Thermal generation, manipulation and thermoelectric detection of skyrmions

Zidong Wang, Minghua Guo, Heng-An Zhou, Le Zhao, Teng Xu, Riccardo Tomasello, Hao Bai, Yiqing Dong, Soong-Geun Je, Weilun Chao, Hee-Sung Han, Sooseok Lee, Ki-Suk Lee, Yunyan Yao, Wei Han, Cheng Song, Huaqiang Wu, Mario Carpentieri, Giovanni Finocchio, Mi-Young Im, Shi-Zeng Lin and Wanjun Jiang

The efficient generation, manipulation and detection of magnetic skyrmions are important for the development of future spintronic devices. One approach is to use electric-current-induced spin torques. Recently, thermally induced skyrmion motion has also been observed, but wider experimental evidence and its capabilities remain limited. Here we report the thermal generation, manipulation and thermoelectric detection of nanoscale skyrmions in microstructured metallic multilayers integrated with on-chip heaters. The local application of heat can facilitate a domain morphological transition and the formation of skyrmions at the device edge, where a low energy barrier exists. We observe the unidirectional diffusion of skyrmions from hot regions to cold regions, which is due to the interplay among the repulsive forces between skyrmions, thermal spin–orbit torques, entropic forces and magnonic spin torques. The thermally generated skyrmions can also be electrically detected via the Nernst voltage.

Magnetic skyrmions are particle-like spin textures that have been observed in chiral bulk magnets\(^1\)–\(^4\) and asymmetric magnetic multilayers\(^5\)–\(^14\). Electrical currents and current-induced spin–orbit torques (SOTs) can be used to manipulate skyrmions in various metallic systems\(^5\)–\(^8\),\(^10\)–\(^14\), and such capabilities could be useful in the development of energy-efficient spintronic devices. Thermal effects can also be used to generate and manipulate skyrmions\(^6\)–\(^8\),\(^10\), which could lead to the development of unconventional computing\(^1\) and energy-harvesting\(^16\) applications. These thermal effects are, however, difficult to be observed in bulk samples and large-area films; therefore, microstructured devices need to be employed. Furthermore, the generation of skyrmions via a pure thermal effect\(^19\)–\(^21\) has not been experimentally demonstrated so far; moreover, whether the skyrmion motion driven by thermal gradients follows the direction of thermal diffusion or, oppositely, the direction of magnonic spin torque\(^15\),\(^20\),\(^22\),\(^23\) remains an open question.

Here we show that nanoscale skyrmions in magnetic multilayers\(^5\)–\(^10\) can be thermally generated; we find that these skyrmions unidirectionally diffuse from hot regions to cold regions. Our microstructured devices are integrated with on-chip heaters that can elevate local temperatures and creating temperature gradients. The application of local heating facilitates the skyrmion generation out of other competing magnetic phases by overcoming the energy barriers\(^19\),\(^20\). In our experiments, in particular, a local increase of temperature can overcome the low energy barrier that results in skyrmion generation at the device edge or through a domain morphological transition in the interior of the devices. A temperature-gradient-induced unidirectional diffusion from hot to cold regions is also experimentally observed and theoretically explained through the combined contribution from the repulsive forces between skyrmions, thermal SOTs, magnonic spin torques\(^6\),\(^8\),\(^10\),\(^13\),\(^21\) and entropic forces\(^24\). We further thermoelectrically detect these skyrmions by measuring the related anomalous Nernst voltages\(^25\). Our results can be useful for studying skyrmions and their dynamics in magnetic metals and insulators\(^26\),\(^27\) and may lead to various technologically relevant physics/device concepts to be investigated\(^7\).

Thermal generation of nanoscale skyrmions

We used asymmetric multilayers made of [Ta/Co\(_{60}\)Fe\(_{20}\)B\(_{20}\)/MgO\(_{15}\)]\(_{15}\) and [Pt/Co/Ta\(_{15}\)]\(_{15}\), which are characterized by a monotonic increase in the interfacial Dzyaloshinskii–Moriya interaction (DMI) strengths\(^5\),\(^8\),\(^10\),\(^13\),\(^21\) and damping parameters\(^10\). Magnetometry measurements reveal hysteresis loops that are similar to multilayers hosting either the Néel-type\(^6\),\(^8\),\(^10\),\(^13\) or hybrid-type\(^15\),\(^28\),\(^29\) skyrmions. Because the size of skyrmions in these multilayers is generally smaller than 200 nm, we employed a full-field, soft X-ray transmission microscope (XM-1 at the Advanced Light Source, Lawrence Berkeley National Laboratory\(^30\)) with a spatial resolution down to 20 nm. The X-ray approach allows us to study the dynamics of skyrmions induced by a perpendicular magnetic field (\(\mu_0 H_z\)), electrical current (\(j_z\)), temperature (\(T\)) and temperature gradient (\(\nabla T(x)\)), with \(\mu_0\) being the vacuum permeability. The magnetic imaging was...
conducted at the Fe $L_2$ edge (708.5 eV) in the $[\text{Ta/Co}_{20}\text{Fe}_{60}\text{B}_{20}/\text{MgO}]_{15}$ multilayer and at the Co $L_2$ edge (778.5 eV) in the $[\text{Pt/Co}_{20}\text{Fe}_{60}\text{B}_{20}/\text{MgO/Ta}]_{15}$ and $[\text{Pt/Co/Ta}]_{15}$ multilayers. Note that the dominant features of the thermal generation of skyrmions in these three multilayers remain the same, indicating that the phenomenology revealed in our experiments is generic in skyrmion-hosting multilayers. We focus on the $[\text{Ta/Co}_{20}\text{Fe}_{60}\text{B}_{20}/\text{MgO}]_{15}$ multilayers, which exhibit the strongest X-ray magnetic circular dichroism contrast and a low-pinning effect$^{13,17}$, unless otherwise specified.

We fabricated devices by integrating magnetic multilayers with on-chip heaters and thermometers made of Ta (20 nm)/Pt (50 nm) for both in situ control/measurement of temperatures and anomalous Nernst measurements. These devices were prepared onto insulating Si$_N$ membrane (100 nm) membranes to ensure X-ray transmission imaging. An optical image of the device is shown in Fig. 1a. By applying a pulse voltage ($V_p$) to the Ta/Pt heater, a local temperature gradient of $VT(x)$ is created via heat dissipation in the multilayer, which could generate skyrmions from different background orderings. Furthermore, the accompanied temperature gradient produces the diffusion of skyrmions and allows the electrical detection of thermally generated skyrmions by measuring the anomalous Nernst voltage ($V_{\text{Nernst}}$) between two contacts. Additionally, symmetric heaters located on both sides of the multilayer enable the directional control of skyrmion generation. The calibrations of temperatures and temperature gradients, as discussed in Supplementary Information Part 8, suggest the existence of quasi-linear temperature gradients in the multilayer. For the maximum voltage applied to the Ta/Pt heater, the Oersted field at the multilayer was calculated to be less than 0.22 mT; therefore, its influence on the skyrmion dynamics is negligible. The threshold depinning electrical current at room temperature (below which skyrmions do not move) is estimated to be of the order of $I_{\text{th}} \approx 10^7 \text{A cm}^{-2}$ by applying electrical currents to the multilayers, which is comparable to similar multilayers$^{13}$.

The temperature profile of the whole device on a 100-nm-thick Si$_N$ membrane ($500 \times 500 \mu\text{m}^2$) was computed by the COMSOL Multiphysics software with material-specific parameters, as shown in Fig. 1b. Detailed descriptions are given in the Methods and Supplementary Information. A linescan of the device (cyan line) is shown in the lower side of Fig. 1b, which confirms a varying temperature profile along the x axis. For different voltages $V_p$ applied to the upper heater ($H_1$), the temperatures of both the heaters ($T_{\text{H}_1,\text{L}_1}$) and those at the upper/lower edges of the multilayer ($T_{\text{U}_1,\text{L}_1,\text{E}}$) were simulated, as shown in the right side of Fig. 1b. From the temperature difference between $T_{\text{U}_1,\text{E}}$ and $T_{\text{L}_1,\text{E}}$, the linear temperature gradient, $VT(x)$, along the x axis in the multilayer can be found. The experimentally measured temperatures of both the heaters (H1,2) agree with the COMSOL simulations.

Representative images of the thermal generation of skyrmions in the $[\text{Ta/Co}_{20}\text{Fe}_{60}\text{B}_{20}/\text{MgO}]_{15}$ multilayers under positive and negative magnetic fields are shown in Fig. 1c,d, respectively. When a pulse voltage of duration 100 µs and amplitude $V_p = 0.59$ V is applied to the upper heater ($H_1$), the original disordered stripe domains transform into densely packed skyrmions, as shown in Fig. 1c for $\mu_H I_1 = -25.6$ mT and Fig. 1d for $\mu_H I_1 = 25.4$ mT. Since the skyrmion topological charge $Q = 1/4\pi |\text{m}| \cdot (\partial_x \text{m} \times \partial_y \text{m}) \cdot dx dy$ is an odd function of the normalized magnetization $\text{m}$, it switches its sign under reversed external magnetic fields, as evidenced by the opposite colour contrasts shown in Fig. 1c,d. The temperatures at the upper/lower edges are $T_{\text{U}_1,\text{E}} = 399.3$ K and $T_{\text{L}_1,\text{E}} = 392.5$ K, respectively, and the calculated temperature gradient in the multilayer is $VT(x) = 1.6$ K µm$^{-1}$. The diameter of the skyrmion is estimated to be around 140 nm by fitting the skyrmion profile (Supplementary Information Part 3), and the skyrmion density is 6.8 µm$^{-2}$. Note that the similar phenomena shown in Fig. 1c,d can also be repeated by using the lower heater (H2) located on the opposite side of the multilayer, as shown in Extended Data Fig. 1.

To resolve the detailed intermediate processes of skyrmion generation, a sequence of smaller pulse voltages was adopted to reduce the generation efficiency. At $\mu_H I_1 = -19.3$ mT, stripe domains prevail in the multilayer. Following the increased number of pulses, three distinct behaviours can be identified, as shown in Fig. 2a: (1) nucleation of skyrmions from the hot edge, (2) transformation from the existing stripe domains into isolated skyrmions and (3) the unidirectional motion of thermally generated skyrmions from the hot region to the cold region. Intriguingly, under a saturated ferromagnetic (FM) background, coexisting stripe domains and isolated skyrmions can also be generated near the hot edge and from the interior of the multilayers (presumably around the structural defects with a low energy barrier$^{10}$), as shown in Fig. 2b. These characteristics can be clearly seen in Extended Data Figs. 1, 2 and 4 and in Supplementary Videos 1–4.

Figure 2c shows the thermal generation of skyrmions in the $[\text{Pt/Co/Ta}]_{15}$ multilayer from a fully saturated FM background ($\mu_H I_1 = -47.8$ mT). The diameter of skyrmions is around 95 nm in this multilayer owing to the elevated DMI strength. After applying a pulse voltage (duration of 100 µs, $V_p = 0.68$ V and $T_{\text{U}_1,\text{E}} = 436$ K) across the upper heater ($H_1$), skyrmions are solely generated from the hot edge, which then propagate towards the cold edge upon applying the next pulse voltage. Note that the pinning effect of skyrmions in the $[\text{Pt/Co/Ta}]_{15}$ multilayer is stronger compared with the $[\text{Ta/Co}_{20}\text{Fe}_{60}\text{B}_{20}/\text{MgO}]_{15}$ and $[\text{Pt/Co}_{20}\text{Fe}_{60}\text{B}_{20}/\text{MgO/Ta}]_{15}$ multilayers$^{13}$. The representative thermal generation of skyrmions in the $[\text{Pt/Co}_{20}\text{Fe}_{60}\text{B}_{20}/\text{MgO/Ta}]_{15}$ multilayer is also shown in Extended Data Fig. 5. Since both the pinning effect and magnetic damping intimately correlate with structural inhomogeneities or defects, we empirically used the damping parameter ($\alpha$) as an indicator to show the effect of pinning on skyrmion generation. As shown in Fig. 2d, a monotonic increase in the threshold temperatures ($T_{\text{th}}^{\text{U}_1,\text{E}}$) is required to produce densely packed skyrmion phases ($\mu_H I_1 = 24.6$ mT). Since a large damping parameter reduces the thermal activation rate of skyrmion crossing the energy barrier, it increases $T_{\text{th}}^{\text{U}_1,\text{E}}$. Other factors such as exchange interactions and boundary geometry are also important in determining $T_{\text{th}}^{\text{U}_1,\text{E}}$, which requires further investigations.

To quantify the skyrmion generation rate as a function of pulse duration and amplitude, the total number of skyrmions was counted. When $375$ K < $T_{\text{th}}^{\text{U}_1,\text{E}} < 385$ K (intercept at the x axis), the increased $T_{\text{th}}^{\text{U}_1,\text{E}}$ results in a linear increase in the skyrmion generation rate by 27 K$^{-1}$, as shown in Fig. 2e. The intercept at 375 K indicates the threshold temperature at which a substantial number of skyrmions are generated after applying a pulse voltage with a duration of 100 µs.

A phase diagram summarizing the evolution of stripe domains, coexisting stripe domains and skyrmions, densely packed skyrmion lattice, and saturated FM states as a function of the magnetic field and temperature of the hot edge ($T_{\text{th}}^{\text{U}_1,\text{E}}$) for the $[\text{Ta/Co}_{20}\text{Fe}_{60}\text{B}_{20}/\text{MgO}]_{15}$ multilayer is shown in Fig. 2f. A similar phase diagram for the magnetic fields and pulse durations (fixed amplitude $V_p = 0.53$ V) is shown in Extended Data Fig. 6. In both phase diagrams, four different magnetic phases can be clearly distinguished. When the magnetic fields are small ($|\mu_H I_1| < 10$ mT), an increase in $T_{\text{th}}^{\text{U}_1,\text{E}}$ only results in a configurational change in the stripe domains. This is due to the fact that the skyrmion phase is locally unstable under weak magnetic fields. When $|\mu_H I_1| > 10$ mT, thermal fluctuations in the range of $375$ K < $T_{\text{th}}^{\text{U}_1,\text{E}} < 397$ K produce a coexisting phase of the stripe domains and sparsely distributed skyrmions. This can be attributed to the stochastic nature of the thermally assisted skyrmion nucleation by overcoming the energy barrier separating the skyrmion and stripe phase. When $T_{\text{th}}^{\text{U}_1,\text{E}} > 397$ K, thermal fluctuations further promote the nucleation of skyrmions and the system enters into a densely packed skyrmion lattice state. When $|\mu_H I_1| > 45$ mT,
Magnetization, while the black colour denotes upward magnetization. μV and transformation from the original stripe domains into densely packed skyrmions after applying a pulse voltage of duration 100 μs. A linescan of the temperature profile (cyan line) from which a linear temperature gradient in the multilayer can be determined is shown on the bottom left. Right: Temperatures of both the heaters (TH1) and those at the upper and lower edges of the multilayer channel were computed and labelled as TUL−E and TUL+E, respectively. c, d. Transformation from the original stripe domains into densely packed skyrmions after applying a pulse voltage of duration 100 μs and V=0.59 V to the upper heater (H1) under negative (μmH=−25.6 mT) (c) and positive (μmH=25.4 mT) (d) magnetic fields. The white colour corresponds to downward magnetization, while the black colour denotes upward magnetization.

Unidirectional diffusion of skyrmions

When skyrmion generation is efficient at the hot edge, there exists an increased repulsive force between the newly generated skyrmions and the existing skyrmions. This naturally results in the unidirectional motion of skyrmions from the hot region to the cold region. However, this unidirectional diffusion can also be attributed to the competition among the entropic forces, magnonic spin torques, and thermal SOTs. To quantify the contribution from these mechanisms, we designed a nanowire pointing to the heater. Skyrmion generation at the hot end is minimized due to the tip-like geometry, as shown in Fig. 3a. In fact, the implementation of this type of device may enable a single skyrmion to be generated in a controllable manner. Additionally, skyrmion generation can be suppressed if the temperature at the tip (TUL−E) can be made lower than the threshold temperature for skyrmion generation (TUL−E), as shown by the phase diagram in Fig. 2f. After applying pulse voltages of duration 500 ms and amplitudes in the range of 0.18–0.23 V (corresponding to 338 K < TUL−E < 365 K) to the heater, the thermal generation of skyrmion is completely suppressed. The resulting unidirectional diffusion driven by the temperature gradients along the nanowire is clearly observed, where VT(x) is in the range of 0.35–0.56 K μm−1, as shown in Fig. 3a. Note that a few skyrmions annihilate when a larger VT(x) is applied. During the diffusion, sparsely distributed skyrmions align in the centre of the [Ta/CoFeB/MgO]15 nanowire, which can be clearly seen from the stochastic trajectory shown in Fig. 3a(8). This occurs as a result of the balanced skyrmion-edge interaction from both the edges. These results also suggest the presence of Brownian-like diffusion. By taking the ratio between the displacements and pulse durations, the diffusion velocity can be calculated, as shown in Fig. 3a(9).

The observed nonlinear velocity and absence of the skyrmion Hall effect are consistent with the stochastic nature of skyrmion...
Fig. 2 | Transformational dynamics and phase diagram in different multilayers. 

**a, b.** Consecutive images acquired from the [Ta/CoFeB/MgO]$_{15}$ multilayer at $\mu_0 H_\perp = -19.3$ mT (**a**) and $\mu_0 H_\perp = -27.6$ mT (**b**) before and after applying the pulse voltages (duration fixed at 100 $\mu$s) to the upper heater (H1), where the computed temperatures at the hot side ($T_{US}^{DE}$) can also be found. Images taken before and after applying the following pulse voltages to the heater are shown in **a**: $V_h = 0.514$ V (first), $V_h = 0.517$ V (second), $V_h = 0.525$ V (third) and $V_h = 0.531$ V (fourth) at $\mu_0 H_\perp = -19.3$ mT. Images taken after applying the following pulse voltages to the heater are shown in **b**: $V_h = 0.556$ V (first), $V_h = 0.560$ V (second), $V_h = 0.571$ V (third) and $V_h = 0.586$ V (fourth) at $\mu_0 H_\perp = -27.6$ mT. While the domains are absent from the original image, skyrmions and stripe domains can also be generated. 

**c.** In the [Pt/Co/Ta]$_{15}$ multilayer, skyrmions can be similarly generated from the hot edge ($436$ K $< T_{US}^{DE} < 464$ K), which then propagate from the hot side towards the cold side followed by the growing area of skyrmion lattices. The amplitude of voltages (100 $\mu$s) at the hot edges are $V_h = 0.682$ V (first), $V_h = 0.701$ V (second), $V_h = 0.712$ V (third) and $V_h = 0.745$ V (fourth). 

**d.** Dependence of the threshold skyrmion generation temperatures ($T_{US}^{DE}$) on $\alpha$ at $\mu_0 H_\perp = 25.4$ mT. 

**e.** Skyrmion generation rate as a function of $T_{US}^{DE}$ for the [Ta/CoFeB/MgO]$_{15}$ multilayer. 

**f.** Phase diagram summarizing the evolution of different magnetic phases as a function of $T_{US}^{DE}$ and $\mu_0 H_\perp$ for the [Ta/CoFeB/MgO]$_{15}$ multilayer.
diffusion. Nevertheless, our experiments clearly show that the thermal diffusion of skyrmions is dominant over the opposite motion driven by magnonic currents.20,21,22,23,36.

Theory on skyrmion generation and diffusion
All the aforementioned experimental observations can be well addressed in a unified theoretical setting as follows. In our multilayer, competing metastable phases exist: stripe domains, mixture of stripe domains and skyrmions, skyrmion lattices, and saturated FM states. Near the (hot) edge, skyrmions can be generated without meeting any singularity. Together with the twisted edge spins induced by the unbalanced interfacial DMI,14,15, the energy barriers for skyrmion generation are relatively low. Local heating at the edge could, therefore, efficiently facilitate skyrmion generation from different magnetic phases. Our calculations based on the statistical rate theory18 and Monte Carlo simulations given in the Supplementary Information confirm that the edge is the dominant source of skyrmion generation. Note that skyrmions can also be generated from the structural defects in the interior of the multilayers and by the coalescence of the stripe domains, which also exhibit low energy barriers.

Our experiments can be numerically reproduced by solving the stochastic Landau–Lifshitz–Gilbert equation in the presence of temperature gradients. In our micromagnetic simulations, other sources that could influence the dynamics of skyrmions, including the thermal spin Hall effect, magnonic spin torques arising from thermally excited magnons22,23,24 and repulsive interaction between the skyrmions are taken into account. The system Hamiltonian reads as $\mathcal{H} = J_{\text{ex}}/2\mathbf{S} \cdot \nabla \mathbf{S} + D S_I (\mathbf{V} \cdot \mathbf{S}) - (\mathbf{S} \cdot \nabla) S_I - \mathbf{H}_S \cdot \mathbf{S}$, where $J_{\text{ex}}$ is the strength of the exchange interaction; $D$, the interfacial DMI parameter; and $\mathbf{H}_S$, the perpendicular magnetic field. The equation of motion for spins ($\mathbf{S}$) can be written as follows:

$$\partial_t \mathbf{S} = -\gamma \mathbf{S} \times (\mathbf{H}_{\text{eff}} + \mathbf{h}_S) + \alpha \mathbf{S} \times \partial_t \mathbf{S},$$  \hspace{1cm} (1)

where $\gamma$ is the gyromagnetic ratio, $\mathbf{H}_{\text{eff}} = -\delta \mathcal{H}/\delta \mathbf{S}$ is the effective field and $\mathbf{h}_S$ is the random thermal fluctuating field at $T(x) = kx$. The choice of $k$ is to ensure that the temperature at the hot edge ($T(x = L_I)$) is comparable to the energy barrier $U_{\text{th}}$ such that appreciable numbers of skyrmions can be generated in the hot region in the timescale of the simulations. Using the saturated FM state as the initial state, the thermal generation of skyrmions from the hot edge of the devices can be seen, which is followed by unidirectional diffusion towards the cold region, as shown in Fig. 3b. If periodic stripe domains were used as the initial state instead, similar phenomena together with a morphological transition from the stripe domains to the isolated skyrmions were identified, as in Extended Data Fig. 7. In both cases, the multilayer is eventually filled with densely packed skyrmions. Once the temperature at the hot side is reduced, skyrmion nucleation is suppressed, and our simulation reproduces the thermal diffusion of skyrmions driven by the temperature gradient indicated in Fig. 3, as shown in Extended Data Fig. 8. Calculations performed by considering material-specific parameters and by
existing skyrmions can be enabled, and the direction of motion
depends on the relative strength of the magnonic spin torque and
SOT of thermoelectric currents.

When \( k_B T \) is comparable with \( U_{\text{pp}} \), the thermally assisted skyrmion
generation becomes important. Subsequently, the dynamics is
governed by the diffusion of skyrmions from the hot region
to the cold region. As a clear demonstration, the time evolution of
skyrmion densities for different amplitudes, namely, \( F_\perp = 0.2 \) and
\( F_\perp = 0 \), is calculated and shown in Fig. 3c,d, respectively. It is evident
that skyrmions can be thermally nucleated at the hot edge regardless
of the choice of magnonic spin torque and spin torques from the
thermoelectric current (\( F_\parallel \geq 0 \)) and subsequently diffuse through
the whole system with a gradient in the density, as indicated by the
integrated probability for skyrmion distribution. Note that an intuitive
picture of skyrmion diffusion driven by temperature gradients
can be derived by treating skyrmions as rigid particles. The entropy
of skyrmions in the hot region is larger than that in the cold region.
The thermalization condition requires the balance of entropy, and
therefore, skyrmions tend to move to the cold region to balance the
entropy gradient. Effectively, skyrmions experience a force associated
with the entropy gradient\(^{3,14} \). This entropic force—together
with the magnonic spin torque, repulsive force between skyrmions
and pinning force—produces the skyrmion motion from the hot
region to cold region.

**Thermoelectric detection of skyrmions**

The presence of skyrmions could affect the dynamics of conduction
electrons\(^{3,14} \). One well-known example is the anomalous

\[
\partial_t P + \partial_x [F_{\text{in}} P] - G_{xx} \partial_x (T \partial_x P) = \omega_s \exp \left( - \frac{U_B}{k_B T} \right),
\]

where \( P(x) \) is the probability of finding skyrmions at time \( t \) and
position \( x \). The second term on the left side describes the average
drift velocity (\( F_{\text{in}} \)) of the skyrmion due to the magnonic spin torque
and spin torque generated by thermoelectric currents, which competes
with the pinning force due to defects. The third term on the left side
describes the diffusion of skyrmions, where \( G_{xx} \) denotes the gyrotropic
coupling component. The term on the right side of equation (2) corresponds to
the thermal activation of skyrmions, where \( U_B \) denotes the energy barrier and \( \omega_s \) denotes
the attempt frequency. In the regime \( k_B T \ll U_{\text{pp}} \), skyrmion nucleation
is greatly suppressed. Under a small temperature gradient, \( F_{\text{in}} P \gg G_{xx} T \partial_x P \). When the pinning is weak, free drift of the
existing skyrmions can be enabled, and the direction of motion
taking into account the magnetostatic field added to the effective
field of equation (1) show qualitatively similar results\(^{30} \).

By assuming that skyrmion diffusion is much faster than the rate
of skyrmion generation, the skyrmion–skyrmion repulsive interaction
can be neglected. In this case, the thermal diffusion of a skyrmion
driven by temperature gradients can be studied
(as experimentally shown in Fig. 3a). After establishing the local
temperature equilibrium with linear \( T(x) \), the thermal generation and
subsequent diffusion of skyrmions can be described by the Fokker–Planck
equation in dimensionless units as follows\(^{36,37} \):

\[
\partial_t P + \partial_x [F_{\text{in}} P] - G_{xx} \partial_x (T \partial_x P) = \omega_s \exp \left( - \frac{U_B}{k_B T} \right),
\]

where \( P(x) \) is the probability of finding skyrmions at time \( t \) and
position \( x \). The second term on the left side describes the average
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\[
\partial_t P + \partial_x [F_{\text{in}} P] - G_{xx} \partial_x (T \partial_x P) = \omega_s \exp \left( - \frac{U_B}{k_B T} \right),
\]
Nernst effect (ANE)\textsuperscript{14,15}, where the Nernst voltage is expressed as $V_{\text{ANE}} \propto M \nabla T(x)$ and $M$ represents the perpendicular magnetization which can be varied by the change in the total number of skyrmions. This motivates the electrical detection of thermally generated skyrmions using the same type of device shown in Fig. 1a. Note that skyrmions contribute to the Nernst voltage through both their magnetization and topology. The skyrmion diffusion could also produce a topological Nernst voltage, but it is expected to be much smaller\textsuperscript{16,17}. By referring to the resistance–current ($R$–$I$) and resistance–temperature ($R$–$T$) curves of both the heaters (H1,2), the corresponding temperatures can be experimentally determined (labelled as $T_{x,E}$), which are consistent with our COMSOL simulations. The temperature differences between $T_{x,E}$ and $T_{E-F}$, therefore, determine the temperature gradients $\nabla T(x)$ across the multilayer, as shown in Fig. 4a,b. For $\nabla T(x) = \pm 2.8$ K m$^{-1}$ generated by either the upper (H1) or lower (H2) heater, opposite signs of voltages can be observed, as shown in Fig. 4c. More ANE data are shown in Extended Data Fig. 9.

At fixed $\nabla T(x)$ and constant $\mu_0 H_L$, the change in $V_{\text{ANE}}$ reflects the change in magnetization and hence the total skyrmion numbers. To demonstrate the electrical detection of a single skyrmion, we first applied a large current $I_{\text{heater}} = 6$ mA ($T_{E-F} = 428$ K > $T_{x,E} = 325$ K) to generate skyrmions and initiate their diffusion. Then, $V_{\text{ANE}}$ was measured under a smaller current of $I_{\text{heater}} = 3$ mA to maintain $V_{\text{TX}} = 0.9$ K m$^{-1}$, where no new skyrmions were generated during the measurement ($\left| (T_{x,E} = 325$ K) < $T_{E-F} = 375$ K$)\right.$. The time-dependent $V_{\text{ANE}}$ measured at $\mu_0 H_L = 25$ mT is shown in Fig. 4d and the corresponding current profile is shown in Fig. 4e. Right after switching to the current of $I_{\text{heater}} = 3$ mA, $V_{\text{ANE}}$ decreases sharply, signifying the reduction in the total number of skyrmions and/or change in the magnetization configuration. Interestingly, we observed many discretized steps in the time evolution of $V_{\text{ANE}}$, where a change in $V_{\text{ANE}}$ is discretized by $\Delta V_{\text{ANE}} = 90 \pm 10$ nV. Each discretized jump can be naturally explained by the annihilation of a single skyrmion in the multilayer, which results in a change in $M$ as thermal equilibrium approaches\textsuperscript{18}. Compared with our micromagnetic simulations shown in Extended Data Fig. 8 and diffusion dynamics in Fig. 3a, we conclude that these discretized jumps, $|V_{\text{ANE}}|$, correspond to the disappearance of a single skyrmion, probably through sample edges or structural defects in the interior of the device. Our experiments, therefore, confirm that the ANE can be used for the thermoelectric detection of a single skyrmion in similar multilayers\textsuperscript{19}.

Conclusions

We have demonstrated the on-chip thermal generation, manipulation and thermoelectric detection of nanoscale skyrmions in metallic multilayers. By applying thermal gradients in devices with on-chip heaters, we observed the unidirectional diffusion of skyrmions from hot regions to cold regions. This effect can be attributed to a combination of repulsive forces between the skyrmions, entropic forces, magnonic spin torque and thermal SOTs. Further, single skyrmions could be thermoelectrically detected via the ANE, as shown by the discretized jumps in the Nernst voltages. Our approach could potentially be integrated with existing electrical manipulation schemes to study the different types of topological spin textures in various FM and ferroelectric materials\textsuperscript{20–24}. In particular, our approach could find applications in platforms based on insulating skyrmion-hosting materials, where electrical currents cannot be applied\textsuperscript{25,26}. Based on the Onsager reciprocal relation, the interacting thermal currents and skyrmion lattices could also be relevant to the topological phenomena, including the topological magnon Hall effect and thermally induced skyrmion Hall effect\textsuperscript{27,28}. Thus, the thermal generation, manipulation and thermoelectric detection of skyrmions could possibly trigger future discoveries in skyrmionics\textsuperscript{3,29} and spin caloritronics\textsuperscript{30}.

Methods

Interfacially asymmetric multilayers of [Ta (30 nm)/Co/Fe:B20 (11.5 nm)/MgO (20 Å)/Co/Fe:B20 (11.5 nm)/MgO (28 Å)]$_3$, [Pt (20 nm)/Co/Fe:B20 (11.5 nm)/MgO (14 Å)/Ta (10 Å)]$_5$, and [Pt (15 Å)/Co (10 Å)/Ta (5 Å)]$_7$, were grown onto semi-insulating Si substrates covered with a 300 nm-thick thermally-formed SiO$_2$ layer and onto 100 nm-thick insulating Si$_3$N$_4$ membranes on top of Si supporting frames. These films were made by using a d.c. magnetron sputtering system (AJAO, Orion) at room temperature under Ar pressure of 3 mtorr with a base pressure of $<2 \times 10^{-7}$ torr. The Si$_3$N$_4$ membranes (electrical resistivity, $\sim 10^{-10}$ to $10^{-14}$ Ω cm) used in this study were obtained from YW MEMS (Suzhou). Multilayer channels on the Si$_3$N$_4$ membranes were patterned by using electron beam lithography and followed by a lift-off process, which were annealed in a vacuum for 30 min to induce the perpendicular magnetic anisotropy. Subsequently, Ta (20 nm)/Pt (50 nm) electrodes were deposited. A Quantum Design superconducting quantum interference device magnetometer was used to measure the magnetic properties. Damping parameters in the multilayers were determined from ferromagnetic resonance. To probe the dominant out-of-plane X-ray magnetic circular dichroism contrast, samples on the Si$_3$N$_4$ membrane for X-ray magnetic circular dichroism imaging were positioned with the plane normal to the incident circularly polarized X-ray beam. Note that the typical imaging acquisition time of a single frame is approximately 60 s, which is faster than the intrinsic domain dynamics; therefore, we probed the morphological changes in the domains before and after applying the pulse voltages to the heater. The best magnetic contrast is obtained at the Fe L$_3$ edge of 708.5 eV for the [Ta/Co/Fe:B$_{20}$/MgO]$_3$ multilayer. Due to the lower (absent) content of Fe and the corresponding weak signal, the magnetic contrasts for the [Pt/Co/Fe:B$_{20}$/MgO]$_3$, [Pt (5 Å)/Co/Fe:B$_{20}$/MgO]$_3$, and [Pt (15 Å)/Co/Fe:B$_{20}$/MgO]$_3$ multilayers were obtained at 778.5 eV. Voltage pulses applied to the on-chip heaters were provided by an Agilent 81150A arbitrary waveform generator and monitored with a 50 Ω-terminated real-time oscilloscope, through which the current flowing in the heater could be calculated. Note that for the anomalous Nernst measurement, the length of the multilayer channel is 30 μm.

Temperature calibration for both the heaters was performed by first measuring the resistance change in the heaters as a function of the current/voltage; by comparing the temperature-dependent resistance changes, temperatures at both the heaters can be determined. The presence of constant temperature gradients is further confirmed through the anomalous Nernst measurement. The presence of quasi-linear temperature gradients in the sample is also experimentally verified and discussed in Supplementary Information Part 8. Temperature profiles of the devices were simulated by using COMSOL Multiphysics software. We implemented a combined ‘Joule heating’ module, which includes the ‘AC/DC’ module to apply the pulse voltages and the ‘heat transfer’ module to describe the heat flow and temperature distribution. The simulation area was within the 500 μm × 500 μm Si$_3$N$_4$ (thickness, 100 nm) membrane window, with the boundary condition fixed at 293 K. For the heaters and electrodes, the following material parameters for Pt are used: thickness of 70 nm and electrical conductivity of $8.9 \times 10^7$ S m$^{-1}$. The multilayer channels were simplified as follows: [Ta (15 nm)/Co/Fe:B$_{20}$/MgO (10 nm)]$_3$, [Pt (10 nm)/Co/Fe:B$_{20}$/MgO (3.5 nm)/MgO (9 nm)/Ta (5 nm)], and [Pt (7.5 nm)/Co (5 nm)/Ta (2.5 nm)], to save the simulation time. All the parameters including density $\rho$, specific heat capacity $C_v$, thermal conductivity $\kappa$ and electrical conductivity $\sigma$ used in the COMSOL simulations are shown in Supplementary Table 1 of Supplementary Information. Micromagnetic simulation studies were independently carried out using a home-built code and by using a state-of-the-art micromagnetic solver, PETASPIN: a complete description can be found in the Supplementary Information.

Data availability

The data that support the plots in this paper and other findings of this study are available from the corresponding authors upon reasonable request.

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References

1. Yu, X. Z. et al. Real-space observation of a two-dimensional skyrmion crystal. *Nature* 465, 901–904 (2010).
2. Jiao, Y. et al. Spin transport in MnSi at ultralow current densities. *Science* 330, 1648–1651 (2010).
3. Fert, A., Cros, V. & Sampaio, J. Skyrmions on the track. *Nat. Nanotechnol.* 8, 152–156 (2013).
4. Nagaosa, N. & Tokura, Y. Topological properties and dynamics of magnetic skyrmions. *Nat. Phys.* 8, 899–911 (2013).
5. Bogdanov, A. N. & Rößler, U. K. Chiral symmetry breaking in magnetic thin films and multilayers. *Phys. Rev. Lett.* 87, 037203 (2001).
6. Heinze, S. et al. Spontaneous atomic-scale magnetic skyrmion lattice in two dimensions. *Nat. Phys.* 7, 715–718 (2011).
7. Romming, N. et al. Writing and deleting single magnetic skyrmions. *Science* 339, 636–639 (2013).
8. Jiang, W. et al. Blowing magnetic skyrmion bubbles. *Science* 349, 283–286 (2015).
9. Chen, G., Mascarque, A., N'Diaye, A. T. & Schmid, A. K. Room temperature skyrmion ground state stabilized through interlayer exchange coupling. *Appl. Phys. Lett.* **106**, 242403 (2015).

10. Woo, S. et al. Observation of room-temperature magnetic skyrmions and their current-driven dynamics in ultrathin metallic ferromagnets. *Nat. Mater.* **15**, 501–506 (2016).

11. Moreau-Luchaire, C. et al. Additive interfacial chiral interaction in multilayers for stabilization of small individual skyrmions at room temperature. *Nat. Nanotechnol.* **11**, 444–448 (2016).

12. Fert, A., Reyren, N. & Cros, V. Magnetic skyrmions: advances in physics and potential applications. *Nat. Rev. Mater.* **2**, 17031 (2017).

13. Everschor-Sitte, K., Masell, J., Reeve, R. M. & Klaui, M. Perspective: magnetic skyrmions—overview of recent progress in an active research field. *J. Appl. Phys.* **124**, 240901 (2018).

14. Jiang, W. et al. Skyrmions in magnetic multilayers. *Phys. Rep.* **704**, 1–49 (2017).

15. Mochizuki, M. et al. Thermally driven ratchet motion of a skyrmion microcrystal and topological magnon Hall effect. *Nat. Mater.* **13**, 241–246 (2014).

16. Everschor, K. et al. Rotating skyrmion lattices by spin torques and field or temperature gradients. *Phys. Rev. B* **86**, 054432 (2012).

17. Závorka, J. et al. Thermal skyrmion diffusion used in a reshuffler device. *Nat. Nanotechnol.* **14**, 658–661 (2019).

18. Bauer, G. E. W., Saitoh, E. & van Wees, B. J. Spin caloritronics. *Nat. Mater.* **11**, 391–399 (2012).

19. Koshibae, W. & Nagaosa, N. Creation of skyrmions and antiskyrmions by local heating. *Nat. Commun.* **5**, 5148 (2014).

20. Lin, S. Z., Batista, C. D., Reichhardt, C. & Saxena, A. AC current generation in chiral magnetic insulators and skyrmion motion induced by the spin Seebeck effect. *Phys. Rev. Lett.* **112**, 187203 (2014).

21. Lemesh, I. et al. Current-induced skyrmion generation through morphological thermal transitions in chiral ferromagnetic heterostructures. *Adv. Mater.* **30**, 1805461 (2018).

22. Kovalev, A. A. & Tserkovnyak, Y. Thermoelectric spin transfer in textured magnets. *Phys. Rev. B* **80**, 100408 (2009).

23. Kong, L. Y. & Zang, J. D. Dynamics of an insulating skyrmion under a temperature gradient. *Phys. Rev. Lett.* **111**, 067203 (2013).

24. Wild, J. et al. Entropy-limited topological protection of skyrmions. *Sci. Adv.* **3**, e1701704 (2017).

25. Shiomi, Y., Kanazawa, N., Shibata, K., Onose, Y. & Tokura, Y. Topological Nernst effect in a three-dimensional skyrmion-lattice phase. *Phys. Rev. B* **88**, 064009 (2013).

26. Seki, S., Yu, Z. X., Ishiwata, S. & Tokura, Y. Observation of skyrmions in a multiferroic material. *Science* **336**, 198–201 (2012).

27. Kézsmárki, I. et al. Néel-type skyrmion lattice with confined orientation in the polar magnetic semiconductor GaV4S8. *Nat. Mater.* **14**, 1116 (2015).

28. Legrand, W. et al. Hybrid chiral domain walls and skyrmions in magnetic multilayers. *Sci. Adv.* **4**, eaat0145 (2018).

29. Li, W. et al. Anatomy of skyrmionic textures in magnetic multilayers. *Adv. Mater.* **31**, 1807683 (2019).

30. Muller, J., Rosch, A. & Garst, M. Edge instabilities and skyrmion creation in magnetic multilayers. *New J. Phys.* **18**, 065006 (2016).

31. Bottcher, M., Heinze, S., Egorov, S., Sinova, J. & Dupe, B. B–T phase diagram of Pb/Fe(0111) computed with parallel tempering Monte Carlo. *New J. Phys.* **20**, 103014 (2018).

32. Yan, P., Wang, X. S. & Wang, X. R. All-magnetic spin-transfer torque and domain wall propagation. *Phys. Rev. Lett.* **107**, 177207 (2011).

33. Zhang, X. C. et al. Skyrmion–skyrmion and skyrmion–edge repulsions in skyrmion-based racetrack memory. *Sci. Rep.* **5**, 7643 (2015).

34. Jiang, W. et al. Direct observation of the skyrmion Hall effect. *Nat. Phys.* **13**, 162–169 (2017).

35. Litzius, K. et al. Skyrmion Hall effect revealed by direct time-resolved X-ray microscopy. *Nat. Phys.* **13**, 170–173 (2017).

36. Chumak, A. V., Vasyuchka, V. I., Serga, A. A. & Hillebrands, B. Magnon spintronics. *Nat. Phys.* **11**, 453–461 (2015).

37. Rohart, S. & Thiaville, A. Skyrmion confinement in ultrathin film nanostructures in the presence of Dyazalolshinskii–Moriya interaction. *Phys. Rev. B* **88**, 184422 (2013).

38. Bessarab, P. F. et al. Lifetime of racetrack skyrmions. *Sci. Rep.* **8**, 3433 (2018).

39. Lin, S. Z. Edge instability in a chiral stripe domain under an electric current and skyrmion generation. *Phys. Rev. B* **94**, 200402(R) (2016).

40. Tomassello, R. et al. Micromagnetic understanding of the skyrmion Hall angle current dependence in perpendicularly magnetized ferromagnets. *Phys. Rev. B* **98**, 224418 (2018).

41. Schlickeiser, F., Rittmann, U., Hinzke, D. & Nowak, U. Role of entropy in domain wall motion in thermal gradients. *Phys. Rev. Lett.* **113**, 097201 (2014).

42. Kim, D. J. et al. Observation of transverse spin Nernst magnetoresistance induced by thermal spin current in ferromagnet/non-magnet bilayers. *Nat. Commun.* **8**, 1400 (2017).

43. Zeiselser, K. et al. Discrete Hall resistivity contribution from Néel skyrmions in multilayer nanodiscs. *Nat. Nanotechnol.* **13**, 1161–1166 (2018).

44. Maciariello, D. et al. Electrical detection of single magnetic skyrmions in metallic multilayers at room temperature. *Nat. Nanotechnol.* **13**, 233–237 (2018).

45. Kanazawa, N. et al. Discretized topological Hall effect emerging from skyrmions in constricted geometry. *Phys. Rev. B* **91**, 041125 (2015).

46. Scricioni, A. F. et al. Thermoelectric signature of individual skyrmions. Preprint at https://arxiv.org/pdf/2001.10251 (2020).

47. Nayak, A. K. et al. Magnetic antiskyrmions above room temperature in tetragonal Heusler materials. *Nature* **548**, 561 (2017).

48. Yu, X. Z. et al. Transformation between meron and skyrmion topological spin textures in a chiral magnet. *Nature* **564**, 95–98 (2018).

49. Das, S. et al. Observation of room-temperature polar skyrmions. *Nature* **568**, 368–372 (2019).

**Author contributions**

W.J. conceived and designed the experiments. H.Z. and T.X. fabricated the thin film. Z.W., H.Z., L.Z., Y.D. and C.S. performed lithographic processing. Z.W. did the COMSOL Multiphysics simulation. M.G., H.B. and H.W. did the anomalous Nernst measurements. Y.Y., H.Z. and W.H. carried out the ferromagnetic resonance experiments. S.L. performed the atomistic micromagnetic simulation and Sokker–Planck calculation. R.T. and G.F. performed the layer-dependent micromagnetic simulations. M.C. and G.F. implemented the micromagnetic solver for multilayer calculations. Z.W., S.J., W.C., H.H., K.L., M.I. and W.J. performed the full-field, soft X-ray microscopy imaging experiments and data analysis. W.J. and S.L. wrote the manuscript with inputs from all authors.

**Competing interests**

The authors declare no competing interests.

**Additional information**

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Correspondence and requests for materials should be addressed to S.-Z.L. or W.J.

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Extended Data Fig. 1 | Skyrmion generation and propagation in the [Ta/Co_{20}Fe_{60}B_{20}/MgO]_{15} multilayer by using the lower heater. At opposite magnetic fields, by applying pulse voltages (duration fixed at 100 μs) into the lower heater (H2), thermal generation of skyrmions, together with their subsequent propagation towards the cold side (upper side) are realized.
Extended Data Fig. 2 | Skyrmion generation and propagation in the [Ta/Co$_{20}$Fe$_{60}$B$_{20}$/MgO]$_{15}$ multilayer at positive magnetic fields (+μ$_{0}$H) by using the upper heater. At different positive magnetic fields, by applying pulse voltages (duration fixed at 100 μs) into the upper heater (H1), the thermal generation of skyrmions, together with the propagation towards the cold side are evident. The experimentally utilized parameters and the estimated temperatures at the upper edge (hot side) are also listed.
Extended Data Fig. 3  | Domain morphological transition in the [Ta/Co_{20}Fe_{80}B_{20}/MgO]_{15} multilayer at smaller magnetic fields by using the upper heater.

At smaller (positive/negative) magnetic fields and by applying pulse voltages (duration fixed at 100 μs) into the upper heater, thermally induced domain morphological transition is observed.
Extended Data Fig. 4 | Skyrmion generation and propagation in the \([\text{Ta}/\text{Co}_{20}\text{Fe}_{60}\text{B}_{20}/\text{MgO}]_{15}\) multilayer by changing the pulse duration via the upper heater. By increasing the duration of pulse voltages (amplitude is fixed at \(V_{\text{h}} = 0.526\) V) in the upper heater, thermal generation of skyrmions and their propagation towards the cold side (lower edge) are observed.
Extended Data Fig. 5 | Skyrmion generation and propagation in the [Pt/Co$_{60}$Fe$_{20}$B$_{20}$/MgO/Ta]$_{15}$ multilayer by using the upper heater. At opposite magnetic fields, by applying increased amplitudes of pulse voltages (duration fixed at 300 μs) into the upper heater, thermal generation of skyrmions, together with their subsequent propagation towards the cold side are realized.
Extended Data Fig. 6 | The phase diagram of skyrmion generation at different pulse durations in the [Ta/Co20Fe60B20/MgO]15 multilayer. a, The response of competing magnetic phases to different pulse durations (with a fixed amplitude $V_h = 0.526\,\text{V}$) and magnetic fields. b, The dependence of the maximum temperatures at the upper (hot) edge ($T_{U-E}$) on the pulse duration ($t_{\text{pulse}}$). The nonlinear increase of $T_{U-E}$ following the increase of pulse duration can be attributed to the fast dissipation of heat through substrate. c, d, Following the continuous increase of pulse duration above 4 ms, the system approaches thermal equilibrium with a constant temperature at the hot edge ($T_{U-E} = 496\,\text{K}$) (c) and a constant temperature gradient in the multilayer $\nabla T(x) = 1.3\,\text{K} \, \mu\text{m}^{-1}$ (d).
Extended Data Fig. 7 | Micromagnetic simulation results of transformation from stripe domains to densely packed skyrmion lattices driven by temperature gradients. Following the increasing time, presented as the number of frames (1, 30, 100, 200, 300, 400), skyrmions are first nucleated at the hot edge, followed by the immediate thermal diffusion from the hot side towards the cold side. Meanwhile, skyrmions are also generated by breaking the stripe domains followed by relaxation in the hot side. The diffusion of skyrmions then pushes the stripe domains out of the simulation box. The time lapse between consecutive frames is $\Delta t = 60J_{ex}/\gamma D^2$. The temperature gradient is $k = 0.01J_{ex}/k_B$ and $H_a = 0.6D^2/J_{ex}$. Here we assume the film thickness is $0.1J_{ex}/D$. The scale bar is $20J_{ex}/D$. The open (periodic) boundary condition is used in the horizontal (vertical) direction.
Extended Data Fig. 8 | Micromagnetic simulation results of the diffusion of skyrmions purely driven by temperature gradients. The micromagnetic simulation of skyrmion diffusion in a nanowire geometry is performed by using the open boundary condition. First, skyrmions are thermally generated at high temperature side using a larger temperature gradient. Subsequently, the temperature gradient is reduced to avoid the nucleation of skyrmions at the hot side, which results in the diffusion of skyrmions towards the cold side. Some skyrmions exit the nanowire through the sample edge during the diffusion. The length and width of the nanowire are $120\, J_\perp/D$ and $40\, J_\perp/D$, respectively. The thermal gradient for diffusion is $k = 0.008J_\perp/k_B$. Disorders in spin anisotropy are introduced to suppress the magnonic spin torque by reducing the magnon mean free path. Here we assume the film thickness is $0.1J_\perp/D$. The scale bar is $10\, J_\perp/D$. 
Extended Data Fig. 9 | Anomalous Nernst effect measured under different temperature gradients in the [Ta/Co$_{30}$Fe$_{50}$B$_{20}$/MgO]$_{15}$ multilayer. a, The evolution of anomalous Nernst voltages ($V_{ANE}$) measured with different currents supplied into the heater ($I_{Heater}$). b, Following the increase of $I_{Heater}$, a parabolic increase of saturated $V_{ANE}(\mu_0H_{\perp}=100\,\text{mT})$ can be found. c, The evolution of $V_{ANE}(\mu_0H_{\perp}=100\,\text{mT})$ as a function of $\nabla T(x)$. d, The time evolution of $V_{ANE}$ measured at a fixed $I_{Heater} = 3\,\text{mA}$ and $\mu_0H_{\perp} = 25\,\text{mT}$, after switching off skyrmion generation currents (from 3.5 mA to 6 mA in 0.5 mA steps). Upon removing the increased DC currents used for generating skyrmions, discretized steps are gradually resolved. e, The corresponding $I_{Heater}$ as a function of time used for the ANE measurement in d.