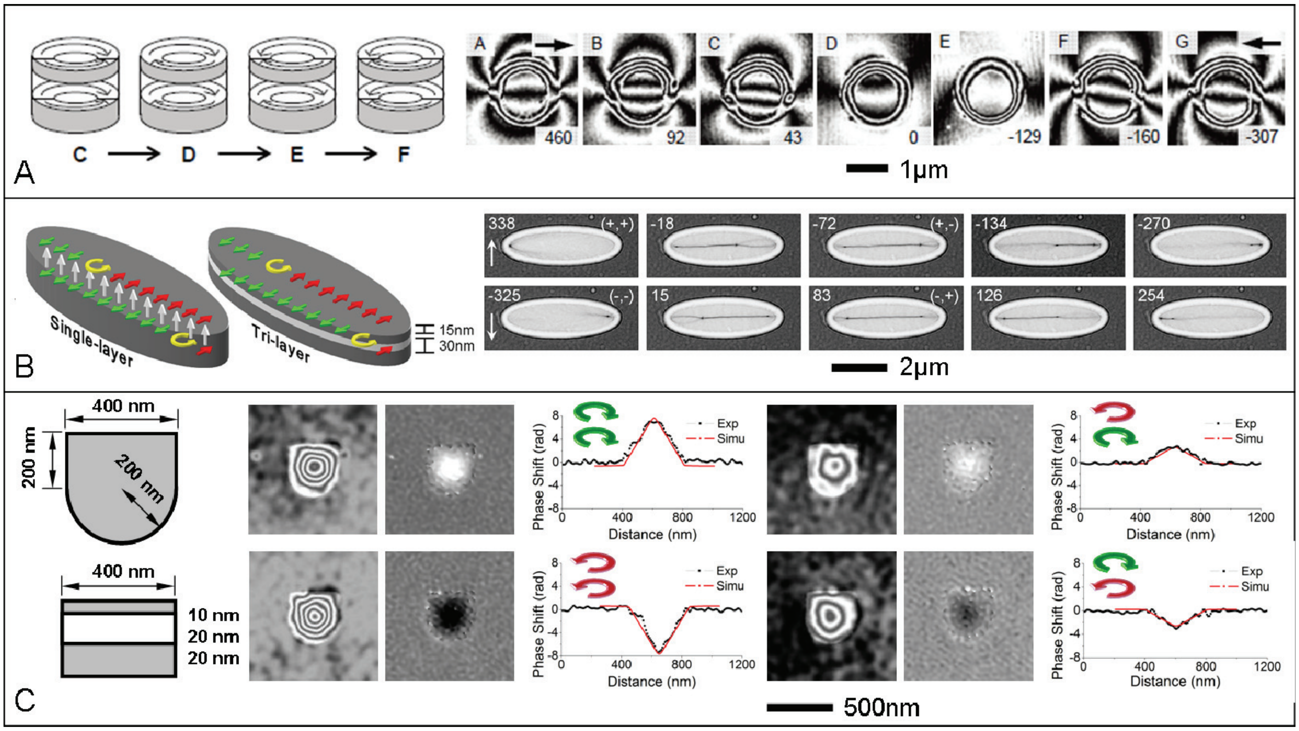

FIG. 1. (A) Holography phase contours of the magnetization reversal of an asymmetric ring trilayer element. (B) Lorentz images of the controlled reversal of coupled Neel walls inside a trilayer elliptical element. (C) Holography phase contours, phase images and phase line-scan profile of the four different types of double-vortex states achieved in a combined square-disk trilayer.

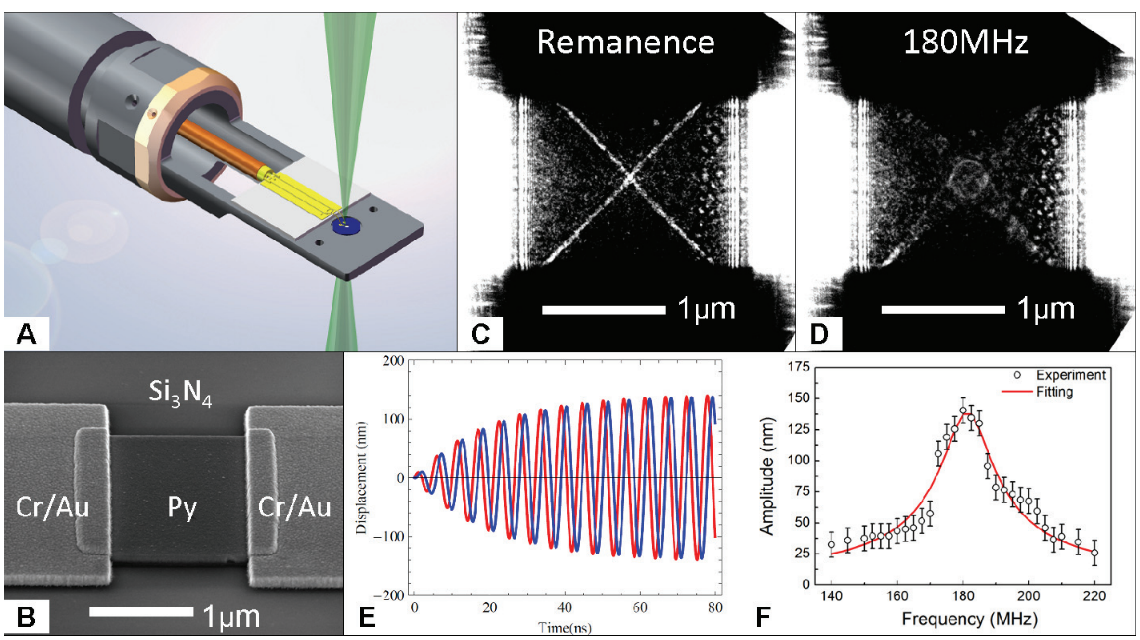

FIG. 2. (A) Schematics of the TEM specimen stage design for application of high-frequency resonant current. (B) SEM image of the patterned device. (C) Lorentz image of the static Landau domain structure. (D) Lorentz image of the resonant precession of the vortex core (180MHz, 7.7×10^{10}A/m^2). (E) Calculated time evolution of vortex core displacement. (Red and blue lines correspond to displacement parallel and perpendicular to current direction) (F) Frequency-sweep curve of the precession amplitude (7.7×10^{10}A/m^2).

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