Development of Operando Magnetic Device for Lorentz Transmission Electron Microscopy

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Primary CNF Tools Used: GCA 5X stepper, wet stations, CVC evaporators, Heidelberg mask writer, dicing saw

Abstract:

We develop a magnetic device for operando Lorentz transmission electron microscope (LTEM) studies of magnetic skyrmions under the application of electric current pulses. We study the creation and annihilation of skyrmions in the presence of a strong pinning defect within a ferromagnetic multilayer with interfacial Dzyaloshinskii-Moriya interaction (DMI). We also show that Joule heating plays a primary role in this process. By controlling the magnetic field and total injected thermal energy, we can control the skyrmion density. Additionally, we study the relationship between skyrmion density and skyrmion stability to variations in the magnetic field. Our results show that the higher density skyrmions resist annihilation over a wider range of magnetic field.

Summary of Research:

Magnetic skyrmions are promising for potential high-performance memory and neuromorphic computing devices, however, to understand their behavior and dynamics at the smallest scales, a method of nanoscale imaging is essential [1,2]. To date, the study of chiral magnetic features in LTEM has been limited to operando changes of the magnetic field and temperature, with a few exceptions of single-crystalline samples, which were thinned and micropatterned by focus ion beam (FIB) for application of DC current [3-5]. To enable the study of skyrmion behavior with the application of electric current pulses, we develop a skyrmion device platform that is compatible with operando electrical biasing inside an electron microscope.

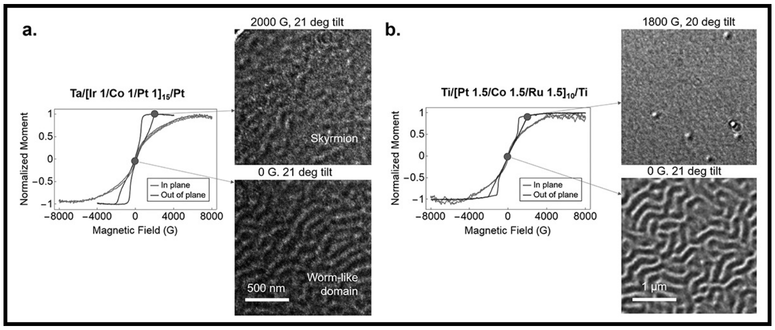

Figure 1: Magnetic hysteresis determined by vibrating sample magnetometry (VSM) and the LTEM image of spin textures for (a) Ta(2)/[Ir (1 nm)/Co (1 nm)/Pt (1 nm)]15 and (b) Ti(3)/[Pt (1.5 nm)/Co (1.5 nm)/Ru (1.5 nm)]10.

We start by optimizing the skyrmion materials. Two important micromagnetic interactions for stabilization of skyrmions in a thin-film multilayer structure are interfacial Dzyaloshinskii Moriya Interaction (DMI) and perpendicular magnetic anisotropy (PMA). We use platinum/cobalt (Pt/Co) bilayers to ensure PMA in our films. Iridium (Ir) or ruthenium (Ru) is used for the third layer because the interface on the opposite side of Pt in Pt/Co/Ir or Pt/Co/Ru trilayer is known to have an additive effect on effective DMI [6]. While we observe nucleation of skyrmions from both Pt/Co/Ir and Pt/Co/Ru stacks, we find that samples seeded from Ti/Pt or Ta/Pt on the membrane shows better LTEM contrast (Figure 1).

To enable an LTEM study of the chiral magnetic materials, we need to fabricate our device on an electron transparent material such as SiN_x membrane with a thickness of less than 100 nm. We use a Protochip™ fusion e-cell, which is composed of a 50 nm thick SiN_x

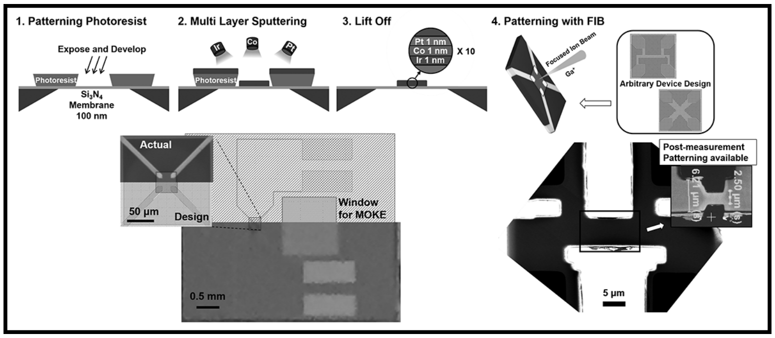

Figure 2: Fabrication process flow for the operando device. Optical image of Protochip™ fusion e-cell template overlaid with mask pattern for photolithography (left below) and a scanning electron micrograph of the device after patterning with FIB (right below). (See pages vi-vii for full color version.)

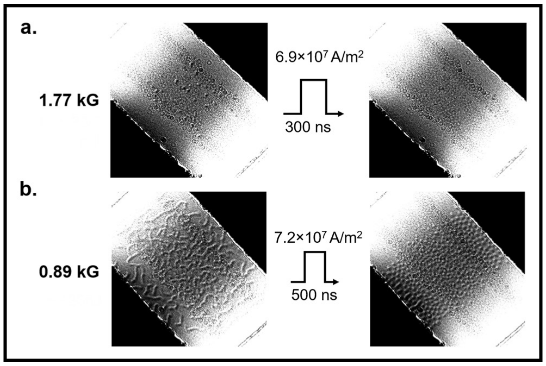

Figure 3: Current induced thermal annihilation (a) and nucleation (b) of skyrmions in the device.

membrane window with gold electrodes that extend toward the center of the membrane as a template to build our device. Multiple repeats of heavy metal/ferromagnet/heavy metal trilayer are deposited using an AJA sputter system (Figure 2). While micrometer-scale devices can be fabricated by lift-off alone, focused ion beam (FIB) can also be used as a post-processing method to define smaller features. We confirm that a versatile approach of defining a larger area of the film first and then direct writing a specific shape using FIB is possible.

Using the device, we observe thermal nucleation and annihilation of skyrmions induced by current-induced Joule heating (Figure 3) and quantify the energetics of the magnetic states with micromagnetic simulations. We find that the skyrmions are strongly bound to point-like pinning sites created by defects that are inherently present on the SiNx membrane provided by Protochip™. The thermal nucleation process enables the control of the skyrmion density choosing the magnetic field and the current pulse energy. Next, we investigate the stability of skyrmions as a function of their density. After systematically initializing a particular skyrmion density, we vary the magnetic field to find the magnetic field range that the skyrmions are stable. We find that while all skyrmions annihilate at high field regardless of the initial density, the lower bound of skyrmion stability is proportional to the initial skyrmion density.

Conclusions and Future Steps:

In conclusion, we have optimized a chiral material heterostructure and established a fabrication process for operando electron microscope studies of skyrmion creation and annihilation using electric current in the presence of strong magnetic pinning sites. We find that a thermal mechanism dominates these processes and that the resulting skyrmions have density-dependent stability. Understanding this mechanism has implications for controlling the density of skyrmions in devices. Additionally, operando transport properties such as the topological Hall effect and its relation to the nature of the chirality and the pinning effects can be investigated in the future based on this platform.

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