Supplementary Materials to:

Dynamics of chiral state transitions and relaxations in an FeGe thin plate via in situ Lorentz microscopy

Ke Chai [1,2], Zi-An Li [2,*], Ruibin Liu [1,*], Bingsuo Zou [1,6*], Michael Farle[3], and Jianqi Li [2,4,5]

[1] Beijing Key Laboratory of Nanophotonics and Ultrafine Optoelectronic Systems, School of Physics, Beijing Institute of Technology, Beijing 100081, China.

[2] Beijing National Laboratory for Condensed Matter Physics and Institute of Physics Chinese Academy of Sciences, Beijing 100190, China.

[3] Faculty of Physics and Center for Nanointegration (CENIDE), University of Duisburg-Essen, 47057 Duisburg, Germany

[4] Yangtze River Delta Physics Research Center Co., Ltd. - Liyang, Jiangsu, 213300, China

[5] Songshan Lake Materials Laboratory - Dongguan, Guangdong, 523808, China

[6] Center on Nano-energy Research, School of Physical Science and Technology, Guangxi University, Nanning, 530004, China.

Email: zali79@iphy.ac.cn; liuruibin8@gmail.com; zoubs@bit.edu.cn

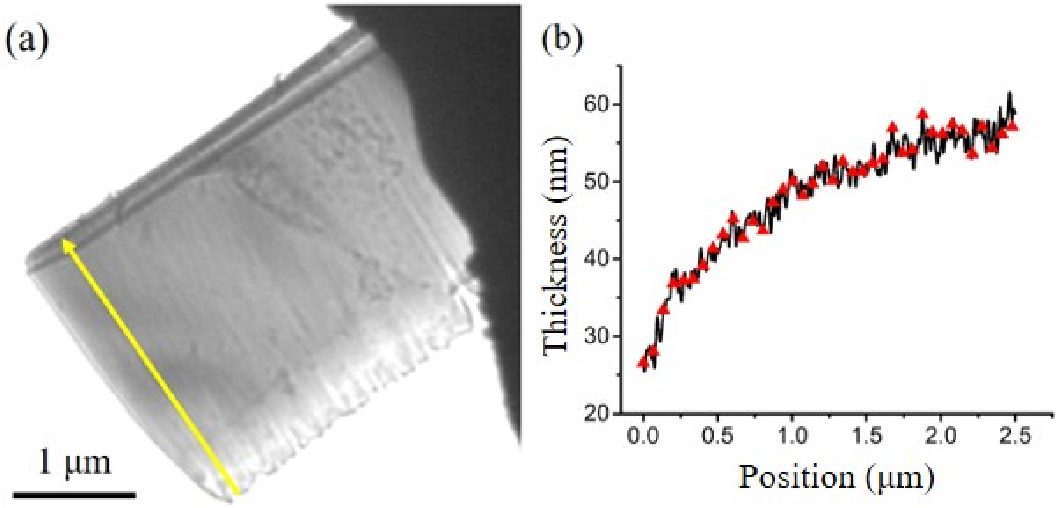

Fig. S1. Morphologies and thickness measurements of the FeGe thin plate by TEM techniques. (a) The overall morphology of FeGe lamella with the lateral dimensions of 3.2-by-2.5 μm. (b) The thickness profile of lamella along the line indicated by the yellow arrow in (a).

The FeGe specimen thickness was measured via using electron energy loss maps in TEM via the Log-ratio model [1, 2]: $t/\lambda = In(I_t/I_0)$, where t is the absolute thickness, λ is the mean free path of inelastic electron scattering which takes the values of 120 nm, I_t and I_0 are integrated intensities for the total area under whole spectrum area and the area under zero-loss peak, respectively.

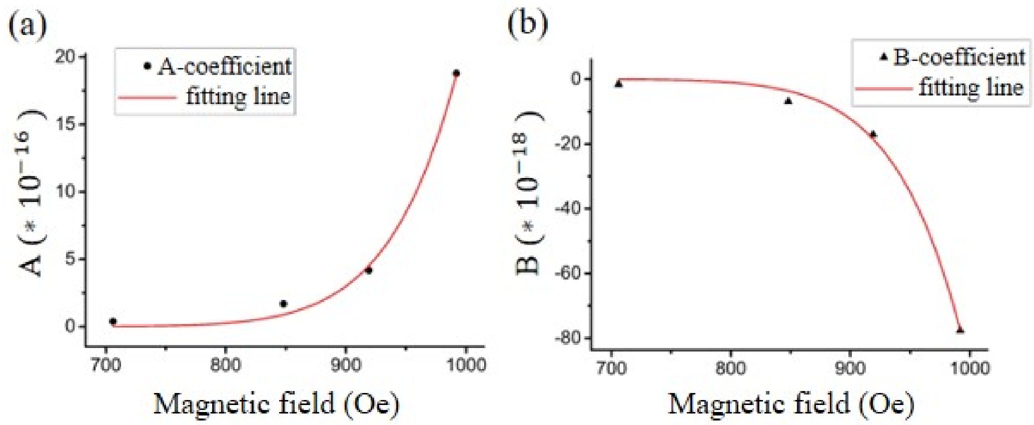

Fig. S2. Fitting of the experimental data for τ_0, which is a temperature- and field-dependent factor in Néel-Arrhenius statistical switching models with the equation form of Eq. s1. (a) Fitting of the measured data to the first term *A(H)* and (b) the second term *B(H)* in Eq. s1.

In some simplified cases of Arrhenius-type relaxation, the pre-exponential factor τ_0 is assumed to be a constant. However, τ_0 is system-specific and may depend on other parameters such as external field and temperature in magnetic transitions [3, 4]. Here, τ_0 is a parameter in Néel-Arrhenius model and can be expressed in the temperature-field-dependent form [4, 5], and reads,

$$\tau_0 = A(H) + B(H) \times T \qquad \text{(Eq. s1)}$$

Where *A* and *B* are two field-dependent coefficients, and T is absolute temperature. Fitting the Eq. s1 with the experimental data (Fig. S2) yields the following:

$$A = 1.05 \times 10^{-7} \times e^{-1.78 \times 10^4 / H}$$

$$B = -4.04 \times 10^{-10} \times e^{-1.78 \times 10^4 / H}$$

Note that both A and B parameters have the same exponential term ($^{-1.78 \times 10^4 / H}$), thus the τ_0 can be expressed by the following equation:

$$\tau_0 = \left(1.05 \times 10^{-7} - 4.04 \times 10^{-10} \times T\right) \times e^{-1.78 \times 10^{4}/H} \qquad \text{(Eq. s2)}$$

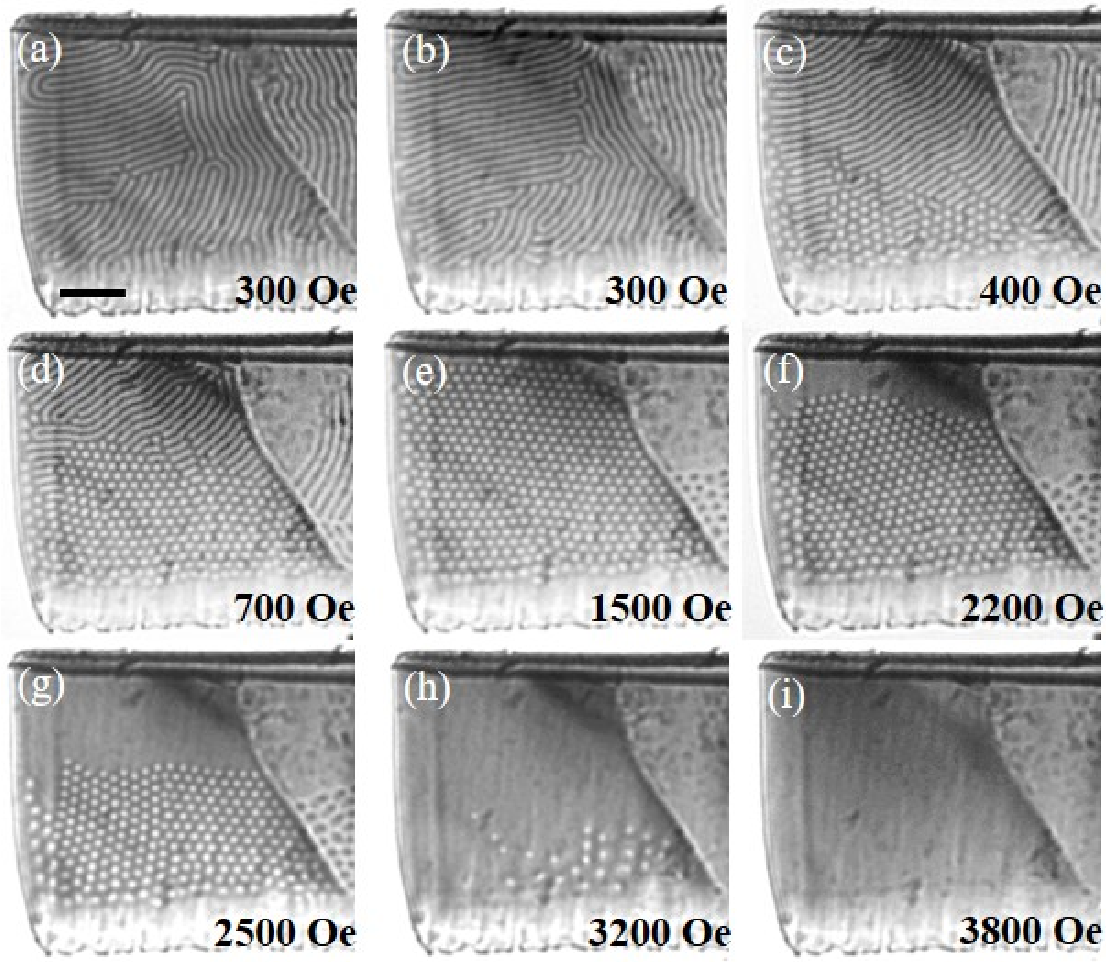

Fig. S3. Representative frames extracted from Supplementary Video-1. The FeGe thin plate was cooled down from room temperature to 120 K under 300 Oe residual field in the TEM. The LTEM images were recorded with defocus value of 0.7 mm and their corresponding applied fields are indicated. (a) 300 Oe as-cooled down. (b) 300 Oe after laser irradiation and subsequent cooled down, (c) 400 Oe, (d) 700 Oe, (e) 1500 Oe, (f) 2200 Oe, (g) 2500 Oe, (h) 3200 Oe, and (i) 3800 Oe. The scale bar in (a) corresponds to 500 nm.

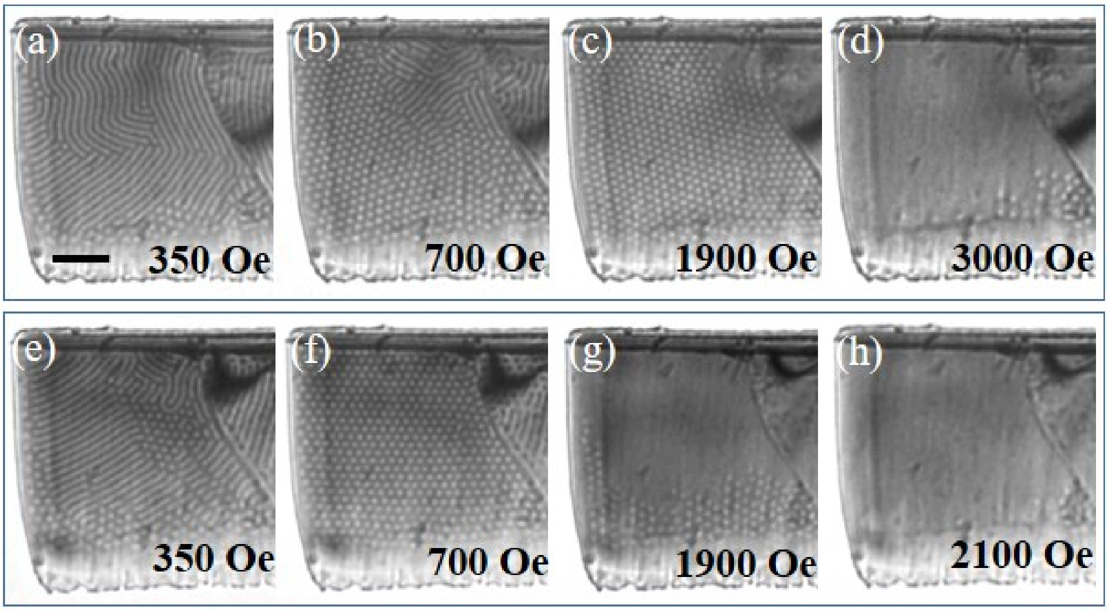

Fig. S4. Representative LTEM images of magnetic states recorded with a defocus value of 0.7 mm. (a-d) LTEM micrographs were taken at 160 K under various fields: (a) 350 Oe, (b) 700 Oe, (c) 1900 Oe, and (d) 3000 Oe. (e-h) LTEM micrographs were taken at 230 K under various fields: (e) 350 Oe, (f) 750 Oe, (g) 1900 Oe, and (h) 2100 Oe. The scale bar in (a) corresponds to 500 nm.

Supporting Video-1

The video-1 recorded the magnetic transitions in FeGe thin plate as a function of applied magnetic fields at 120 K, in which the magnetic states transformed between the helical stripes, skyrmions, cones, and field-saturated ferromagnetic state as the applied field ramped up from 300 Oe (residual field in L-TEM mode) to 3800 Oe. After each application of field, femtosecond laser pulses were used to heat up the specimen above T_c. After thermal demagnetization, the specimen rapidly cooled down to 120 K by switching off the laser pulses, resulting in the corresponding magnetic states. Exposure time for each frame in the video is 0.2 s.

Supporting Video-2

The video-2 recorded the magnetic transition and relaxation process of the metastable magnetic state of FeGe thin plate at 232.90 K-919 Oe conditions. Exposure time for each frame in the video is 0.2 s. Counting the number of generated skyrmions allows one to estimate the critical relaxation parameters for the description of metastability and relaxation processes.

References

1. H.R. Zhang, R.F. Egerton, M. Malac, *Micron*, 2012, **43**, 8-15.

2. K. Iakoubovskii, K. Mitsuishi, Y. Nakayama, K. Furuya, *Microsc Res Tech*, 2008, **71**, 626-631.

3. W. Wernsdorfer, E. Bonet Orozco, K. Hasselbach, A. Benoit, B. Barbara, N. Demoncy, A. Loiseau, H. Pascard, D. Mailly, *Phys. Rev. Lett.*, 1997, **78**, 1791.

4. X. Wang, H.N. Bertram, *J. Appl. Phys.*, 2002, **92**, 4560.

5. P. A. Adam, *J.C.S. Faraday*, 1980, **76**, 2124-2127.