

Spin polarization of the quantum spin Hall edge states

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The prediction and experimental verification of the quantum spin Hall state marked the discovery of a new state of matter now known as topological insulators. Two-dimensional topological insulators exhibit the quantum spin-Hall effect, characterized by gapless spin-polarized counter-propagating edge channels. Whereas the helical character of these edge channels is now well established, experimental confirmation that the transport in the edge channels is spin polarized is still outstanding. We report experiments on nanostructures fabricated from HgTe quantum wells with an inverted band structure, in which a split gate technique allows us to combine both quantum spin Hall and metallic spin Hall transport in a single device. In these devices, the quantum spin Hall effect can be used as a spin current injector and detector for the metallic spin Hall effect, and vice versa, allowing for an all-electrical detection of spin polarization.

The discovery that HgTe quantum wells with an inverted band structure are two-dimensional (2D) topological insulators has generated great interest in this state of quantum matter^{1–3}. When the thickness d of the HgTe quantum well is increased beyond a critical value d_c , a quantum phase transition turns a conventional insulator into its topologically non-trivial counterpart. In this so-called quantum spin Hall (QSH) phase^{4,5}, current-carrying states are confined at the edge of the sample, whereas the bulk is insulating. These edge states are protected against backscattering from non-magnetic impurities^{6–8} and their propagation direction is helical, that is, opposite spin states counter-propagate along a given edge of the sample. When the applied gate voltage places the Fermi level inside the bulk gap, two-terminal transport experiments measure a quantized conductance of $2e^2/h$, where e is the electron charge and h is the Planck constant, independent of the sample width, which constitutes strong evidence for edge-state conduction². More recent non-local transport measurements in the QSH regime unambiguously establish that transport occurs through topologically protected edge channels^{9,10}. Whereas edge-state conduction in the QSH regime is thus experimentally well established, there exists so far no direct experimental evidence that the transport in the helical edge states of 2D topological insulators is spin polarized, which is a fundamental characteristic of this new state of matter.

In this work, we construct devices (Figs 1 and 2a) that enable us to study the spin polarization of the QSH edge states by purely electrical means. First, these devices allow us to detect the spin polarization of the QSH edge states (Fig. 1b) via the inverse spin Hall effect^{11–13} (SHE⁻¹). Second, our devices enable us to show that because of their helical nature, the QSH edge states can be used as a detector of spin current (Fig. 1a). In our devices, the spin current is generated by the intrinsic ballistic spin Hall effect^{11,14} (SHE) exhibited by a HgTe quantum well in the metallic regime¹³.

These two experiments establish spin polarization of the helical edge states in topological insulators, and also demonstrate potential applications of the QSH effect for spintronic devices.

All-electrical detection of spin polarization

Before presenting our results, we first describe the principle of our experiment in more detail. As the magnetic field originating from spin-polarized carriers in helical edge channels is too small to be detected directly, we have designed an experiment that converts magnetic information into an electrical signal. Figure 1 illustrates the idea of the experiments, which are performed on an H-shaped mesa structure (which we call ‘H-bar’) in which the carrier concentration in the two legs of the ‘H’ can be adjusted separately. Consider the situation illustrated in Fig. 1, where the bottom leg is metallic (indicated by the green colour, and either n- or p-type) and the top leg is tuned into the QSH regime (indicated by the yellow colour), with the counter-propagating helical edge channels depicted as blue and red trajectories. We perform two separate complementary experiments.

In Fig. 1a, the current is injected into the metallic part of the structure (contacts 3 and 4) while a voltage signal is detected across the top leg (contacts 1 and 2), which is gated into the QSH insulator state. The inverted band structure in HgTe results in a large spin-orbit coupling^{14,15}, which has previously enabled us to observe a ballistic intrinsic SHE in a small H-bar structure with a homogeneous carrier profile¹³. Similarly, when in the experiment of Fig. 1a a charge current is injected into the metallic leg, the intrinsic SHE will induce a separation of carriers with opposite spin polarizations towards opposite edges of this leg. This leads to a difference in chemical potential for opposite spin states in the area where the metallic part of the structures borders the QSH region. The spin-polarized helical edge channels coming from the QSH region couple selectively to the chemical potential of the matching spin

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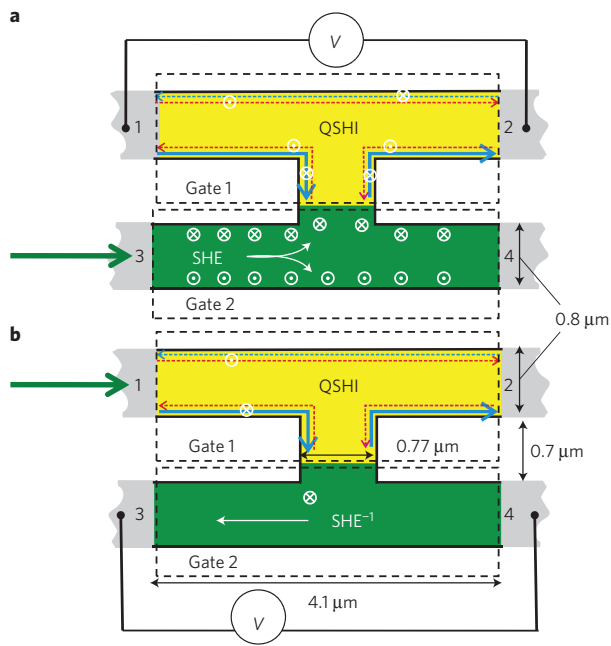


Figure 1 | Schematic layout of the two experiments on split-gated H-bar devices discussed in this paper. The dimensions indicated are those of the actual devices used in the experiments. **a**, The configuration where the current is injected into a metallic region (green, contacts 3 and 4). The spin-orbit interaction leads, through the SHE, to spin accumulation at the edges of the leg, as indicated schematically. The upper part of the structure (yellow) is in the QSH regime; the difference in chemical potential between the two spin states in the interface region is transferred by the helical edge channels to voltage contacts 1 and 2. **b**, The injector and detector regions are interchanged: the current is injected into the (spin polarized) helical edge channels of the upper leg, causing spin accumulation in the lower metallic region. The SHE^{-1} converts the spin accumulation into a voltage signal.

species in the metallic region and transfer this difference in potential to voltage contacts 1 and 2. For non-spin-selective edge channels the voltage signal is expected to be zero, whereas for the spin-polarized QSH edge channels we expect a nonzero signal. Thus, the observation of a non-local signal in this configuration is evidence that the metallic leg develops an intrinsic SHE, as well as that the helical edge channels are spin polarized in the QSH insulator regime.

In the reverse configuration of Fig. 1b, the current is injected (contacts 1 and 2) into the area of the sample that is gated into the QSH regime, while a non-local voltage drop is measured across the metallic leg (contacts 3 and 4). In this configuration, the spin-polarized helical edge channels inject a spin-polarized current into the metallic leg, causing a local imbalance in the chemical potential of spin-up and spin-down polarized carriers. Owing to the SHE^{-1} (see refs 11–13), the spin current in the metallic region induces a voltage between contacts 3 and 4. Again, this voltage can develop only if the helical edge channels are spin polarized, and at the same time the metallic leg exhibits the SHE^{-1} .

A possible complication in both of the above experiments is the detection of a stray spreading voltage. In the configuration of Fig. 1a, this could result from a voltage drop in the metallic leg along the interface with the area in the QSH insulator regime, and in Fig. 1b, the finite distance between in- and outgoing edge channels at this interface could produce a similar effect. However, in practice such stray voltages are strongly reduced by the exact layout of the experiment, the quasi-ballistic nature of the transport in the metallic leg and the finite width of the edge channels (see Supplementary Information).

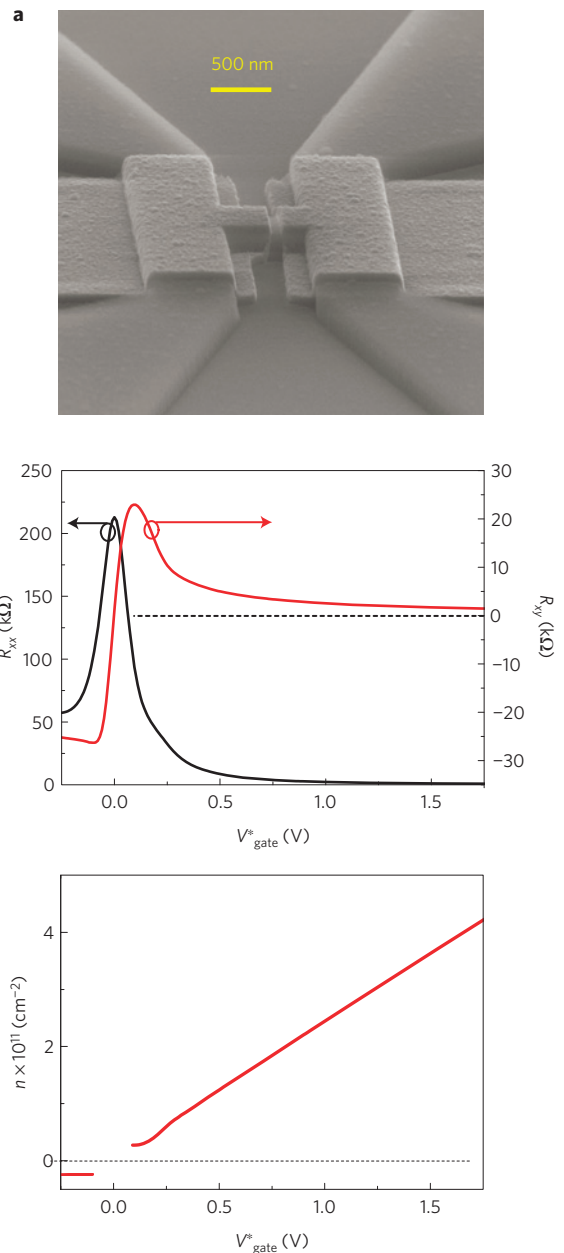


Figure 2 | Characterization of devices. **a** An electron micrograph of the actual device structure (rotated by 90° when compared with Fig. 1). **b,c** Gate-voltage dependence of the longitudinal resistance R_{xx} (black) and Hall resistance R_{xy} (red) at $B = 1$ T, and the inferred carrier density, n , of a macroscopic Hall bar, $600 \mu\text{m} \times 200 \mu\text{m}$ in size, fabricated from the same HgTe wafer as the nanostructures used in the experiments of Figs 3 and 4.

Sample fabrication and characterization

Our H-bar structures are fabricated from inverted symmetrically doped HgTe/HgCdTe type-III quantum wells with a nominal well width of 9 nm, located 74 nm below the surface. At a temperature of 4 K (and for a grounded gate), the carrier density is $n \approx 4 \times 10^{11} \text{ cm}^{-2}$. The carrier mobility is then $\mu \approx 1.1 \times 10^5 \text{ cm}^2 (\text{V s})^{-1}$, yielding an elastic mean free path larger than $2 \mu\text{m}$. The devices are patterned using optical and electron beam lithography, with dimensions as indicated in Fig. 1. To control the carrier density, the device is gated by Au gate electrodes separated from the sample surface by a 110-nm-thick insulating $\text{Si}_3\text{N}_4/\text{SiO}_2$ multi-layer stack. By applying a voltage V_{gate} to the top gates, the electron carrier density of the quantum well can be

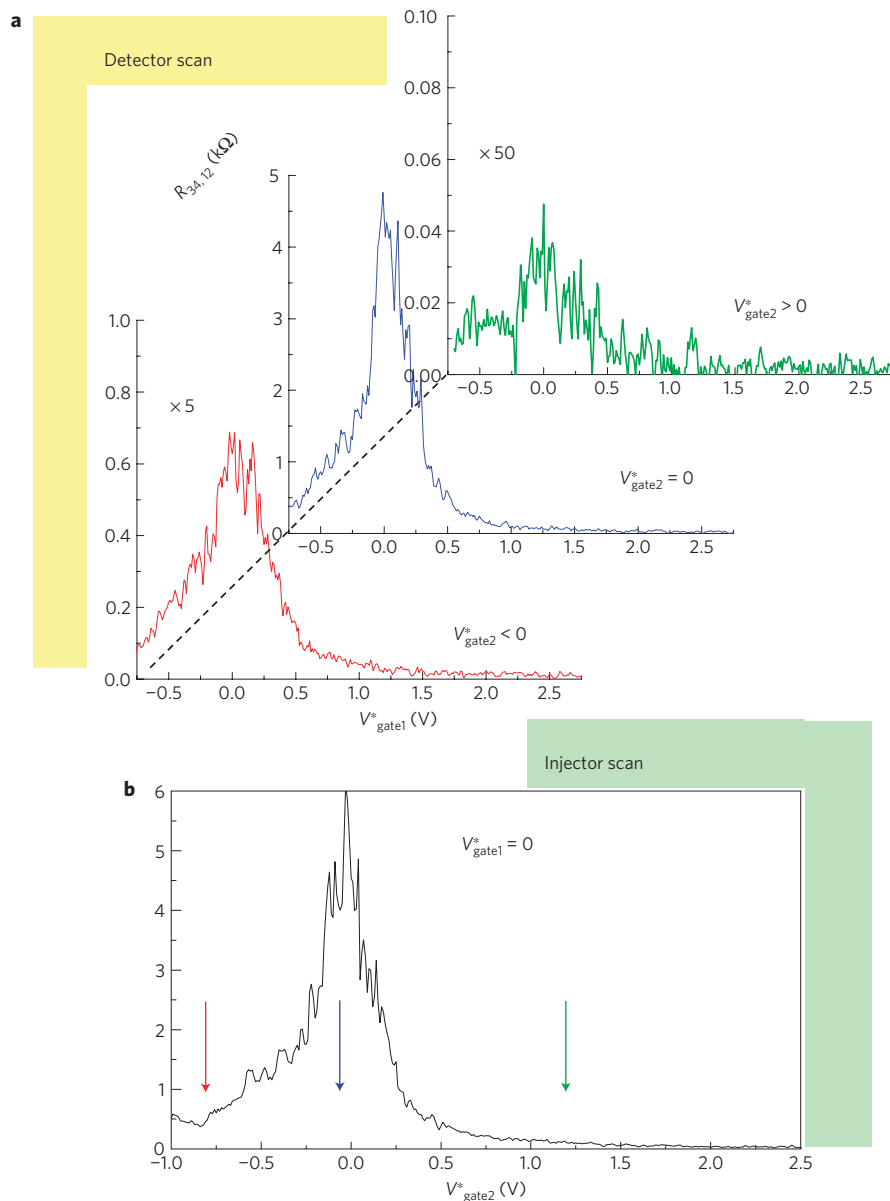


Figure 3 | Experimental non-local resistance data corresponding to the measurement configuration of Fig. 1a. In **b** (green) the gate on the current injection leg is swept, varying the area from p- to n-metallic conductance, while the detector (top) leg is kept in the middle of the QSH insulator regime. The red, blue and green arrows denote gate voltages where the injector region is p-type metallic, QSH insulating and n-type metallic, respectively. In **a** the gate in the detector area is varied at exactly these injector settings.

adjusted, going from an n-type behaviour for $V_{\text{gate}} > 0$ through the bulk insulator state into a p-type regime for $V_{\text{gate}} < 0$. For reasons of comparison, the experimental data in Figs 2, 3 and 4 are plotted as a function of a normalized gate voltage $V_{\text{gate}}^* \equiv V_{\text{gate}} - V_{\text{thr}}$, where the threshold voltage V_{thr} is defined as the voltage for which the resistance is largest in a particular fixed reference measurement. As is evident from the characterization data in Fig. 2b,c, which were obtained from a Hall bar fabricated from the same wafer material as the H-bar nanostructures, we find that for gate voltages $V_{\text{gate}}^* \gtrsim 0.5 \text{ V}$ the quantum well is n-type metallic, and for $V_{\text{gate}}^* \lesssim -0.5 \text{ V}$ it is p-type metallic. The split-gate design (gates 1 and 2) of Fig. 1 provides an independent control of the carrier density for each leg of the H-bar structure, enabling us to gate one part of the sample into the QSH insulator regime and the other part into either n- or p-type metallic regimes. An electron micrograph of the actual device structure is shown in Fig. 2a. The transport measurements are done at a constant temperature of 1.8 K

employing quasi-d.c. low frequency (13 Hz) lock-in techniques using a voltage bias below $100 \mu\text{V}$.

Deducing the spin polarization

Although experiments have been performed on a variety of different devices and yield similar results, for reasons of consistency we will discuss here a single device with dimensions as indicated in Fig. 1. The results of the experiments are shown in Figs 3 and 4, corresponding to the measurement configurations of Fig. 1a and b, respectively. In Figs 3a and 4a, the non-local resistance is plotted as a function of gate 1, and in Figs 3b and 4b, gate 2 is swept.

Figure 3 corresponds to the layout of Fig. 1a, and the detected non-local signal can consequently be denoted as $R_{34,12}$, that is the voltage measured between contacts 1 and 2 divided by the current passed between contacts 3 and 4. When we sweep the gate on the injector area (gate 2) while the detector is tuned into the QSH regime ($V_{\text{gate1}}^* = 0$), we observe (Fig. 3b) a pronounced maximum around

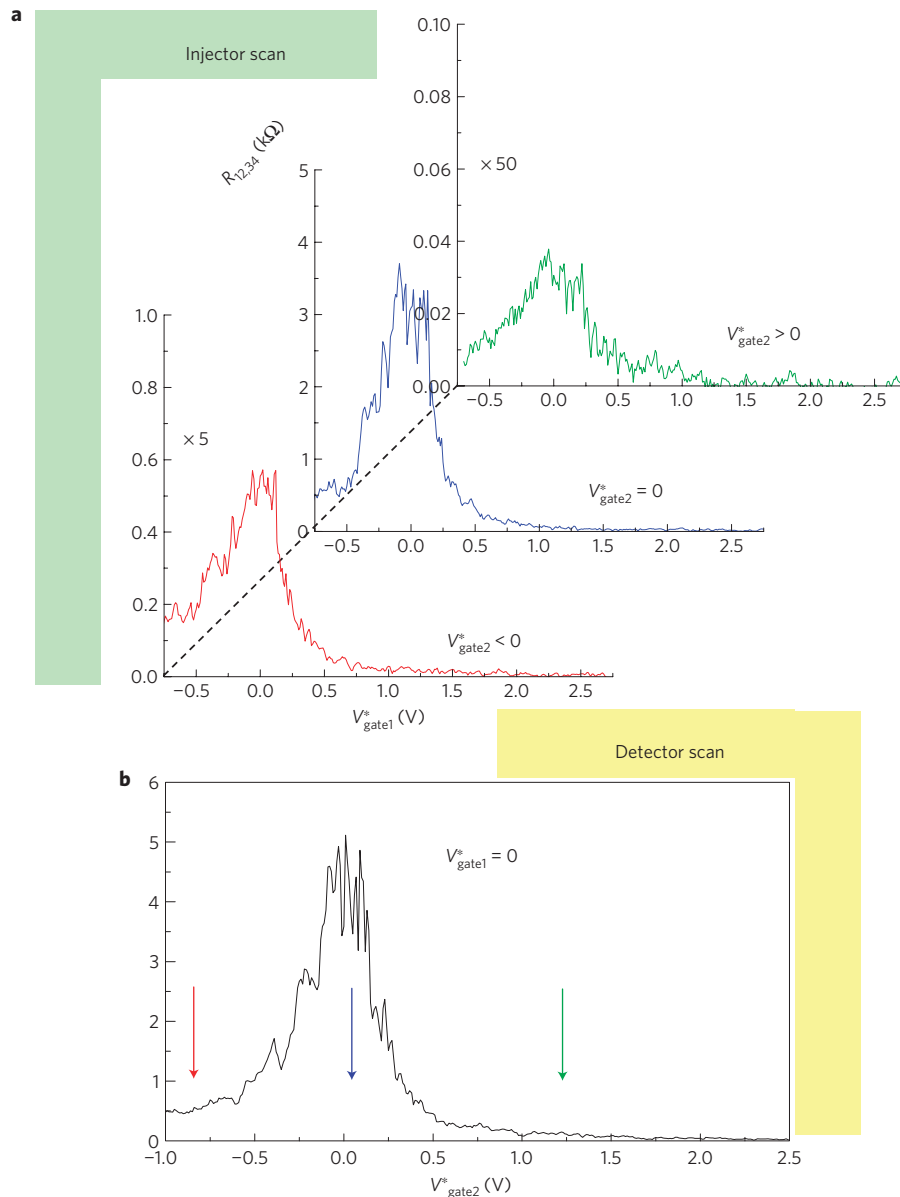


Figure 4 | Experimental non-local resistance data corresponding to the measurement configuration of Fig. 1b. In **b** (detector scan) the gate on the detection leg is swept, varying the area from p- to n-metallic conductance, while the injector (top) leg is kept in the middle of the QSH insulator regime. The red, blue and green arrows denote gate voltages where the detector region is p-type metallic, QSH insulating and n-type metallic, respectively. In **a** the gate in the injector area is varied at exactly these detector settings.

$V_{\text{gate1}}^* = 0$, and smaller but finite values on both sides. The signal around $V_{\text{gate1}}^* = 0$ reaches approximately the quantized value ($h/4e^2$) observed in our previous experiments on non-local transport in the QSH regime⁹. We attribute the slight deviation from perfect quantization to imperfect gating in the non-gate-covered region between gates 1 and 2. Imperfectly gated regions in the sample can act as dephasing centres for edge electrons, which can lead to a deviation from the expected quantized non-local resistance^{8,9}. In addition, in HgTe quantum well devices subsequent gate voltage sweeps can charge interface trap states in a different way¹⁶, leading to different dephasing effects and a different magnitude of the deviation from quantized resistance for each gate voltage sweep.

Apart from the large signal in the QSH regime, the measurements also exhibit a non-vanishing non-local signal when the area underneath gate 2 is metallic, either n- or p-type, and thus corresponds to the injector region depicted in Fig. 1a. The origin of this finite signal becomes more evident when the injector gate voltage

is set at a fixed value either in the p-type ($V_{\text{gate2}}^* = -0.75 \text{ V} < 0$) or in the n-type metallic regime ($V_{\text{gate2}}^* = 1.0 \text{ V} > 0$) while the voltage on gate 1 is swept (Fig. 3a). Evidently, a significant increase in the non-local signal is observed, with a peak when the detector is exactly in the QSH insulator regime. This is the observation anticipated above: one may expect a non-local signal of this amplitude only when the metallic leg exhibits a SHE and the edge channels in the QSH leg are spin polarized. Our data also show that the non-local signal for the p-type injector ($V_{\text{gate2}}^* = -0.75 \text{ V}$) is more than ten times larger than that for the n-type injector ($V_{\text{gate2}}^* = 1.0 \text{ V}$). This is consistent with our experimental observations on the SHE signal in all-metallic HgTe quantum wells¹³, where the non-local signal is about an order of magnitude larger in the p-regime than in the n-regime and results from enhanced spin-orbit splitting in the valence band¹⁵.

Our data for the reverse configuration of Fig. 1b are shown in Fig. 4. The sweep of gate 2 in Fig. 4b now corresponds to

the detection leg, and one can directly see that also in this configuration we observe a finite non-local signal (in this case $R_{12,34}$), even when the detector is metallic (red and green arrows). The upper panel shows the effect of sweeping the injector leg (gate 1), and indicates that the non-local signal peaks when the injector is in the QSH state. As in the previous configuration of Fig. 3, we observe an order of magnitude increase in the non-local signal when the metallic detector is p-type ($V_{\text{gate}2}^* = -0.82$ V) as compared with an n-type detector ($V_{\text{gate}2}^* = 1.2$ V). As noted above, our observation of the non-local signal is evidence that the helical edge channels generate a spin accumulation at the interface between the QSH injector and the metallic detector, which responds by the SHE^{-1} .

The results in Figs 3 and 4 look very similar and, in fact, are expected to do so on account of the Onsager–Casimir symmetry relations for the non-local resistances $R_{mn,kl}$ in a four-probe device^{17,18},

$$R_{mn,kl}(\mathbf{B}) = R_{kl,mn}(-\mathbf{B}) \quad (1)$$

where the first pair of indices refers to the current probes, the second pair refers to the voltage probes and \mathbf{B} is the magnetic field. In the present set-up, the magnetic field is zero and we expect $R_{34,12} = R_{12,34}$. One possible explanation for the small deviations from exact Onsager–Casimir symmetry observed in Figs 3 and 4 is the random charging effects of pinned inhomogeneities (or ‘trap states’) mentioned earlier. Two subsequent gate voltage sweeps can result in a different interface potential due to these charging effects¹⁶, which changes the internal state of the conductor. Note however that the symmetry between Figs 3 and 4 is more accurate in the doped regimes away from the nominally insulating regime, which is expected because a higher carrier density can more effectively screen the interface trap potentials and thus make the internal state of the conductor less sensitive to trap charging effects.

Modelling and further discussion of the experiment

To better understand the experimental results, we have performed semiclassical Monte Carlo calculations to obtain a theoretical estimate of the non-local resistance based on the sample geometry (Fig. 1). We focus on the set-up illustrated in Fig. 1b, where the QSH insulator acts as a spin injector and the metallic region detects the spin polarization of edge channels through the SHE^{-1} . We calculate the non-local resistance $R_{12,34}$ when the current is driven between contacts 1 and 2 and the voltage is measured between contacts 3 and 4. $R_{12,34}$ can be expressed in terms of the transmission coefficients^{17,18} T_{ij} for the metallic region alone (Supplementary Equation S1). The T_{ij} are calculated within the semiclassical Monte Carlo method¹⁹, which is a reasonable approximation for Fermi wavelengths $\lambda_F \ll L$, where $L \sim 1 \mu\text{m}$ is the characteristic linear size of the device (Figs 1 and 2a). Electrons are injected at the QSH– SHE^{-1} interface (yellow–green interface in Fig. 1b), and propagate quasi-ballistically into the metallic T-structure (green region in Fig. 1b) according to semiclassical equations of motion²⁰. These equations are derived using an effective four-band model for HgTe quantum wells¹ that explicitly contains the effects of intrinsic spin–orbit coupling due to atomic coupling between bands¹⁴. This intrinsic spin–orbit coupling can be visualized as resulting from a Rashba field due to the edges of the typical mesa structure used in experiments¹⁴. In contrast, the Rashba term originating from the applied gate voltage is minimal because the samples used in the experiments were symmetrically modulation-doped. Therefore, we omitted this contribution in the simulations. Details of the calculation are included in the Supplementary Information.

We find that the conversion of the spin signal to the electrical signal through the SHE^{-1} is dominated by the intrinsic spin–orbit

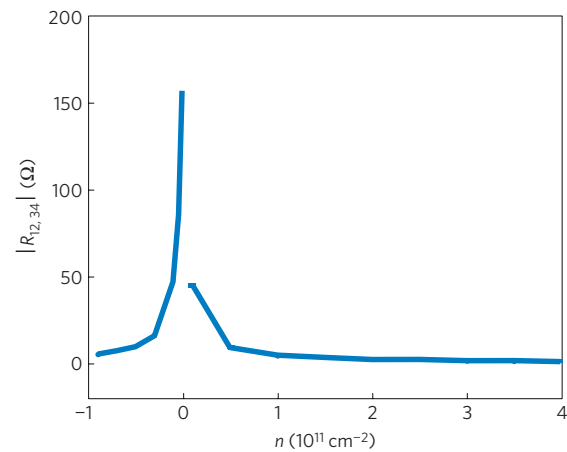


Figure 5 | Semiclassical Monte Carlo simulation of the non-local resistance. Non-local resistance signal calculated in the set-up of Fig. 1b, as a function of carrier concentration in the metallic detector.

interaction, and stray contributions due to voltage spreading are negligible (see Supplementary Fig. S3). Figure 5 shows the theoretical prediction of the non-local resistance signal as a function of the carrier concentration in the metallic detector. (Note that the semiclassical simulation breaks down when the chemical potential is too close to the insulating gap.) The scattering induced by the intrinsic spin–orbit interaction is more effective when carriers have smaller kinetic energy, and therefore smaller wave vectors at the Fermi level. As the effective mass in the p-regime is larger than that in the n-regime¹³, for comparable densities the kinetic energy will be smaller in the p-regime. This can explain the larger non-local resistance signal for the p-regime in comparison with the n-regime, as well as the decrease of the signal on increase in carrier concentration.

To further validate the above interpretation, we have performed a number of control experiments. First, varying the injector size (from 200 nm to 400 nm) hardly influences the observed resistance signals. This rules out that the signal has a contribution due to (diffusive) voltage spreading and confirms that our samples are indeed in the quasi-ballistic regime. Moreover, we have measured the dependence of the non-local resistance signals on perpendicular and in-plane magnetic fields. Whereas the in-plane magnetic field does not influence the signal strength in the perpendicular case a decrease of the non-local signal can be observed. This shows that the effect indeed depends on the spin polarization of the electrons. More detailed information about these further experiments can be found in the Supplementary Information.

The experiments presented in this paper are a first example of how helical edge states can be implemented in spintronic quantum transport studies. One can imagine many further experiments using the concepts presented here.

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Author contributions

C.B., A.R., H.B. and L.W.M. have contributed to the experiments, E.M.H., J.M., X.-L.Q. and S.-C.Z. contributed to the theory. All authors have participated in the interpretation of the experiments. The paper was written by C.B., J.M., E.M.H., S.-C.Z. and L.W.M., and the Supplementary Information by J.M., X.L.Q. and E.M.H.

Additional information

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