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Insights into the Origin of Skyrmion Pinning in [Pt/Co/Cu] Magnetic Multilayers

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There has been considerable interest in spintronic devices based on magnetic skyrmions, which are topological protected magnetic spin textures that can be used as information carriers in racetrack memories [1]. Over the past decade, substantial effort has been given in the exploration of materials to stabilize small skyrmions at room temperature. Recent theoretical predictions suggest that room-temperature skyrmions may emerge in magnetic multilayer systems, for example in Pt/Co/Z systems (Z=Pd, Cu, Ag, Au, Zn and Cd), where skyrmions size can be controlled by the sample structure (thickness of each layer and number of periods) [2]. A crucial step in using these multilayer systems in memories devices is the ability to move skyrmions through the material. However, the pinning effects increase as the size of the skyrmions decreases to the same order of structural inhomogeneities, especially in multilayer thin films [3,4]. To the date, the origin of skyrmion pinning effects in these materials is not well understood and has become of fundamental importance to realize future functional skyrmion devices.

In this work, we study skyrmion pinning effects in $[Pt/Co/Cu]_5$ magnetic multilayer specimens by applying *in situ* magnetic fields or/and biasing in Lorentz transmission electron microscopy (LTEM) using a DENS wildfire/lightning holder. $[Pt/Co/Cu]_5$ multilayer specimens were epitaxy grown on Al_2O_3 [111] substrate with Pt buffer layer using molecular beam epitaxy (MBE). High angle annular dark field (HAADF) STEM analysis was performed to characterize the structure and quality of the films in cross-section specimens prepared using dual focused ion beam (FIB) instrument. In order to study skyrmion pinning effects, plan view (PV) specimens were prepared from the cleaving edge of the specimens also using FIB and characterized by *in situ* LTEM. Multiple advanced TEM techniques (spectroscopy and 4DSTEM) were used to characterize the structural inhomogeneous in the sample.

First, room-temperature magnetic phase transitions were established in PV specimens by applying magnetic field in LTEM. Initially, a labyrinth phase was observed at room-temperature and 0 mT transitioning to Néel-type skyrmions (size < 130 nm) around 100 mT as shown in Figure 1. Secondly, a PV specimen was montaged on a biasing chip for *in situ* biasing experiments, and engineered channels were made for an easy track of the movement of skyrmions. Figure 2a shows a schematic structure of an engineered channel with a width of 800 nm. Short current pulses were applied by a pulse generator. After a current pulse of 50 ns and 27 V, we observed that most skyrmions were pinned at their original positions, although with one exception highlighted by red circles in Figure 2b. Structural characterization shows the specimens are formed by epitaxial gains with low angle boundaries and sizes smaller than the skrymions. Due to the different sizes, the origin of the different pinning effects of these skyrmions cannot be directly related to the grains in the film. Combining with micromagnetic simulations, we will attempt to give a fundamental physical picture to explain the mechanism of the skyrmion pinning effects. [6]

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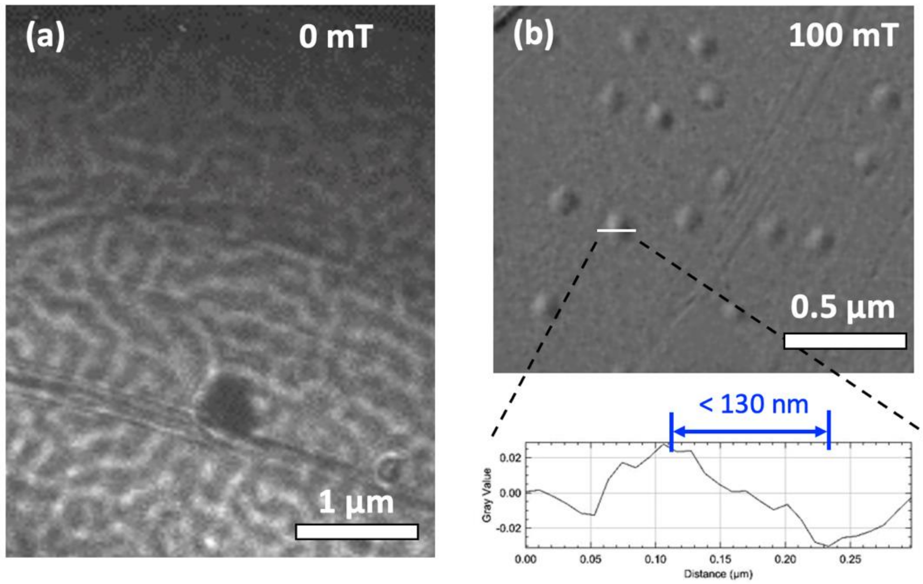

Figure 1. Magnetic phase transition in [Pt/Co/Cu]$_5$ magnetic multilayers as the magnetic field change acquired using defocused Lorentz TEM. (a) Labyrinth phase at zero field. (b) Néel-type skyrmions and their determined size at 100 mT. The Lorentz TEM image in (b) is background removed following [5]. The specimen was tilted 10 degrees off to the zone direction.

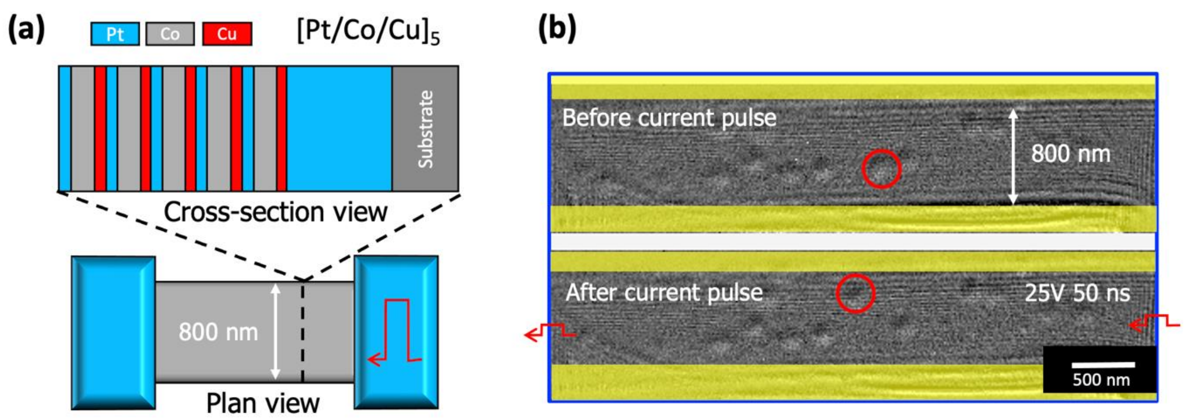

Figure 2. (a) Schematic structure of an engineered channel in plan-viewed [Pt/Co/Cu]$_5$ magnetic multilayers mounted on biasing chip and the cross-section view of the structure of the specimen along the beam direction. (b) The *in situ* biasing experiment on a 800 nm width channel schematized in (a) showing the pinning effects with a 50 ns current pulse at 25 V and 100 mT. Most skyrmions were pinned despite a case highlighted with red circles.

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