Formation and Relaxation Dynamics of Magnetic Skyrmion

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Magnetic skyrmions (MS), a group of quasiparticle with topological charge, have attracted extensive research interest because they are promising candidates as information carriers in future spintronic application. MS was first detected by Mühlbauer et al.[1] with neutron scattering in bulk MnSi with a form of long-range magnetic ordered lattice-like structure. Subsequently, systematic real-space observations of skyrmion lattice (SkL) with Lorentz transmission electron microscopy (L-TEM) in B20 magnets of metallic MnSi, $Fe_{1-x}Co_xSi$, FeGe, and insulating Cu_2OSeO_3 led to significant breakthroughs in this field.[2] Both metastable zero field and thermal dynamically equilibrium magnetic field supported skyrmions has been reported.[2] Despite extensive research in this field in the past decade, the formation and relaxation dynamics of magnetic skyrmions is still elusive. In this study, we focus on using *in situ* L-TEM to study dynamics of magnetic skyrmions.

Single crystals of bulk FeGe were grown by the chemical vapor transport technique. A FeGe TEM thin plate with its surface normal to the [001] crystallographic direction was prepared using a FEI Helios dual beam focused-ion-beam instrument. High resolution HAADF STEM and SAED were performed using a probe aberration-corrected FEI Titan Themis. All the defocused L-TEM images of magnetic domains were recorded using the Lorentz mode of a Tecnai F20 TEM. The quantitative in-plane magnetizations of L-TEM Fresnel images are analyzed by a phase-retrieval QPt software on the basis of the transport of intensity equation (TIE).

Figure 1a, b shows HAADF-STEM image of the high quality FeGe single crystal without discernible structural defects along [001] zone-axis. The Fe-Ge dumbbells are clearly resolved, consistent with symmetry-broken B20 structure (Fig. 1c). Transformation from spontaneous stripe domains with a modulation length of ~75 nm (Fig. 1d) to equilibrium SkL in triangular pattern (Fig. 1e) was observed after applying a magnetic field of 87.8mT at 263K. Moreover, field cooling under the magnetic field of 87.8 mT from 263 K to 96 K sustains the SkL even after the field is removed.[2]

Figure 2 summarized zero-field skyrmion evolution dynamics over temperatures, after classifying the switching process into three types according to the environment of the skyrmion, i.e. isolated skyrmions, boundary skyrmions and interior skyrmions of a SkL. For each type, the average switching time is estimated using $\tau=Mt/N$, where N is the number of switching events over the observation time interval t and M is the total number of skyrmion sites for the same type under observation. Other types of stripe-skyrmion switching do not occur in sufficient numbers to yield reliable statistics. The relaxation time is fitted as a function of temperature using $\tau = \tau_0 \exp\left(\frac{E_s}{k_B T}\right)$, where τ_0 is the pre-exponential factor ($1/\tau_0$ defines the attempt frequency), k_B is the Boltzmann constant and E_s is the activation energy, which is

assumed to be temperature-dependent ($E_s = C\sqrt{T_S - T}$, where $T_S = 263$ K). The summrized zero temperature activation energies $C\sqrt{T_S}$ is plotted in insets of Figure 2a. These results suggest non-Arrhenius law behavior for zero-field skyrmion relaxation.[2] Moreover, skyrmion formation dynamics in other systems will be discussed as well [3].

References:

[1] S Mühlbauer et al. Science **323**, (2009) 915.

[2] L Peng et al, Nano Letters **18**, (2018) 7777.

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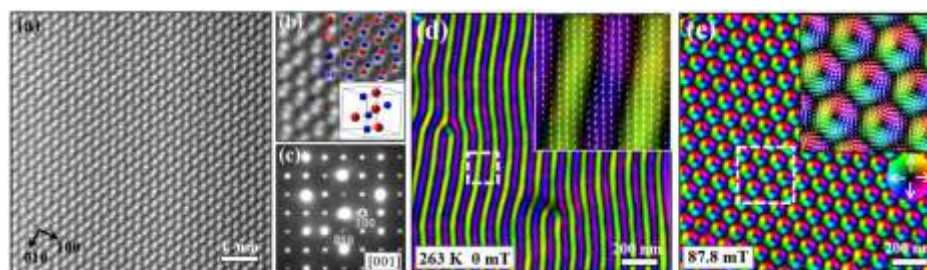
Figure 1 (a) High resolution HAADF-STEM image of FeGe taken along [001] zone axis. (b) Enlarged image from (a) revealing the Fe-Ge dumbbell in cubic B20 structure. (c) Selected area electron diffraction pattern along [001] zone axis. (d-e) Magnetic domain configuration via TIE method of (d) helical ground state and (e) skyrmion lattice at a magnetic field of 87.8 mT.[2]
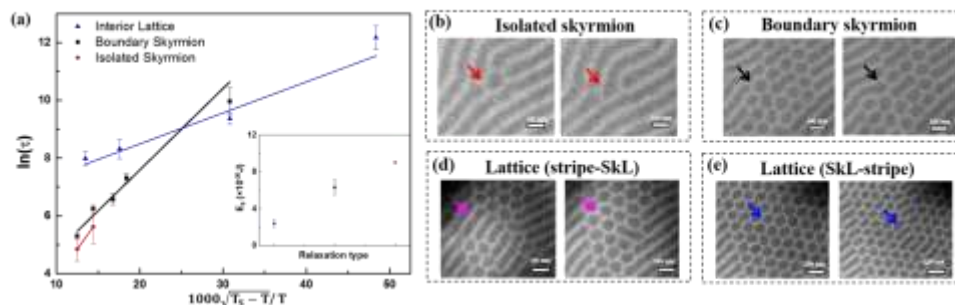

Figure 2. Relaxation dynamics of metastable zero-field skyrmions at different temperatures. (a) Linear fitting plots of ln(τ) versus $(1000(T_S-T)^{1/2})/T$ for three switching processes based on direct real-space L-TEM observations. The switching processes are classified into (b) Isolated skyrmion at 253 K, (c) Boundary skyrmion at 250 K, (d) Stripe to SkL at 243 K, (e) skyrmion to stripe at 218 K. The summary of corresponding energy barriers Es at 0 K in the insets of (a).[2]