Direct observation of the skyrmion Hall effect

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The well-known Hall effect describes the transverse deflection of charged particles (electrons/holes) as a result of the Lorentz force. Similarly, it is intriguing to examine if quasi-particles without an electric charge, but with a topological charge, show related transverse motion. Magnetic skyrmions with a well-defined spin texture with a unit topological charge serve as good candidates to test this hypothesis. In spite of the recent progress made on investigating magnetic skyrmions, direct observation of the skyrmion Hall effect has remained elusive. Here, by using a current-induced spin Hall spin torque, we experimentally demonstrate the skyrmion Hall effect, and the resultant skyrmion accumulation, by driving skyrmions from the creep-motion regime (where their dynamics are influenced by pinning defects) into the steady-flow-motion regime. The experimental observation of transverse transport of skyrmions due to topological charge may potentially create many exciting opportunities, such as topological selection.

Because of their topologically non-trivial spin textures, chiral magnetic skyrmions enable many novel phenomena based on their spin topology1–9, such as emergent electro-dynamics10 and effective magnetic monopoles11. As compared to (vortex-like) Bloch skyrmions in most bulk chiral materials1,12, utilizing interfacial inversion symmetry breaking13–15 in heavy metal/ultrathin ferromagnet/insulator heterostructures (with an interfacial chiral Dzyaloshinskii–Moriya interaction (DMI)16) has enabled the observation of robust chiral spin textures17 such as (hedgehog) Néel skyrmions, even at room temperature18,19. In addition, the spin-orbit torques from the spin Hall effect of the incorporated heavy metals (typically Ta, Pt and W)20–22 provide efficient avenues for the electrical generation and manipulation of magnetic skyrmions23,24–29.

Theoretical consideration based on the Thiele equation

By considering an isolated Néel skyrmion as a rigid point-like particle (with its spin texture illustrated in Fig. 1a), the translational motion driven by the spin Hall effect can be described by a modified Thiele equation22,26–31:

$$G \times v - \alpha D \cdot v + 4\pi B \cdot j_{\text{hm}} = 0$$ (1)

Here $G = (0, 0, -4\pi Q)$ is the gyromagnetic coupling vector, with the topological charge $Q$ being defined as $Q = 1/4\pi \int m \cdot (\partial, m \times \partial) dx dy$. $v = (v_x, v_y)$ is the skyrmion drift velocity along the $x$ and $y$ axes, respectively, or is the magnetic damping coefficient and $D$ is the dissipative force tensor. The tensor $B$ quantifies the efficiency of the spin Hall effect with respect to the spin Hall current. $j_{\text{hm}} = j_f/\theta_{\text{hm}}$ is the electrical current density flowing in the heavy metal, $j_f$ is the spin current density, and $\theta_{\text{hm}}$ is the spin Hall angle of the heavy metal. The first term in equation (1) is the topological Magnus force that results in the transverse (gyrotropic) motion of skyrmions with respect to the driving current27,30–32. This term acts equivalently to the Lorentz force for electric charge, and thus gives rise to a Hall-like behaviour of magnetic skyrmions3. The second term is the dissipative force that is linked to the intrinsic magnetic damping of a moving magnetic skyrmion, and the third term is the driving force from the spin Hall spin torque. We note that equation (1) does not include possible pinning effects that may impede skyrmion motion due to the presence of material imperfections33–35, nor does it include the possibility of exciting internal degrees of freedom of the skyrmion. Such internal degrees of freedom may modify the dynamics and dissipation of the driven skyrmion36,37.

It should be mentioned that the gyrotropic motion of dipole-stabilized magnetic bubbles driven by magnetic field gradients has been extensively studied in insulating yttrium iron garnets37,39. However, due to the lack of a chiral DMI in these materials, a uniform spin topology of magnetic bubbles is absent—which, in turn, results in a random transverse motion37–39. In contrast, inversion asymmetric multilayers, such as those studied in the present work, are technologically appealing by hosting chiral skyrmion bubbles with a uniform topological charge that gives rise to a well-defined motion driven by the current-induced spin Hall spin torques32,36,20,21,25–27.

Upon applying a spatially homogeneous current along the $x$ direction $j_{\text{hm}} = (j_x, 0)$, the resultant velocity along the $x$ and $y$ axes can be calculated as $v_x = -(\alpha D/(Q + \alpha^2 D^2))B_{yj_y}$, $v_y = (Q/(Q + \alpha^2 D^2))B_{xj_x}$, respectively30,31. Here $B_j$ is a constant that can be estimated based on the detailed spin configuration and topological charge $Q = \pm 1$ depending on the detailed spin profile. This leads to the expression for the ratio of in-plane velocity components to be written as:

$$\frac{v_x}{v_y} = \frac{-Q}{\alpha D}$$ (2)

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Figure 1 | Schematic of Hall effects for electronic and topological charges. a, Spin texture of a Néel skyrmion. b, Micromagnetic simulation study of the motion of a Néel skyrmion driven by a positive electron current from left to right (+je). After applying a current, the skyrmion gains a transverse velocity (vy) with respect to the driving current direction (+x). Parameters used in this simulation are: electron current density je = +3 × 10^9 A m^-2, exchange stiffness A = 10 × 10^{-12} J m^{-1}, DMI strength DDMI = 0.5 mJ m^{-2}, effective perpendicular magnetic anisotropy Keff = 2.3 × 10^4 J m^{-3}, saturation magnetization Ms = 6.5 × 10^{5} A m^{-1}, damping coefficient α = 0.02. Blue colour corresponds to magnetization orientation downwards into the plane (−mz), grey colour corresponds to magnetization orientation upwards out of the plane (mz). Inset is the evolution of topological charge (Q) as a function of time (and hence the size of skyrmion) which remains constant at −1. c–f, Comparison between the electronic Hall effect and skyrmion Hall effect. c, d, For the electronic Hall effect, holes with a unit electronic charge of +e accumulate at opposite edges of the device upon reversal of the magnetic field directions. e, f, For the skyrmion Hall effect, the reversal of magnetic field directions (from positive to negative) reverses the sign of the topological charge from Q = −1 to Q = +1, leading to the accumulation of skyrmions of topological charges at opposite edges of device.

where $\alpha \approx 0.02$ is the damping parameter (for the magnetic bilayer involved in this study). The dissipative tensor is given by $D = D_x = D_y = (1/4\pi) \int (\partial m/\partial x) \cdot (\partial m/\partial x) dx dy$ and $D_{xy} = D_{yx} = 0$. Assuming a Néel-type skyrmion with a linear change of the spin profile along the radial direction inside the domain wall (the angle ($\theta$) with respect to the z axis going from $\pi$ inside the skyrmion to 0 outside of the skyrmion), the dissipative tensor can be analytically expressed as:

$$D = \pi^2 d / 8 \gamma_{\text{sw}}$$
Thus, $D$ depends on the domain wall width $y_{dw}$ and is proportional to the skyrmion diameter $d$ (see Supplementary Methods). Thus, for small Néel skyrmions $v_1/v_\alpha \gg 1$ (large skyrmion Hall angle close to $\pm 90^\circ$) results in mostly transverse motion, while for larger skyrmions the perpendicular motion can be less pronounced with $v_1/v_\alpha \approx 1$ (smaller skyrmion Hall angle). In either case, this should lead to the accumulation of skyrmions at the device edge, as demonstrated by micromagnetic simulations shown in Fig. 1b. The size of the numerically simulated skyrmions in Fig. 1b is about 160 nm, which results in $D \approx 9.4$ for $y_{dw} = \sqrt{A/K_{\text{eff}}} \approx 21$ nm, assuming an exchange spin wave stiffness $A = 10 \times 10^{-12}$ J m$^{-1}$ (refs 16,22,40), and effective perpendicular magnetic anisotropy $K_{\text{eff}} = 2.34 \times 10^7$ J m$^{-3}$ that is measured from in-plane hard axis hysteresis loop$^3$. Thus, for $\alpha \approx 0.02$, resulting in $v_1/v_\alpha \approx 5.3$, the skyrmion Hall angle $\Phi_\alpha = \tan^{-1}(v_1/v_\alpha)$ corresponds to about $\Phi_\alpha \approx 79^\circ$.

According to the definition of topological charge $Q = 1/4\pi \int m \cdot (\partial \times \partial.m) dx dy$, the spin topology of a skyrmion texture is independent of the size. This is demonstrated by the micromagnetic simulation given in the inset to Fig. 1b, where the size of skyrmion changes from 160 nm to 50 nm (with a fixed Néel-type domain wall of width $y_{dw} = 21$ nm), yet the calculated topological charge remains constant as $Q = -1$. Furthermore, the independence of topological charge on the detailed spin profile is also discussed in part 3 of the Supplementary Methods. Note that during the motion along the edge, the size of skyrmion shrinks due to the dipolar repulsive force from the edge$^{15,17,30,31}$.

Comparison between charge Hall and skyrmion Hall effects

Reversing the perpendicular magnetic field, and correspondingly the magnetization from positive to negative, the sign of the skyrmion topological charge is also reversed from $Q = -1$ (shown in Fig. 1e) to $Q = +1$ (shown in Fig. 1f). This is because the topological charge $Q = 1/4\pi \int m \cdot (\partial \times \partial.m) dx dy$ is an odd function of the magnetization vector $m$, and therefore reverses sign upon inversion of the spin textures—that is, by applying opposite magnetic fields. This sign reversal leads to the opposite direction of the topological Magnus force (since $G \times m$ is linked to the sign of the topological charge), and hence the accumulation of skyrmions at the opposite edge, as suggested by equation (1). This behaviour resembles phenomenologically the electronic Hall effect of electrons/holes in conductors in the presence of a perpendicular magnetic field (see Fig. 1c,d); therefore, this behaviour is referred to as the skyrmion Hall effect (Fig. 1e,f). In the conventional charge Hall effect, reversing perpendicular magnetic fields ($B_z$), however, does not change the sign of the charge carriers but instead reverses the sign of the Lorentz force from $\mathbf{v} \times (0,0,B_z)$ to $\mathbf{v} \times (0,0,-B_z)$. This is a distinct difference between the conventional charge Hall effect and the skyrmion Hall effect from the topological charge. While the occurrence of the skyrmion Hall effect driven by electrical currents has been predicted theoretically$^{30,36}$, and suggested numerically via micromagnetic simulations$^{30,31}$, an experimental observation was still lacking and is addressed here.

By utilizing a geometrical constriction, we have previously demonstrated that spatially divergent spin Hall spin torques can dynamically convert a chiral band domain into Néel skyrmions$^{18}$. That work was performed with an asymmetric Ta(5 nm)/Co$_{0.8}$Fe$_{0.2}$B$_{2.8}$(CoFeB)(1.1 nm)/TaO$_{x}$(3 nm) trilayer with an interfacial DMI$^{30}$ of strength $<0.5$ mJ m$^{-2}$. These electrically generated skyrmions, however, did not show any clear signature of the skyrmion Hall effect$^{18,37}$, in contrast to expectations from theoretical modelling$^{28}$. As these experiments were performed at low current densities ($j_e < 1 \times 10^{5}$ A cm$^{-2}$), the absence of transverse motion can be attributed to the creep motion of skyrmions in the low-current-density regime, in which the direction of motion is influenced strongly by the pinning potential of randomly distributed defects$^{33,34,40}$. By progressively increasing the current density, it should be possible to drive skyrmions from the creep-motion regime into the steady-flow-motion regime, as suggested by recent theoretical studies on the collective transport of skyrmions with random disorder/defects$^{33,34,42}$.

In the present study, we employ a modified design of Hall bar devices prepared from the same material system Ta/CoFeB/TaO$_x$ with dimensions wherein a larger current density can be applied. In the low-current-density regime, isolated skyrmions were created by sweeping the perpendicular magnetic field. In the high-current-density regime ($j_e > 4 \times 10^{4}$ A cm$^{-2}$), skyrmion production underneath the Ti/Au electrodes is observed. This can presumably be attributed to the perpendicular inhomogeneous current-injection-induced magnetization instability around defects. Current-driven imaging data were acquired by using a polar magneto-optical Kerr effect (MOKE) microscope in a differential mode at room temperature.

Drive-dependent skyrmion Hall angle

We first discuss the creep motion of the skyrmions in the low-current-density regime. Individual polar-MOKE images are shown in Fig. 2a–f for $Q = -1$ skyrmions ($H_J = +4.8$ Oe) and in Fig. 2g–l for $Q = +1$ skyrmions ($H_J = -5.2$ Oe), respectively, for a device of dimensions 100 nm (width) $\times$ 500 nm (length). Note that we studied individual skyrmions that are well-isolated to avoid complications due to a topological repulsive force between skyrmions$^{31}$. These two experiments were performed by applying pulsed electron currents of amplitude $j_e = +1.3 \times 10^{5}$ A cm$^{-2}$ and with a duration of 50 µs.

In this report, $j_e$ denotes the direction of electron motion; that is, opposite to the charge motion. The red arrow refers to a positive electron motion direction $+j_e$ from left to right. The current density is normalized by the total thickness of Ta (5 nm) and CoFeB (1.1 nm). By comparing the trajectories shown in Fig. 2f for the $Q = -1$ skyrmion and Fig. 2l for the $Q = +1$ skyrmion, it is clear that a stochastic motion is observed without net transverse components.

By increasing the current density to $j_e = +2.8 \times 10^{5}$ A cm$^{-2}$, it is observed that the direction of motion develops a well-defined transverse component, which is exemplified by a straight and diagonal trajectory. Snapshots in Fig. 2m–r correspond to a $Q = -1$ skyrmion ($H_J = +5.4$ Oe), and in Fig. 2s–x to a $Q = +1$ skyrmion ($H_J = -5.2$ Oe). The opposite sign of slopes in Fig. 2r and x are consistent with the opposite sign of the topological Magnus force, that consequently gives rise to opposite directions for the transverse motion. By reversing the electron current direction, the direction of motion is also reversed, as shown in the Supplementary Methods.

Current-skyrmion motion phase diagram

A current–velocity relationship is subsequently established and is shown in Fig. 3a, indicating a monotonic increase of the average velocity as a function of current density. The average velocity $\overline{v}$ is defined as $\overline{v} = L/(N \cdot \Delta t)$, where $L$ is the total displacement, $N$ is the number of pulses, and $\Delta t$ is the duration of pulse. The number of pulses was typically chosen to be $N > 10$ to minimize the uncertainty due to the stochastic motion of skyrmions in the creep-motion regime. For a fixed pulse duration of 50 µs, there is a threshold depinning current density $j_e = (0.6 \pm 0.1) \times 10^{5}$ A cm$^{-2}$, below which skyrmions remain stationary (blue region in Fig. 3a). Above this threshold depinning current two features were observed. The first is stochastic migration of skyrmions following the electron current direction when $j_e < 1.5 \times 10^{5}$ A cm$^{-2}$ (orange region in Fig. 3a). The second is motion of skyrmions with a well-defined transverse velocity when the current density $j_e > 1.5 \times 10^{5}$ A cm$^{-2}$ (green region in Fig. 3b). For example, the velocity is estimated to be $\overline{v} = 0.75 \pm 0.02$ m s$^{-1}$ at a current density $j_e = 6.2 \times 10^{5}$ A cm$^{-2}$. It is also noticed that the threshold depinning current density evolves
Figure 2 | MOKE microscopy images of pulse current-driven skyrmion motion. All experiments were done by using 50-μs pulsed currents. a–e, Snapshots of (Q=−1) skyrmion motion captured after applying successive current pulses of amplitude $j_e = +1.3 \times 10^6 $ A cm$^{-2}$ and external perpendicular magnetic field ($H_z = +4.8$ Oe). f, Summary of the skyrmion trajectory from a–e shows no net transverse motion along the y direction. g–k, Snapshots of (Q=+1) skyrmion motion at $j_e = +1.3 \times 10^6 $ A cm$^{-2}$ and magnetic field ($H_z = −5.2$ Oe). l, Stochastic trajectory from g–k, again showing no net transverse motion. m–q, Snapshots of (Q=−1) skyrmion motion at $j_e = +2.8 \times 10^6 $ A cm$^{-2}$ and magnetic field ($H_z = +5.4$ Oe). r, Summary of the trajectory from m–q, with its nearly straight and diagonal trajectory indicating the presence of transverse motion along the +y direction. The size of skyrmion shrinks slightly as compared to a–e due to the larger perpendicular magnetic fields. Two other skyrmions that moved into the frame, marked with green circles, were not studied. s–w, Snapshots of (Q= +1) skyrmion motion at $j_e = +2.8 \times 10^6 $ A cm$^{-2}$ and magnetic field ($H_z = −5.2$ Oe). x, Summary of the trajectory from s–w. Again, there is a nearly straight and diagonal trajectory. However, the slope is opposite, indicating the presence of transverse motion in the opposite direction (along the y direction).

As a function of pulse duration. Namely, for shorter pulses, larger amplitudes are required to result in skyrmion motion, indicative of a thermally assisted depinning process of magnetic skyrmions from local pinning sites due to disorder.

The onset of transverse motion is shown in Fig. 3b. The deviation of skyrmion motion with respect to the applied current direction (+x) can be quantified by a skyrmion Hall angle $\Phi_x = \tan^{-1}(v_y/v_x)$. With increasing current density ($j_e > 1.5 \times 10^6 $ A cm$^{-2}$), the ratio of $v_y/v_x$ (blue symbols) and consequently the skyrmion Hall angle $\Phi_x$ (dark red symbols) increase monotonically. The skyrmion Hall angle can be as large as $\Phi_x \approx 16^\circ$, with a ratio of $v_y/v_x \approx 0.28$ at the maximum current density $j_e = 6.2 \times 10^6 $ A cm$^{-2}$. Given the roughly linear dependence on the current density without indication of saturation, it is expected that the skyrmion Hall angle $\Phi_x$ can be even larger for even higher current densities. However, the electrical resistance of the first type of devices prevented application of higher...
current densities. We addressed this issue with slightly modified devices, as discussed further below. This current density dependence is inconsistent with the simple theoretical prediction given in equation (2), which suggests a constant value of $v_s/v_e$ that is given by $1/(\alpha D)$ and is independent of the driving current. On the other hand, the magnitude obtained at the highest achievable current density is approximately in the range of what can be expected theoretically. While for most theoretical studies, small skyrmions are considered (10 nm), leading to a small dissipative term $D$ and $v_s/v_e > 1$, the skyrmions imaged here are significantly larger ($\approx 1,000$ nm). For skyrmions of diameter $\approx 1,000 \pm 300$ nm with a fixed domain wall widths $\gamma_{dw} \approx 21$ nm, the value of the dissipative term $D$ is estimated to be around 60 and increases proportionally with the area of the skyrmion, as discussed in Supplementary Fig. 1. The error bar of 300 nm arises from the optical diffraction limit. This suggests a skyrmion Hall angle $\Phi_{sk}$ around $40^\circ$ as an upper limit, which is compatible with the observed values of $v_s/v_e$ being less than 0.3 for current density $j_e < 7 \times 10^6$ A cm$^{-2}$. A further increase of the current density could thus lead to higher values of $v_s/v_e$ and the saturation of skyrmion Hall angle.

One possible reason for the apparent discrepancy between our experimental observation of the current-dependent increasing value of $v_s/v_e$ and the simple prediction of equation (2) is the presence of pinning that affects the skyrmion motion. Such pinning may originate from random disorder/defects in the sputtered films, which is consistent with the experimentally observed threshold depinning of skyrmions and stochastic motion at low driving currents. Detailed theoretical investigation of the dynamics of skyrmions interacting with randomly distributed disorder/defects has shown a significant reduction of the skyrmion Hall angle $\Phi_{sk}$, as well as complex skyrmion trajectories. Specifically, the skyrmion Hall angle is minimized around the depinning threshold and increases monotonically with the driving current, due to side-jump scattering of skyrmions from the scattering potentials. This is reminiscent of our experimental observations in the absence of interactions between multiple skyrmions. Experimentally for $j_e < 1.5 \times 10^6$ A cm$^{-2}$, skyrmions escape from the pinning potential and exhibiting a hopping-like motion along the driving direction with a zero skyrmion Hall angle. In the strong-driving regime $j_e > 1.5 \times 10^6$ A cm$^{-2}$, increasing the driving force increases monotonically the skyrmion Hall angle $\Phi_{sk}$. In fact, a recent study

Figure 3 | Phase diagram of current-driven skyrmion motion. a. The average skyrmion velocity ($v$) as a function of electron current density ($j_e$). The blue region corresponds to the skyrmion-pinning regime (when $j_e < (0.6 \pm 0.1) \times 10^6$ A cm$^{-2}$). The orange region corresponds to the regime of stochastic motion without net transverse motion ($(0.6 \pm 0.1) \times 10^6$ A cm$^{-2} < j_e < 1.5 \times 10^6$ A cm$^{-2}$). b. Evolution of the skyrmion Hall angle ($\Phi_{sk}$) and the ratio between the transverse and longitudinal velocities of the skyrmion ($v_s/v_e$). The green region corresponds to the regime without net transverse motion (when $j_e < 1.5 \times 10^6$ A cm$^{-2}$). When $j_e > 1.5 \times 10^6$ A cm$^{-2}$, both $\Phi_{sk}$ and $v_s/v_e$ are monotonically increasing as a function of current density. Data shown in a and b are collected by tracking a single skyrmion in a device of dimensions 100 $\mu$m (width) $\times$ 500 $\mu$m (length) with an external magnetic field $+5.2$ Oe. c. Phase diagram of the skyrmion Hall angle as a function of current density/sign of topological charge in a modified device of dimensions 80 $\mu$m (width) $\times$ 100 $\mu$m (length), obtained by tracking the motion of several tens of skyrmions. In the low-current-density regime, the skyrmion Hall angle $\Phi_{sk}$ exhibits a linear dependence similar to that shown in b. A further increase of current density $j_e > 8 \times 10^6$ A cm$^{-2}$ results in the saturation of the skyrmion Hall angle. By alternating the sign of the driving electron current density ($\pm j_e$) and the sign of topological charge ($\pm Q$), a phase diagram for the four different regimes was determined. Namely, for negative topological charge (under positive magnetic fields), regime I ($+j_e$, $-Q$) with positive $\Phi_{sk}$ and regime III ($-j_e$, $-Q$) with negative $\Phi_{sk}$ were identified by changing the polarity of the electron current. For skyrmions with positive topological charge (under negative magnetic fields) a positive $\Phi_{sk}$ in regime II ($-j_e$, $+Q$), and negative $\Phi_{sk}$ in regime IV ($+j_e$, $+Q$) were detected. The decrease of skyrmion Hall angle from $|\Phi_{sk}| \approx 32 \pm 2^\circ$ to $|\Phi_{sk}| \approx 28 \pm 2^\circ$ is also demonstrated by increasing the skyrmion diameter from $d = 800 \pm 300$ nm ($+5.4$ Oe/$-5.2$ Oe) to $d = 1,100 \pm 300$ nm ($+4.8$ Oe/$-4.6$ Oe).
of the dependence of skyrmion Hall angle on the driving force in the presence of random defects reproduced the experimentally observed behaviour and suggested the saturation of the skyrmion Hall angle in the strong-driving regime.

To probe the saturation of the skyrmion Hall angle, we adopted a modified device design of dimensions 80 µm (width) × 100 µm (length) with a smaller electrical resistance. Experimentally, when the applied current density is larger than $|j_x| > 8 \times 10^6$ A cm$^{-2}$, indeed a saturation of the skyrmion Hall angle is observed (shown in Fig. 3c). For regime I (+$j_x$, −$Q$) we present data for the positive electron current density (+$j_x$) and positive perpendicular magnetic fields (−$Q$). For $H_z = +5.4$ Oe, a saturation of skyrmion Hall angle $\phi_h \approx 32 \pm 2^\circ$ is observed (skyrmion of diameter $d = 800 \pm 300$ nm), and $\phi_h \approx 28 \pm 2^\circ$ is observed for $H_z = +4.8$ Oe (with a larger diameter $d = 1,100 \pm 300$ nm). This trend agrees with the dependence of $D$ on $d$ given by equation (3). The values are just below the expected range of values based on equations (2) and (3), which are $47 \pm 1^\circ$ and $38 \pm 8^\circ$ for $d = 800$ nm and 1,100 nm, respectively, using the estimated domain wall width of 21 nm, and taking only the uncertainties in the skyrmion diameter into account. The quantitative agreement is reasonable considering the uncertainty in the exchange stiffness $A$ in thin films, which impacts the estimated value of the domain wall width, and the fact that equation (1) is derived assuming point-like rigid skyrmions.

It is noted that the size of skyrmions does not change significantly as a function of perpendicular fields due to the strong dipole contribution in the present system. Above +5.4 Oe, skyrmion bubbles collapse, whereas below +4.8 Oe, skyrmion bubbles transform into stripe domains. Nevertheless, by varying the strength of magnetic field and hence the size of skyrmion bubbles, we observed a size-dependent skyrmion Hall angle.

A negative electron current direction ($-j_x$) reverses the direction of skyrmion motion that leads to a negative saturation skyrmion Hall angle, shown in regime II (−$j_x$, −$Q$). In the presence of a negative perpendicular magnetic field with a positive topological charge (+$Q$), such a trend is reversed, as summarized in the regime II (−$j_x$, +$Q$), and regime IV (+$j_x$, +$Q$), respectively. This is consistent with the opposite topological Magnus force. As shown in the Supplementary Methods, micromagnetic simulations reproduce the above experimental observation.

On the other hand, given the large size of magnetic skyrmions (of diameter ~1,000 nm), and the weak strength of interfacial DMI $D_{\text{DMI}} \leq 0.5$ m$^{-2}$ in the present material system, it is also possible that the current-induced spin Hall spin torque could modify the spin texture of the skyrmions$^{39,40}$. This could invalidate the assumption of a rigid spin structure underlying Thiele’s equation. Indeed, micromagnetically generated large skyrmions in the weak-DMI regime ($D_{\text{DMI}} \leq 0.5$ m$^{-2}$) exhibit considerable dynamics because of internal degrees of freedom$^{39,40}$. These could potentially modify the response to an external field as well as the response to a pinning potential, in addition to modifying how energy is dissipated in the system.

### Skyrmion motion along the edge

Furthermore, it is expected that close to the sample edge the motion of skyrmions is modified. The experimentally observed motion is shown in Fig. 4. The skyrmion marked by the green circle is annihilated by the structural defects, which has also been observed in other material systems$^{25}$. In the high-current-density regime, a $Q = +1$ skyrmion in the centre of the device moves with a fixed skyrmion Hall angle of $\phi_h \approx 8^\circ$ and an average velocity of $\bar{v} \approx 0.25 \pm 0.01$ m s$^{-1}$, as shown in Fig. 2s–w. However, the $Q = +1$ skyrmion close to the edge shows an ‘oscillatory’ transport feature at the same current density. Namely, the moving skyrmion is repelled away from the edge, as a result of the competition between the driving force from the spin Hall spin torque and the repulsive force from the edge of the sample$^{16,30,31}$. This repulsive force, due to dipolar interactions and the boundary condition of DMI$^{44}$, kicks the skyrmion back from the edge after a current pulse. This motion is clearly visible on the relatively slow observational timescales, indicative of a slow, almost diffusive motion, probably due to creep because of random defects. This explains the ‘oscillatory’ trajectory, and hence the absence of a well-defined skyrmion Hall angle close to the edge, as summarized in Fig. 4g. The corresponding average velocity is calculated to be $\bar{v} \approx 0.15 \pm 0.01$ m s$^{-1}$, which is around 40% less than the skyrmion moving in the interior of the sample, in contrast to theoretical predictions suggesting an increased velocity at the edge$^{42}$. This indicates a possible significant pinning effect from disorder at the device edge, possibly created during the lithographic process.

### Skyrmion accumulation at the edge of device

In order to draw the close link between the conventional charge Hall effect and the Hall effect from topological charge, we demonstrated experimentally the accumulation of skyrmions at the edge of device. This was done in a narrow device of 60 µm in width and 500 µm in length. By applying a pulse train (50 repetitions) of amplitude $j_x = -6 \times 10^6$ A cm$^{-2}$, the accumulation of $(Q = -1)$ skyrmions is observed at the lower edge of the device (see Fig. 5a). Again, reversing the magnetic field from positive (+5.4 Oe in (a)) to negative (−5.2 Oe in (b)) leads to the reversal of topological charge, and the accumulation of skyrmions $(Q = +1)$ at the upper edge (Fig. 5b). This observation resembles the charge accumulation due to the Hall effect in conductors. In the future,
one could electrically probe the skyrmion accumulation due to the skyrmion Hall effect, from which the reciprocity between the topological Hall effect and the skyrmion Hall effect can be established. For the topological Hall effect it should be beneficial to have smaller skyrmions with consequently larger emerging magnetic field.

By changing the sign of the topological charge, and the sign of the electric current, we have revealed a strong similarity between the conventional Hall effect of the electronic charge and the Hall effect due to the topological charge. Furthermore, our results suggest the important role of defects for understanding the detailed dynamics of magnetic skyrmions. In the future, similar to the topological effects of the electronic charge, rectifying motion of skyrmions from ratchets, and quantized transport of magnetic skyrmions, our observations also indicate that the topological charges of magnetic skyrmions, in combination with the current-induced spin Hall spin torque, can be potentially integrated to realize novel functionalities, such as topological sorting.

**Methods**

Methods, including statements of data availability and any associated accession codes and references, are available in the online version of this paper.

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**Figure 5** | Accumulation of skyrmions at the device edge. a, Demonstration of skyrmion (Q = −1) accumulation at the edge of the device (width 60 μm and length 500 μm). This is done by repetitively applying 50 pulsed currents of 50 μs duration at a frequency of 1 Hz with a current density $j_e = -6 \times 10^7$ A cm$^{-2}$ and an applied field of +5.4 Oe. b, Reversing the magnetic field from positive (+5.4 Oe) to negative (−5.2 Oe) leads to the accumulation of skyrmions with positive topological charge $Q = +1$ at the opposite edge.
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Author contributions
W.J., A.H. and S.G.E.t.V. conceived and designed the experiments. G.Y. and K.L.W. fabricated the thin film. W.J., W.Z., X.W., M.B.J. and J.E.P. performed lithographic processing. X.Z., Y.Z. and O.H. performed micromagnetic simulation. W.J., X.W. and X.C. performed MOKE experiments and data analysis. W.J., A.H. and S.G.E.t.V. wrote the manuscript. All authors commented on the manuscript.

Additional information
Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to W.J., A.H. or S.G.E.t.V.

Competing financial interests
The authors declare no competing financial interests.
Methods
The Ta(50 Å)/CoFeB/Ru(30 Å) trilayer was grown onto a semi-insulating Si substrate with a 300-nm-thick thermally formed SiO₂ layer by using a d.c. magnetron sputtering technique. The TaOₓ layer was prepared by oxidizing the top Ta layer with an oxygen plasma of 10 W for 60 s. The trilayers were annealed in vacuum for 30 min to induce perpendicular magnetic anisotropy. Devices were patterned by means of standard photolithography and subsequent Ar ion milling. Differential polar magneto-optical Kerr effect imaging experiments were performed in a commercial MOKE microscope from Evico Magnetics. Electrical pulses were generated by using a pulse generator (Quantum Composer model 9045).

Data availability. The data that support the plots within this paper and other findings of this study are available from the corresponding author upon reasonable request.