Supplementary Online Information: Images of edge current in InAs/GaSb quantum wells

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NON-LINEARITY

Our measurements of the Si-doped device were not made in the linear regime, i.e. the amount of current applied to take images (150\(nA_{rms}\) in the case of all images in the main text) is outside the range where the voltage drop across the sample scales linearly with the applied current. V-I characteristics of the device near the resistance maximum taken in the same gate sweep as FIG.1 c,e,g are shown in Fig. S1. At \(150\sqrt{2}\) nA applied current amplitude (red-highlighted data), the V-I characteristic already noticeably deviates from the low-current behavior (black dashed line).

To discover the effect of non-linearity on our images, we applied higher currents (500\(nA_{rms}\)) to a Si-doped device. This device is a 2nd Si-doped device which was prepared identically to the one presented in the main text. The device was tuned to the resistance peak, using the front gate (\(V_g\)) which was defined with respect to ground, and an applied current was sent from the left most contact to the rightmost contact which was grounded (Fig S2 a). Closest to ground, the sample showed behavior close to what was expected on the resistance maximum, with the majority of the current along the edges. Farther away from ground, the current appears to flow more along the bulk (Fig S2 b,c). We attribute this non-linearity to the AC potential which deviates farthest from zero on parts of the sample farthest away from ground. This interpretation is confirmed by switching which contact is grounded, and observing that the trend in the images also flips (Fig S2 d-f). The lock-in measured images are the amplitude of the first harmonic of the applied current, which will be determined primarily by the high-current behavior. We do not see a systematic gradient in the images taken at 150 nA, and therefore conclude that the main features of the images are not affected by the non-linearity. A strongly gate-voltage dependent scatterer, such as those observed in [1] could be affected by such non-linearity and may be masked by this effect.

SHORTING OF THE EDGE THROUGH THE BULK

The contacts on the top edge of the sample provide striking evidence of the strong conductivity of the edge. In the gap, the current flows along \(\sim 60 \mu m\) of extra edge rather than shorting across the relatively small \(\sim 10 \mu m\) gap of bulk material (FIG. 1 c,e,g). At a certain finite bulk conductivity, this is no longer the case and more current flows across
FIG. S 1. V-I Characteristics of the Si-doped device when it is tuned into the gap using a front gate ($V_g = -2.35 V$). The range of the applied current for the images shown (150 nA, rms) is indicated by the red portion of the curve. A linear fit to the low current resistance between 5 nA and +5 nA is indicated by the dashed black line.

the bulk rather than taking a detour along the edges of the contacts. An example of this behavior is shown in FIG. S3, where at $V_g=-2.7 V$ there is significant conduction through the bulk. The edges are more conducting than the bulk, but current no longer flows all the way up and down the contacts. The bulk shorting of this portion of the contacts reduces the effective length of the edge by a factor of two. This behavior is especially important for interpreting the effective resistance of the edge (FIG. 3 d). The bottom edges resistance remains constant as a function of temperature, while the resistance of the top edge drops by a factor of 2 as the temperature was raised. The drop as a function of temperature is consistent with the bulk become more conducting and shorting the contacts, rather than the resistance per unit length of the top edge changing as a function of temperature. Therefore we find that the behavior of both the top and bottom edges are consistent with an intrinsic edge resistance (and therefore backscattering mechanisms) which does not change in our measured temperature range.
FIG. S 2. Images of the Si-doped device at high applied currents (500 $nA_{rms}$) in the middle of the gap. The front gate voltage is applied with respect to a ground that is shared with side of the sample, while an AC excitation is applied to the other side. (a-c) When the left contact is grounded, as shown schematically in (a), the behavior closest to ground is that of a device tuned into the gap, showing strong edge conduction with very little current flowing in the bulk. However, the right side of the image is much more bulk like indicating that the potential of the interface with respect to the gate become important (b,c). When the right side is grounded and the excitation applied to the left, the non-linear behavior flips as well (d-f).
FIG. S 3. Comparison of edge current flow with and without bulk conduction (a,b) The x component of the current density shows enhanced current flow along the in the main body of the device both with (a) and without (b) significant bulk conduction. (c,d) The y component of the current density shows that current flows up the entirety of the gated contact when there is little bulk conduction (c), but when there is bulk conduction current does not flow up the narrow contacts (d), showing that the edges along the narrow contact are effectively shorted by the conducting bulk.

**SPIN-POLARIZATION OF THE EDGE STATES**

In the quantum spin Hall state, each edge state is doubly-degenerate and the two states are time-reversed pairs (Kramers pairs), meaning they have opposite spin and crystal momentum. In the presence of an applied charge current, there is also an associated net spin...
polarization due to the non-equilibrium occupation of the edge states. We estimated the associated magnetic signal from the excess spins and find that they are well below our experimental resolution in this geometry.

The spin-polarization of the edge current can be estimated from the applied current and properties of the quantum well in question. We naively calculate the net linear magnetic moment density induced by edge current as

$$\lambda_s = g \mu_B I / (e v_F)$$

where $g$ is the g-factor, $\mu_B = e h / (2 m_e)$ is the Bohr magneton, $I$ is the applied current, $e$ is the electron charge, and $v_F$ is the Fermi velocity of the edge states. For an InAs/GaSb quantum well, we use $g = 10$ and $v_F = 4 \times 10^4 m/s$ with our experimentally applied current of 150 nA. For comparison we also investigate the expected spin polarization for HgTe, using the values $g = 18$ and $v_F = 5 \times 10^5 m/s$. We have estimated values for the bulk g factors from the literature [2, 3], however it is unclear that these values are necessarily correct for typical quantum wells or that the g-factor of edge electrons would be the same.

Our scanning SQUID magnetometer measures the magnetic flux penetrating the SQUID’s pickup loop

$$\int g(x,y) \vec{B} \cdot d\vec{a} \sim \int g(x,y) B_z(x,y,h) da,$$

where the integral is taken over the plane of the SQUID, $g(x,y)$ is the point spread function, $\vec{B}$ is the magnetic field produced by the sample and $B_z$ is the out of plane component of that field at a scan height, $h$. Here we present $B_z$ for simplicity, however we have separately confirmed all of the conclusions using a calculated flux signal with an experimentally determined point spread function, as described in Ref. [4].

We assumed a semi-infinite strip of quantum spin Hall insulator with a 20 $\mu m$ width and currents running along the edges of the strip. We calculated $B_z(y)$, where $y$ points along the width of the strip. Each edge carries half of the applied current, and the top and bottom edges have opposite spin polarization (FIG. S4a). We used a height of 1$\mu m$ in our calculation, a typical scan height for our SQUIDs. We calculated the expected magnetic field for both HgTe quantum wells (FIG. S4 b and c) and InAs/GaSb quantum wells (FIG. S4 d and e). We found in both cases that the expected field from the edge current is much larger than the spin-polarization signal. In InAs/GaSb, the estimated field is a factor of 40 smaller than the signal from the current. The signal from spins in HgTe is an order of magnitude smaller owing to its much faster Fermi velocity.

In the main text we fitted our SQUID flux signal to a model of how currents flow in the InAs/GaSb device. We can subtract the fitted flux profiles, which may in principle allow us
FIG. S 4. Calculation of the z-compononent of the magnetic fields from edge currents and resulting spin-polarization. Our SQUID measures the sum of the fields from the current and spin polarization. (a) A schematic of the geometry used to calculate the expected magnetic fields for in-plane (green) and out-of-plane (red) spins as well as the applied edge current (green). The fields were calculated at a height of 1 μm (not shown). We used approximate numbers for the electron g-factor and fermi velocity to calculate the expected spin polarization in (b,c) HgTe quantum wells and InAs/GaSb quantum wells (d,e). Signal were calculated using an applied current of 150 nA, however all signals are expected to scale linearly with current.
FIG. S 5. Calculated flux profiles for InAs/GaSb spin polarization and residuals from fitted experimental data. The residuals shown are the result of bootstrapping data from FIG. 1d 100 times. Error bars indicate the full range of the bootstrapped residuals.

to extract information about the spin polarization. However, residuals of a fit performed on an averaged profile of Fig. 1d of the main text display features that are much larger and different in shape than the calculated SQUID signal from spins (FIG. S5). We attribute these residuals to systematic errors in our experimentally calculated PSF and errors in the assumed height.

UNDOPED INAS/GASB DEVICES

We also imaged three devices made from InAs/GaSb wafers without Si doping at the interface. Similar devices were investigated by transport [5], and showed evidence for edge conduction in parallel with residual bulk conduction. An optical image of the area of the sample we imaged is shown in FIG. S6 a. The left half of the device is covered with a gold front gate and can be tuned into the insulating gap, while the area outside the gate is n-type
conducting. The magnetic flux from 250 $\mu A_{rms}$ of current through the device is shown in FIG. S6b. We extracted a 2D current, and find that the current density along x shows enhanced edge conduction when the device is tuned to its most resistive point. The bulk of the device is still carrying a measurable portion of the current, in contrast to the Si-doped devices presented in the main text.

To further characterize the current flow in the undoped device, we fitted flux profiles with an experimentally obtained bulk flux profile (at $V_g = 0\,V$) and calculated edge current flux profiles. We found that at the resistance peak coincides with the maximum percentage of current flowing in the edges of the device. In contrast to the Si-doped sample, a maximum of on $\sim 10\%$ of the total current flows along the edge of the sample. The majority of the current is carried by the bulk of the device, consistent with residual bulk conductivity [6].

The residual bulk carriers in the gap of the InAs/GaSb are localized [7] by Silicon doping, in contrast to the undoped sample presented here. Although these localized 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 [8]. 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 [9]), which may be important for determining the scale of potential disorder as well as aiding in localizing the bulk.

**EFFECTIVE RESISTANCE OF A FOUR-TERMINAL DEVICE**

We fitted flux profiles to extract the amount of current flowing in the top and bottom edges and homogenously through the bulk: $I_{top}, I_{bottom}, I_{bulk}$, respectively. The three contributions sum to $I_{total}$, the total applied current. Assuming that the three channels are in parallel, the resistance of the channels is given by:

$$R_{\text{eff}}^{\text{top}} = \frac{I_{total}}{I_{top}} R_{14,23}; R_{\text{eff}}^{\text{bottom}} = \frac{I_{total}}{I_{bottom}} R_{14,23}; R_{\text{eff}}^{\text{bulk}} = \frac{I_{total}}{I_{bulk}} R_{14,23}$$

(1)

where $R_{14,23}$ is the measured four terminal resistance. We have defined these extracted quantities as "effective" resistances because they are not the true resistance of the edge and bulk channels in a four-terminal geometry. Here we use a slightly more complicated resistor model to evaluate the applicability of the effective resistance in a four-terminal geometry. The difference from the initial more simple model is to break the top edge into three resistors
FIG. S 6. Image of 2D current in an undoped InAs/GaSb quantum well. (a) Optical image showing the portion of the device which was imaged. (b) Flux image of current flow in a InAs/GaSb quantum well which was tuned with a front gate to its resistance peak. (c) 2D current image along x. Current flows uniformly in the quantum well in the ungated portion, while a higher current density flows along the edges in the gated region. The bulk still carries a large portion of the current, in contrast to the Si-doped device presented in the main text.

in series \( R_{\text{top,1}}, R_{\text{top,2}}, R_{\text{top,3}} \), and the sum of the three is equal to \( R_{\text{top,total}} \). The measured resistance is given by the voltage measured across \( R_{\text{top,2}} \) and \( I_{\text{total}} \). Contact resistances drop out of the equation, which is not the case for a two-terminal measurement.

In this model, the effective resistances we measure are given by:

\[
R_{\text{eff,top}}^{\text{top}} = \frac{R_{\text{top,2}}}{R_{\text{top,total}}} \quad R_{\text{eff,top}}^{\text{bottom}} = \frac{R_{\text{top,2}}}{R_{\text{top,total}}} \quad R_{\text{eff,bulk}} = \frac{R_{\text{top,2}}}{R_{\text{top,total}}} R_{\text{bulk}}
\]

Therefore, the effective resistance (which is the value we extract from SQUID images) is proportional to the actual resistances of the edges with a proportionality constant that we did not directly measure. However, as long as the ratio \( R_{\text{top,2}}/R_{\text{top}} \) is temperature-independent (as we expect as long as the backscattering mechanism is the same in both edges) the measured effective resistance is directly proportional to the actual edge resistance.


FIG. S 7. Gate tuning of an undoped quantum well. (a) Two terminal resistance trace vs. applied front gate voltage. The sample is much less resistive in its insulating gap than the same device geometry made from a Si-doped wafer. (b) Fitted current flowing through the top edge, bottom edge and bulk of the device as a function of front gate voltage. When the device is at its most resistive, only ~10 percent of the current flows in each edge. (Inset) A comparison of the reconstructed 2D current in the insulating gap of a Si-doped device (gray) and the undoped device (black).


FIG. S 8. Resistor network model of the device. (a) Schematic of the device geometry and (b) a resistor model including the three segments of the top edge to account for the four-terminal geometry.