Electronic Supplementary Material (ESI) for Nanoscale.

Supporting Information of "Generation of skyrmions by combining thermal and spin-orbit torque: breaking half skyrmions to skyrmions"

Sheng Yang,[#,1] *Laichuan Shen,*[#,2,3] *Yuelei Zhao,*[#,1] *Kai Wu,*[1] *Xiaoguang Li,*[4] *Ka Shen,*[2,3] *Senfu Zhang,*[5] *Xiaohong Xu,*[6,7] *Johan Åkerman*[8,9] *and Yan Zhou*[*,1]

[1]*School of Science and Engineering, The Chinese University of Hong Kong, Shenzhen, 518172, China*

[2]*The Center for Advanced Quantum Studies and Department of Physics, Beijing Normal University, Beijing, 100875, China*

[3]*Key Laboratory of Multi-scale Spin Physics, Ministry of Education, Beijing Normal University, Beijing, 100875, China*

[4]*Center for Advanced Material Diagnostic Technology, College of Engineering Physics, Shenzhen Technology University, Shenzhen, 518118, China*

[5]*Key Laboratory for Magnetism and Magnetic Materials of the Ministry of Education, Lanzhou University, Lanzhou, 730000, China*

[6]*School of Chemistry and Materials Science of Shanxi Normal University & Key Laboratory of Magnetic Molecules and Magnetic Information Materials of Ministry of Education, Taiyuan, 030006, China*

[7]*Research Institute of Materials Science of Shanxi Normal University & Collaborative Innovation Center for Shanxi Advanced Permanent Magnetic Materials and Technology, Taiyuan, 030006, China*

[8]*Department of Physics, University of Gothenburg, Gothenburg, 41296, Sweden*

[9] *Science and Innovation in Spintronics Research Institute of Electrical Communication, Tohoku University, Aoba-ku, 980-8577, Japan*

#These authors contributed equally.

Corresponding Author

* E-mail: zhouyan@cuhk.edu.cn

Supporting Information S1: Evolution of a single stripe domain

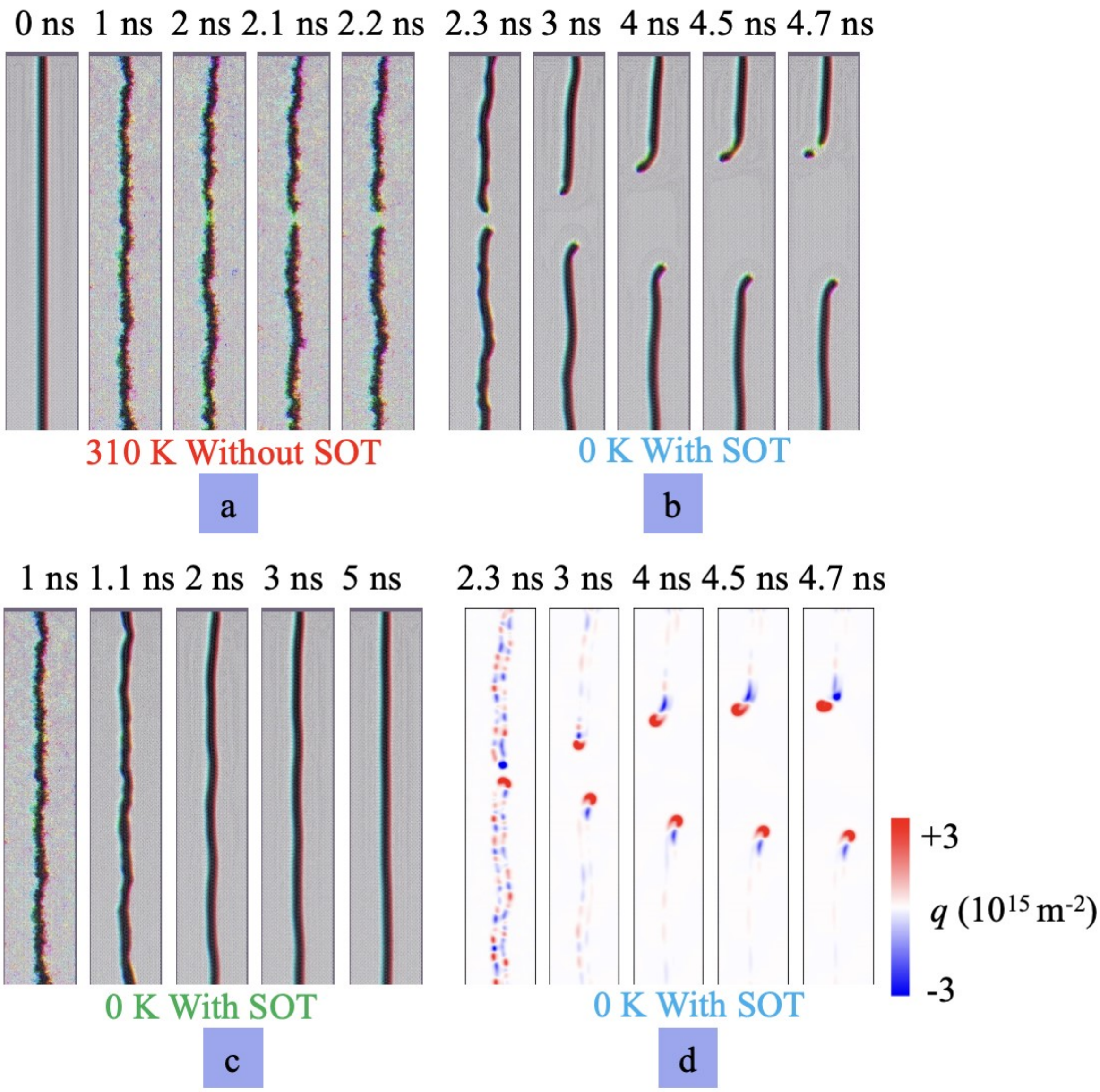

Figure S1. Effects of SOT and heat on a single stripe domain. **a**. Heat causes the stripe domain to curl and split into two segments. **b**. Under the application of SOT, a skyrmion is cut from the end of the split stripe domain. **c**. SOT can restore the straightness of the stripe domain in the absence of heat. **d**. The topological density map of **b**. The heat creates the non-uniform topological density and varies the spin configuration along the stripe domain.

Figure S1a shows the time evolution of a single stripe domain under thermal effects at 310 K. As one can see, such a domain is split into two segments. Then, we set the temperature to 0 K and turn on the SOT. As shown in Figure S1b, a skyrmion is generated from the end of a split domain, where the distribution of the topological density q is plotted in Figure S1d, confirming the existence of skyrmion. This result indicates that the SOT has a significant impact on the transition of stripe domains into skyrmions. It is noteworthy that unlike the thermal effect, the SOT cannot break the single stripe domain, as shown in Figure S1c.

Supporting Information S2: Temperature measurement

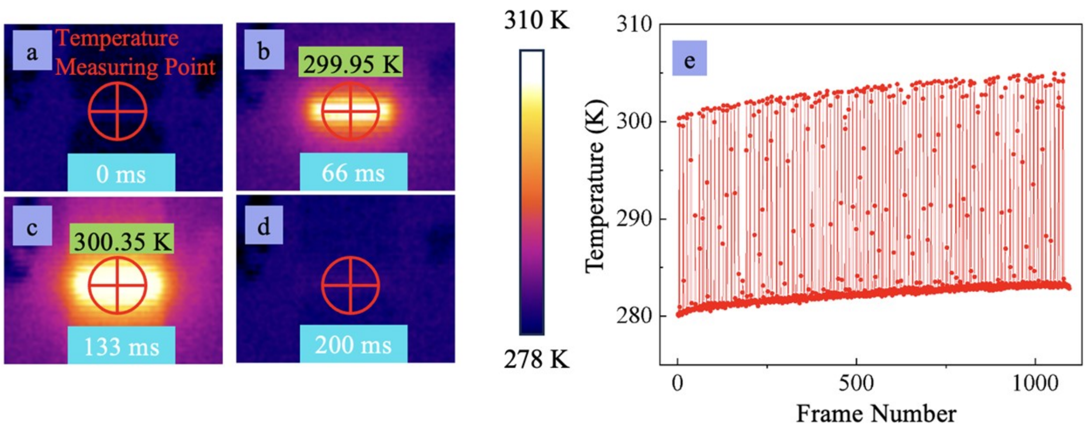

Figure S2. A demonstration of the infrared camera image of the heated device. **a**-**d**. The snapshot of the heated device at time 0 ms, 66 ms, 133 ms, and 200 ms. The position of the temperature measurement is manually chosen and positioned at the central point of the track. **e**. The plot of temperature vs. frame number of the infrared camera.

Figures S2a-d demonstrate the temperature changes measured by the infrared camera of our racetrack device under the stimulation of currents. The device has an initial temperature of 280.15 K (Figure S2a) and is subjected to a current pulse with a density of 2.40×10^{11} A/m^2 and a duration of 100 ms. The temperature rises to 299.95K at 66 ms and to 300.35K at 133 ms (Figures S2d-c). Following the pulse, the device undergoes a cooling process, yet it remains at a considerably elevated temperature relative to the initial state. The device In Figure S2e, the temperature of the device measured by the infrared camera increases from 280.15 K to 299.00 K after the first current pulse, and after 100 pulses (current density of 2.40×10^{11} A/m^2 and width of 100 ms), the temperature of the device reaches 304.85 K. Finally, the temperature drops to 284.15 K when the pulses ceased. Nevertheless, the device's dimensions are excessively diminutive for the infrared camera to accurately gauge the temperature at the center of the device (or the “hot spot”). Consequently, the precise temperature at the specific site responsible for the transition between stripe domains and skyrmions remains unsure.

Supporting Information S3: Filming region of the racetrack device

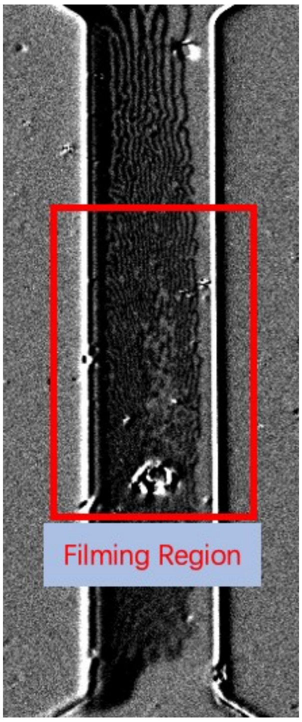

Figure S3. Filming region of the racetrack device.

As shown in Figure S3, the area of maximum temperature, or the “hot spot,” is located at the center of the racetrack device, where the electrical current distribution is more concentrated, resulting in higher Joule heating. Therefore, the stripe domain – skyrmion transition is first occurred in the center of the device.

Supporting Information S4: Domain evolution for a 2400 nm×6000 nm×1 nm film

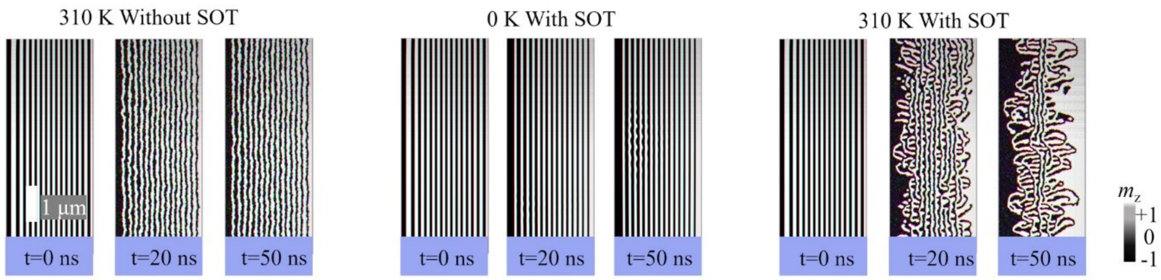

Figure S4. Snapshot of magnetic domains of a 2400 nm×6000 nm×1 nm film at simulation time 0, 20 and 50 ns, with three scenarios (with/without the SOT at different temperatures). Other parameters are the same as those used in Figure 4 of the main text.

In Figure 4 of the main text, the model size is 1200 nm×3000 nm×1 nm. Its increase does not give a qualitative change, but only introduce a quantitative modification in the evolution of magnetic domains, as shown in Figure S4.

Supporting Information S5: Evolution of magnetic domains driven by spin-orbit torques in the presence of defects

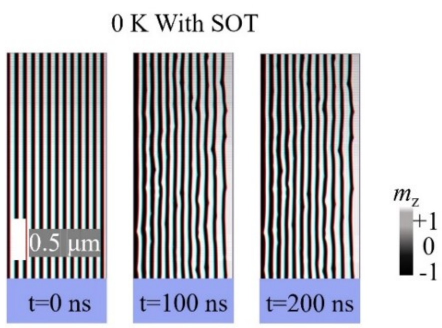

Figure S5. Snapshot of the magnetic domains at different simulation times in the presence of spin-orbit torques and defects. The parameters are the same as those used in Figure 4 of the main text.

Figure S5 shows the time evolution of the magnetic domains driven by spin-orbit torques in the presence of defects, modeled by randomly modifying the magnetic anisotropy within the range of 0.6 MJ/m^3 – 0.8 MJ/m^3. As seen, considering only spin-orbit torque as the driving source, the introduction of defects into the magnetic film does not give rise to a magnetic state similar to that presented in Figure 4u, even after 200 ns (a very long simulation time).