

Real-space observations of 60-nm skyrmion dynamics in an insulating magnet under low heat flow

Xiuzhen Yu^{1*}, Fumitaka Kagawa^{1, 2}, Shinichiro Seki^{2,3}, Masashi Kubota^{1†}, Jan Masell¹, Fehmi S. Yasin¹, Kiyomi Nakajima¹, Masao Nakamura¹, Masashi Kawasaki^{1, 2}, Naoto Nagaosa^{1, 2} and Yoshinori Tokura^{1,2, 4}

¹RIKEN Center for Emergent Matter Science (CEMS), Wako 351-0198, Japan

²Department of Applied Physics, University of Tokyo, Tokyo 113-8656, Japan

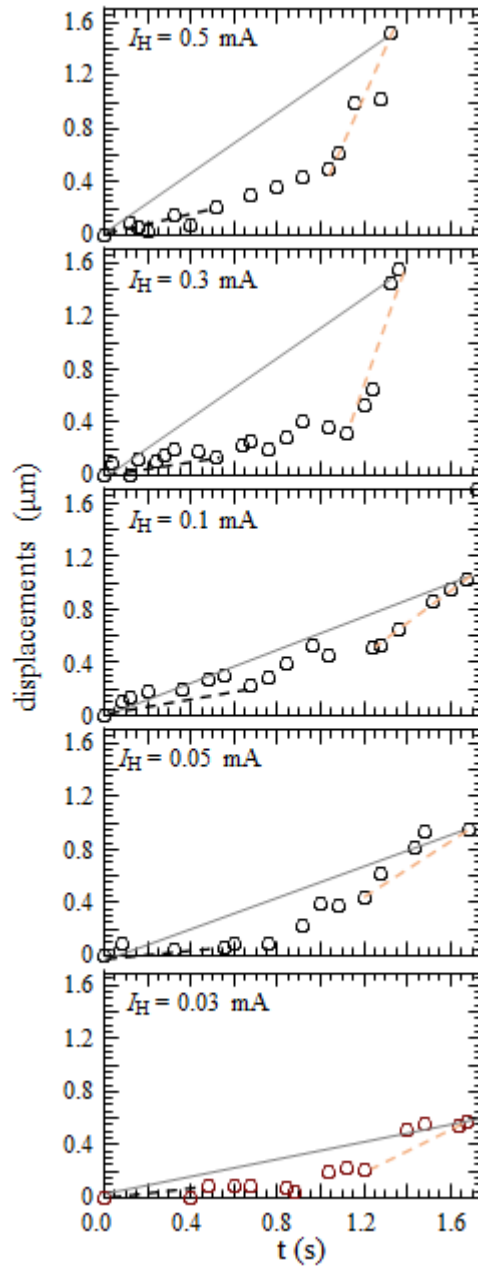
³Institute of Engineering Innovation, University of Tokyo, Tokyo 113-0032, Japan

⁴Tokyo College, University of Tokyo, Tokyo 113-8656, Japan

*Correspondence to: yu_x@riken.jp

† Present affiliation: Technology and Business Development Unit, Murata Manufacturing Co., Ltd., Kyoto 617-8555, Japan

14 **Skyrmion motions under various heater currents in the thin Cu_2OSeO_3**



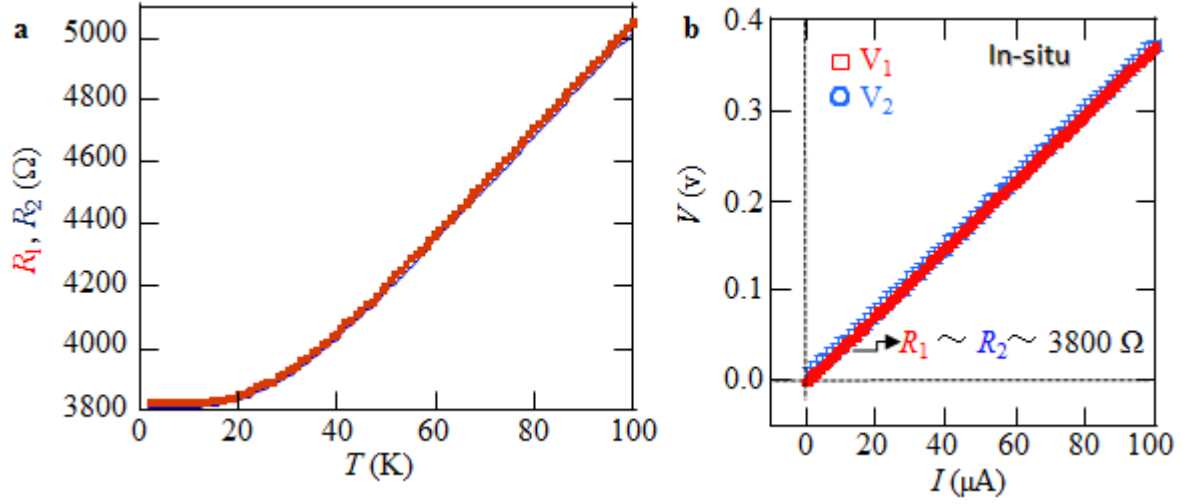
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16 **Supplementary Figure 1: Plots of the displacement of skyrmions at the elapsed times, are**
17 **obtained by analyzing in-situ Lorentz TEM movies observed at 160-mT-normal field and 20**
18 **K under various heater currents.** Circular symbols show data points extracted from Lorentz
19 TEM movies. The black solid lines represent the slop of estimating the averaged velocity of
20 skyrmions, while black and orange dashed lines marked slops for estimating the minimal and
21 maximal velocities of skyrmions at each heater current, respectively.

22 Supplementary Figure 1 shows the displacements of skyrmions under several heater-current
23 excitations in the Cu_2OSeO_3 thin plate, indicating that monotonically increasing functions of the
24 moving distance as the time under each current excitation; the slope of displacements tends
25 increasing with the heater current. We estimated the averaged velocity of skyrmions by taking
26 the ratio of the total drift distance to the duration (the duration is 1.36 s for the heater current I_H
27 = 0.3 mA, 0.5 mA, while it is 1.68 s for $I_H = 0.3$ mA, 0.05 mA, 0.1 mA) of skyrmion motion
28 (marked by the solid lines in the supplementary Fig. 1), as shown in Fig. 3k. The dashed black
29 and orange lines represent slopes to estimate the minimal and maximal velocities deduced from
30 the locally-averaged values approximately over the shorter period of 0.2-0.6s, which were used
31 to define the error bars for the averaged velocity, as shown in Fig. 3k.

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33 **Characterization of thermometers on the thin Cu_2OSeO_3**

34 We measured the temperature dependence of thermometer resistances, as shown in supplementary
35 Figure 2a, by using a Physical Property Measurements System (PPMS, Quantum Design). Both
36 resistances R_1 and R_2 are the same value at 20 K, $\sim 3800 \Omega$. Supplementary Figure 2b represent
37 I-V curves measured in TEM chamber, indicating the same value of the resistance for both R_1
38 and R_2 . Thus, the temperature gradients caused by such small heater currents cannot be evaluated
39 by changes of the resistance of thermometers in the present device.



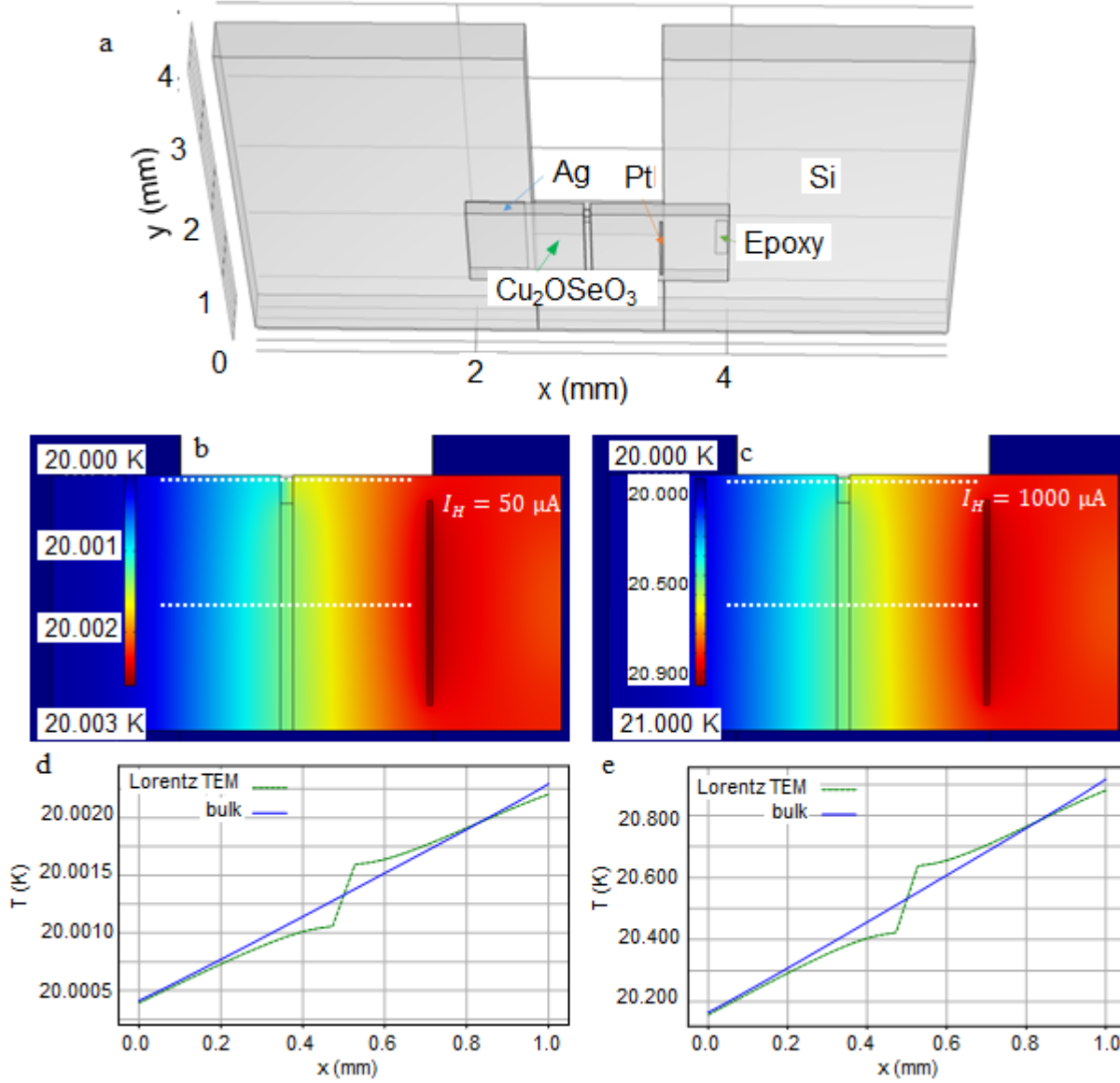
Supplementary Figure 2: Resistance curves (a) and I - V curves (b) of thermometers R_1 and R_2 in the thin Cu_2OSeO_3 plate. **a.** Resistance profiles of R_1 and R_2 with decreasing temperature obtained by Physical Properties Measurement System (PPMS) measurements with 1- μA current through the heater and thermometers. **b.** I - V curves of thermometers R_1 and R_2 under the same current flow through the heater measured *in-situ* in the TEM chamber.

Temperature map of finite element simulations

Supplementary Figure 3 shows the results of a finite element simulation performed using COMSOL Multiphysics commercial software. The model geometry is shown in Supplementary Figure 3a, with a ‘U’ shaped silicon base plate which is 0.3 mm thick and acts as the cold bath. The silicon substrate is contacted to the sample thin plate in two places: on the left-hand-side using Ag paste (thermal conductivity $k_{isoAg} = 1 \text{ W}/(\text{m} \cdot \text{K})$, density $\rho_{Ag} = 1000 \text{ kg}/\text{m}^3$, and heat capacity $C_{pAg} = 50 \text{ J}/(\text{kg} \cdot \text{K})$), and on the right side using epoxy resin ($k_{isoepoxy} = 0.2 \text{ W}/(\text{m} \cdot \text{K})$, $\rho_{epoxy} = 1100 \text{ kg}/\text{m}^3$, and $C_{p_{epoxy}} = 1110 \text{ J}/(\text{kg} \cdot \text{K})$). The Pt wire heater ($k_{isoPt} = 70 \text{ W}/(\text{m} \cdot \text{K})$, $\rho_{Pt} = 21447 \text{ kg}/\text{m}^3$, and $C_{pPt} = 130 \text{ J}/(\text{kg} \cdot \text{K})$) is located on the top right side of the Cu_2OSeO_3 thin plate ($k_{iso\text{Cu}_2\text{OSeO}_3} = 40 \text{ W}/(\text{m} \cdot \text{K})$, $\rho_{\text{Cu}_2\text{OSeO}_3} = 5070 \text{ kg}/\text{m}^3$,

57 and $C_{p_{\text{Cu}_2\text{OSeO}_3}} = 55.54 \text{ J}/(\text{kg} \cdot \text{K})$). The temperature gradient is calculated from these results to
 58 be $\nabla T \approx 11 \text{ mK}/\text{mm}$ for $I_H = 50 \mu\text{A}$ and $\nabla T \approx 4.6 \text{ K}/\text{mm}$ for $I_H = 1 \text{ mA}$.

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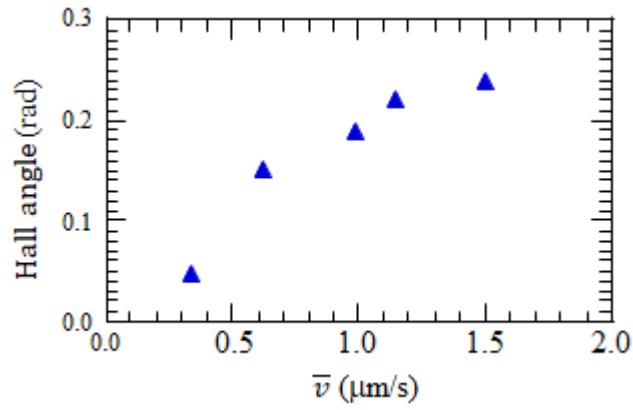


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61 **Supplementary Figure 3: Temperature maps of finite element simulations.** **a.** Geometry of
 62 the device setup. **b-c.** Temperature map resulting from running an electric current (b) $I_H = 50 \mu\text{A}$
 63 and (c) $I_H = 1 \text{ mA}$ through the heater wire. **d-e.** Line profiles extracted from the bulk (blue solid
 64 line) and Lorentz TEM (green dashed line) regions of the sample marked (white dashed lines) in
 65 (b) and (c), respectively.

66 **The relationship of the skyrmion Hall angle and velocity**

67 The Supplementary Figure 4 shows that the skyrmion Hall angle (blue triangles) increases
68 nonlinearly with its velocity in the increase of the ∇T .



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70 **Supplementary Figure 4: The relationship of the skyrmion Hall angle and skyrmion velocity**
71 **($\bar{v}$).**

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