Images of edge current in InAs/GaSb quantum wells

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Abstract

Various mechanisms may explain why, in quantum spin Hall devices with edges longer than several microns, the measured conductance is much less than the theoretically expected value of $e^2/h$ per edge. We imaged 2D current flow in InAs/GaSb quantum wells with long edges. We found that edge currents are present, and are consistent with an edge resistance that is constant from 4.5 K to 32.5 K. These results make unlikely that candidate inelastic scattering mechanisms with strong temperature dependence are the dominant scattering mechanism in the edge states of InAs/GaSb, and suggests that elastic processes may be more relevant.
The quantum spin Hall effect (QSHE) is an instance of a two dimensional topological insulator that hosts counter-propagating spin-polarized edge states \[1–3\]. Due to this spin polarization, elastic single-particle backscattering in the edge states is not allowed because it violates time reversal symmetry. Therefore the primary transport signature of the QSHE is ballistic conduction along the edges. Specifically, a single-mode ballistic channel will have a quantized conductance \(e^2/h\), and the conductance of multi-terminal devices with ballistic channels between contacts is described by the Landauer-Büttiker formalism \[4\]. Experimentally, deviations from this model would indicate that backscattering occurs in the edge.

Single-particle elastic scattering cannot cause electrons to scatter between the counter-propagating, opposite spin QSH edge modes, but both inelastic and multi-particle scattering processes can, in principle, introduce backscattering. Disorder in the electric potential combined with electron-electron interactions are at the heart of many proposed scattering mechanisms, specifically through the formation of Kondo impurities \[5, 6\], charge puddles \[7\], inhomogeneous Rashba spin-orbit coupling \[8, 9\], or in general any impurity that breaks translational symmetry coupled with electron-electron interactions and Rashba spin-orbit coupling \[10\]. The hyperfine interaction between the electronic and nuclear spins can also decrease the conductivity of the edge \[11, 12\]. It remains unknown which, if any, of these mechanisms are important in the two known realizations of the QSHE, specifically type III HgTe quantum wells \[13\] and type II InAs/GaSb asymmetric quantum wells \[14\]. In HgTe quantum wells, sufficiently small samples show close to quantized resistance \[15\] and non-local transport measurements show close to the expected quantized values based on Landauer-Buttiker formalism \[16\]. Both experiments are consistent with ballistic edge channels.

In InAs/GaSb quantum wells, the experimental situation in the initial reports were complicated by residual conduction of the bulk even when the Fermi level was tuned into the gap, which was explained by level broadening leading to a finite conductivity in the gap even at zero temperature \[17, 18\]. Recently, Si doping in the interface \[19\], Be doping in the barrier layer \[20\], and use of a Ga source with a sufficient amount of charge-neutral impurities \[21\] have all been shown to reduce the residual bulk conductivity. In samples with a
reduced bulk conductivity in the insulating gap, conductances close to the quantized value expected for ballistic transport were observed in micron-sized samples \[19, 20\]. However, as in HgTe quantum wells, samples with longer edges have lower values of conductance when tuned into the gap \[18, 19\], indicating that edge states are not perfectly ballistic.

Here we present scanning superconducting interference device (SQUID) magnetic flux images \[22\] of current flow in InAs/GaSb quantum wells (as we previously applied to HgTe quantum wells \[23\]). We imaged current in devices made from two different quantum wells, one with Si dopants at the interface with a dopant density of \(\sim 10^{11} \text{ cm}^{-2}\), ("Si-doped sample") and one without Si dopants ("undoped sample"). The Si doping acts to suppress residual bulk conductivity in the gap \[19\]. Based on the layer thicknesses, both devices (FIG. 1a) are predicted to exhibit the QSHE. Growth details of the doped and undoped quantum wells are described in Refs. \[19\] and \[18\], respectively. We used a front gate to tune the chemical potential of the devices.

To image current, we applied an AC current to the sample and used lock-in techniques to measure the resulting flux through the SQUID’s pickup loop (shown schematically in FIG. 1b) produced by current in the sample. We used Fourier techniques \[23, 24\] to extract both components of the 2D current density from each individual flux image. All images of the Si-doped device (undoped device) were taken at an applied alternating current with a nominal rms amplitude of 150 nA (250 nA). We recorded both in phase and out of phase signals and the images presented were corrected for phase and attenuation that comes from unintentional RC filtering of the applied current. Transport was taken with a constant rms current of 10 nA at quasi DC frequencies (< 5 Hz) or extracted from the low-current behavior (< 10 nA) of full I-V characteristics. All measurements were performed at \(\sim 4.2 \text{ K}\) unless otherwise noted.

First, we present images of current in the Si-doped sample. Small devices on similar heterostructures have shown close to quantized conductance \[19\]. The dimensions of the sample and the contacts used to flow current are shown in FIG. 1b. The length of the edges in this device (> 50 \(\mu\text{m}\)) is much larger that the phase coherence length observed in similar samples (4.2 \(\mu\text{m}\)) \[19\]. Current was applied from contacts 1 to 4, and we measured the voltage between contacts 2 and 3, which gave a 4-terminal resistance \(R_{14,23}\) of 10 k\(\Omega\) at zero applied front gate voltage. A typical measurement of \(R_{14,23}\), as a function of front gate voltage \((V_g)\) is shown in FIG. 1c, with a peak in the resistance occurring around \(V_g\).
= -2.35 V. \( R_{14,23} \) depends on the gate voltage history (it was consistently more resistive on downward sweeps of the gate) and its values before and after taking each image are indicated (FIG. 1c).

FIG. 1 shows two images of magnetic flux through the SQUID’s pickup loop produced by current in the Si-doped device, contrasting the cases where the chemical potential was tuned into the conduction band (\( V_g = 0 \) V) and into the gap (\( V_g = -2.35 \) V). When tuned into the conduction band, the magnetic flux varied smoothly and monotonically across the device (FIG. 1b), indicating that current flowed uniformly inside the sample. When the device was tuned near its resistance peak (\( V_g = -2.35 \) V), the flux had sharp features centered on the edges of the device, signifying that current flowed along the edges of the sample (FIG. 1d). We extracted the current density along x and y, confirming that in the conduction band, the current was distributed uniformly throughout the device (FIG. 1e,i). In the gap, the current flowed almost entirely along the edges (FIG. 1f,h). Edge currents are particularly illustrated in the vertical leads (FIG. 1h), in which current flowed along the lead until it reached an un-gated part, where the current crossed and returned along the opposite edge of the lead. The apparent width of the conducting edges in our images was limited by the geometry of the SQUID’s pickup loop, the height above the sample, and the parameters of the current inversion, rather than by the physical width of the edge states.

Our images were not taken in the linear regime of the I-V characteristics when the sample was very resistive; the main source of nonlinearity was the electric potential change across the sample. At higher applied currents, we observe artifacts in the image of the non-linearity, which changed character depending on which side of the sample was spatially closer to ground [25]. In FIG. 1 the left and the right sides of the images look qualitatively similar, showing that although current in the sample was not imaged in the linear regime, non-linear effects in the image were not observed.

To understand the evolution of current flow in the Si-doped sample we imaged current at a series of gate voltages (FIG. 2). In FIG. 2b we present selected profiles of the x-component of the current density as a function of gate voltage. We fit flux profiles, as described in [23], to quantify the amount of current flowing in the top edge, bottom edge, and homogeneously through the bulk (FIG. 2c). Near the resistance maximum the amount of current that flowed along the top edge is approximately half that flowing along the bottom. The length of the top edge is twice that of the bottom, therefore the amount of current flowing in the edges is
consistent with an edge resistance that scales with length.

For comparison, we imaged a sample made from a quantum well without Si doping at the interface (see FIG. 2d). The peak two-terminal resistance for this device was 64kΩ, an order of magnitude lower than the sample with a Si-doped interface. Fits of magnetic flux profiles of the undoped sample show that even at the resistance maximum, only \( \sim 10\% \) of the total current flowed in each edge. In comparison to the Si-doped interface, the undoped sample also shows higher conductivity along the edge on the resistance maximum, however the bulk carries the majority of the total current for all gate voltages (see FIG. 2d, inset for comparison).

Next we studied (in the Si-doped sample) how the current flow changes as a function of temperature. The sample becomes less resistive as temperature increases (FIG. 3a). We measured flux profiles along \( y \) at the center of the device at several temperatures. By assuming that the flux profile is independent of the exact position along \( x \) near the center of the sample (which is confirmed in full images taken at 4.5 K), we can extract a 2D current density from a single flux profile (FIG. 3b). The total resistance dropped with increasing temperature as more current flowed in the bulk of the sample, indicating that the bulk’s conductivity is also increasing relative to the edges. We can quantify this by fitting as done above (FIG. 3c).

To further analyze the temperature dependence, we model the bulk and edges as parallel resistors, and extract an effective resistance of the edges and bulk taking the \( R_{14,23} \) over the ratio of the current flowing in each channel. This effective resistance is valid measure of the resistance of the channels as long as the resistance per unit length is uniform over the three segments of the top edge [25]. The effective resistance vs. temperature is presented in FIG. 3d. As a function of temperature, the bulk effective resistance decreases strongly with temperature, consistent with thermally activated carriers and the bulk gap measured elsewhere [19]. The effective resistance of the bottom edge remained relatively constant from 4.5 K to 32.5 K, while the top edge’s effective resistance decreased by a factor of 2 over this range. The behavior of the top edge is consistent with a constant resistance per length of the edge, but with the length along the vertical leads (compare FIG. 1f) getting shorted by the bulk at higher temperatures. This behavior is confirmed by images at gate voltages with moderate bulk conduction, where current flows along the horizontal edges, but not up the contact [25].
This work shows that in InAs/GaSb quantum wells, the resistance of the edge states remains relatively constant in the presence of bulk conduction activated by elevated temperature. In [19], the resistance of long devices remain constant from 20 mK to 4 K. With these two results, the resistance of long edges has been shown to remain constant over three orders of magnitude of temperature. The lack of strong temperature dependence of the edge resistance puts constraints on existing proposals for scattering mechanisms explaining the non-ballistic nature of long edges. Single impurities in the presence of Rashba spin-orbit coupling lead to a $T^4$ correction of the conductivity [10]. Tunneling into charge puddles similarly predicts power-law dependence, which is not observed. In the presence of inhomogeneous Rashba spin-orbit coupling, Ref. [8] predicts an exponential decrease of edge conductivity with lower temperature, although this result may be unphysical [9]. A single Kondo impurity provide a logarithmic increase of edge conductivity with temperature at higher temperatures [5], which is hard to distinguish from constant behavior with this method, and taking into account multiple impurities of this nature may lead to non-ballistic conduction which persists to low temperature [6], or may not contribute in the DC limit [26]. Coupling of the electron and nuclear spins can lead to backscattering [12], however the slow fermi velocity in InAs/GaSb leads to estimated length scales much longer than samples studied here. The observed lack of temperature dependence of the edges conductivity seems to suggest elastic processes may be important to scattering (e.g. [27]).

One effect of introducing charged dopants is a more disordered potential landscape, which is important to many of the scattering proposals mentioned above. In comparison to HgTe quantum wells, InAs/GaSb has a much slower Fermi velocity [13, 14] which implies stronger e-e interactions and InAs/GaSb is a structurally asymmetric interface, leading to stronger Rashba spin-orbit coupling. In light of these differences, it is surprising that ballistic conduction at similar device sizes and similar scattering lengths are observed in both materials, if the main scattering mechanism is dependent on e-e interactions or Rashba spin-orbit coupling.

The residual bulk carriers in the gap of the InAs/GaSb are localized [19], and although these carriers do not directly contribute to charge transport, they may be important for the feasibility of observing exotic effects in experiments in QSHI/Superconductor structures [28]. The character of atomic substitutions which act as dopants in bulk semiconductors may become deep-level traps in heterostructures (e.g. in InAs/GaSb superlattices [29]),
which may be important for determining the scale of potential disorder as well as aiding in localizing the bulk.

In conclusion, we imaged current flow in InAs/GaSb quantum wells and show that the edges are more conducting than the bulk for a range of gate voltages and temperatures, in the presence of bulk conductivity. These observations are consistent with quantum spin Hall edge states, which are not ballistic due to the presence of backscattering. The source of the backscattering is still up for debate, but the absence of large changes of the edges resistance as a function of temperature allows us to discriminate between the proposed scattering mechanisms, showing that it is unlikely that those which exhibit a power-law or stronger dependence on temperature are the dominant mechanism.

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FIG. 1. (color) Flux and current maps in a device made from a Si-doped InAs/GaSb quantum well. (a) Schematic of the InAs/GaSb heterostructure. Si doping suppresses residual bulk conductance in the gap. (b) Schematic of the measurement. Alternating current (orange arrows) flows from left to right. A voltage \( V_g \) applied to the front gate (yellow box) tunes the Fermi level. The SQUID’s pickup loop (red circle) scans across the sample surface, with lock-in detection of the flux through the pickup loop from the out of plane magnetic field produced by the applied current. (c) Four-terminal resistance \( R_{14,23} = V_{23}/I_{14} \) as a function of \( V_g \), showing both the upwards (black) and downwards (gray) gate sweeps. The resistance peaks when the Fermi level is tuned into the gap. (d,e) Flux images for the sample tuned into (d) the bulk gap, \( V_g = -2.35 \) V, and (e) the n-type regime, \( V_g = 0 \) V. (f-i) Reconstructed horizontal (\( j_x \)) and vertical (\( j_y \)) 2D current densities, showing that the current flows on the edges in the bulk gap and uniformly outside the gap.
FIG. 2. (color online) Analysis of current flowing in the edges as a function of $V_g$ in the Si-doped device (a-c) and the undoped device (d). (a) Resistance vs. $V_g$ in a downward gate voltage sweep before imaging the current (gray), and immediately before (o) and after (x) each image in a subsequent sweep. (b) Selected profiles of the x-component of the current density show the evolution from bulk-dominated to edge-dominated transport, offset for clarity, the zero of each profile is indicated by the dashed line. Profiles were averaged over the region between the contacts, as shown in Fig. 1g. (c,d) The percentage of current flowing in the top edge (green circles), bottom edge (blue) and bulk (purple exes) as a function of gate voltage from fitting described in the text in a (c) Si-doped structure and (d) undoped structure, obtained from fitting flux profiles. (Inset) A comparison of the 2D current density near the maximum resistance in the Si-doped and undoped structures.

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FIG. 3. (color online) Temperature dependence of the edge and bulk currents. All measurements are performed at a constant gate voltage of $V_g=-2.35$ V (a) $R_{14,23}$ of the Si-doped device as a function of sample stage temperature. (b) Profiles of the x-component of the current density at selected temperatures, showing more bulk conductivity at higher temperatures, and the presence of edge states up to 30 K. The profiles are offset for clarity and the zero of each profile is indicated by a dashed line. (c) Percentage of current flowing in the top (green circles), bottom (blue diamonds), and bulk (purple exes), obtained from fitting flux profiles (see main text). (d) The extracted effective resistance of the edges and bulk, calculated using the values in panels (a) and (c), showing that the effective resistance of the bulk varies strongly with temperature, while the effective resistance of the bottom edge remains constant. The effective resistance of the top edge is reduced by a factor of 2, which is caused by shorting of the top contacts by the bulk, rather than a change in the resistance per unit length (see text).

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