Unexpected edge conduction in mercury telluride quantum wells under broken time-reversal symmetry

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The realization of quantum spin Hall effect in HgTe quantum wells is considered a milestone in the discovery of topological insulators. Quantum spin Hall states are predicted to allow current flow at the edges of an insulating bulk, as demonstrated in various experiments. A key prediction yet to be experimentally verified is the breakdown of the edge conduction under broken time-reversal symmetry. Here we first establish a systematic framework for the magnetic field dependence of electrostatically gated quantum spin Hall devices. We then study edge conduction of an inverted quantum well device under broken time-reversal symmetry using microwave impedance microscopy, and compare our findings to a non-inverted device. At zero magnetic field, only the inverted device shows clear edge conduction in its local conductivity profile, consistent with theory. Surprisingly, the edge conduction persists up to 9 T with little change. This indicates physics beyond simple quantum spin Hall model, including material-specific properties and possibly many-body effects.
Quantum spin Hall (QSH) theory predicts that when the thickness of an HgTe quantum well (QW) exceeds a critical value \( d_c \), a band inversion happens and the QW transitions from a trivial insulator to a QSH insulator with gapless edge channels protected by time-reversal symmetry (TRS) \(^1\). While edge conduction in the presence of TRS has been well established in various transport \(^2\) and microscopy studies \(^3\), its predicted breakdown under broken TRS remains unverified \(^10\), except for earlier works showing suppression of conductance by weak field in devices with strong backscattering at zero field \(^3\), and a gap opening at the otherwise protected Landau level (LL) crossing near the field-induced topological phase transition \(^2\). A systematic magnetic-field-dependent study of QSH edge conduction combining microscopy and transport techniques is therefore highly desirable to gain further insight into this key prediction.

In this work, we combine transport and microwave impedance microscopy (MIM), a scanning probe technique that measures local electromagnetic response \(^14\), to study two HgTe/(Hg\(_0.3\)Cd\(_{0.7}\))Te QW devices, above (7.5 nm) and below (5.5 nm) the theoretical \( d_c \) of 6.7 nm. At zero magnetic field, edge conduction is only observed in the 7.5 nm device, consistent with QSH theory. In the case of broken TRS by a magnetic field, we first develop a rigorous treatment for the field dependence of QSH edge channels protected by time-reversal symmetry (TRS) \(^1\,\,^2\).

**Results**

5.5 versus 7.5 nm QW in zero magnetic field. We first establish the influence of the different QW thicknesses in transport measurements. We use a two-step etching process to define mesas with clean physical edges for both devices (Fig. 1a, Supplementary Fig. 1 and Supplementary Note 1). The conductive substrate (n++ GaAs) 4 µm below the QW is used as the back gate to tune the QW from p-type through the bulk gap to n-type, as shown in the two-terminal resistance \( R(T) \) taken at 4.5 K and 0 T, of a strip 50-µm long and 1,225-µm wide (Fig. 1c,f). When the Fermi level...
\((E_F)\) is gate-tuned to the bulk gap, \(R_2\) reaches 6 M\(\Omega\) (150 M\(\Omega/\Box\)) for the 5.5 nm QW but only 50 k\(\Omega\) for the 7.5 nm QW, consistent with contribution from edge conduction.

We then use MIM to confine the edge conduction in real space. MIM delivers a small excitation (< \(\sim 0.1\) \(\mu\)W) at 1 GHz to a metallic tip and measures the reflected signal with a spatial resolution of ~150 nm. The two output channels, MIM-Im and MIM-Re, are proportional to the change of the imaginary and real parts of the tip-sample admittance. For a buried QW structure, MIM-Re, are proportional to the change of the imaginary and real modes' at the crossover field of \(E_F\); the excess \(v_o\) factor \(\sim 0.15/\sim 0.2\) in this particular device, orange and blue lines in Fig. 2c–e).

**Magnetic field dependence of 7.5 nm QW.** The field dependence of the 7.5 nm device can be best illustrated through comparison with the 5.5 nm device. We start with expectations from a simple QSH model. Comparing Fig. 2g,b, we know that the bulk should behave similarly in both devices, insulating between the two mobility edges (\(|v|<\sim 0.2\) and conductive outside this range. The major predicted difference lies in the regime with insulating bulk (Fig. 2h): edge states are expected to exist between 0 and 3.8 T (Region I) due to the anomalous bending of the ‘zero modes’ near physical edges (Fig. 2f inset), but become progressively weaker due to disorder scattering and evolution of the ‘zero modes’, until completely disappearing into the bulk at 3.8 T, at which point the QW becomes a ‘trivial insulator’ (Region II). We stress here that the LL filling factor in region I and II is low enough (\(|v|<\sim 0.2\) that no integer quantum Hall effect should be present, as opposed to previous expectations (Supplementary Fig. 5). The gradual disappearance of the edge conduction from region I to II should be directly observable in real-space images; a reduced resistance should also be measured in region I due to the edge conduction, contrasting with a fully insulating behaviour in region II.

In the measured two-terminal resistance data on the 7.5 nm device, however, the expected fully insulating region II breaks into two sub-regions II and II* (Fig. 2i), where II* is not insulating. The nature of this discrepancy is readily revealed in the MIM images (Fig. 2j): whereas the bulk has already become insulating in II*, edge conduction, which is predicted to disappear beyond the crossover field (3.5 \(\pm 0.5\) T as determined experimentally), persists up to 9 T with no sign of disappearing, therefore making the QW continue to appear conductive in transport. The edge conduction gradually disappears towards the \(p\)-type side; the QW thus becomes homogeneously insulating and the resistance goes up by 2 orders of magnitude in region II of Fig. 2i. The boundary between II and II* (green dashed line in Fig. 2i) has a similar slope as the bulk mobility edge (\(|v|<0.2\), orange dashed line) but with an offset in density, and therefore extrapolates to a different ‘charge-neutral point’ at 0 T (green dotted line). The regions where edge conduction is present (Region I and II*), although artificially divided, show virtually no discontinuity. In fact, the edge conduction appears even clearer at finite field (compare 0 T/1.0 V and 5 T/1.0 V in Fig. 2j), as the bulk becomes more homogeneously insulating, likely due to the localization caused by the magnetic field.

A careful analysis of the MIM line profile further demonstrates that the local edge conductivity dominates electronic transport in both low- and high-field regimes. Figure 3a,c shows the averaged line-cuts of the MIM images in the two columns corresponding to the 3 and 7 T case in Fig. 2j. The extracted edge and bulk MIM signal is plotted against \(v_o\) in Fig. 3b,d, together with the corresponding \(R_2\) data. It is immediately obvious that both the peak position and magnitude of \(R_2\) have a strong correlation with the edge signal, but not the bulk signal. This excellent agreement between local signal and transport confirms that the unexpected edge conductivity is due to edge states that can conduct DC current across mesoscopic distances, instead of localized states at the edges.

**Discussion**

These results in HgTe QWs represent an opportunity to learn physics beyond the simple textbook QSH theory—a rare

Expected magnetic field dependence for gated HgTe QW devices. We now move on to the magnetic field dependence. Figure 2a,f is the calculated LL fan chart for 5.5 nm and 7.5 nm QWs, respectively. We included an inversion symmetry breaking term to reproduce the observed avoided crossing of the ‘zero modes’ at the crossover field of ~3.8 T (Fig. 2f)\(^{12,13,18}\). Previously the LL fan charts were directly compared with gate- and field-dependent transport data to demonstrate a ‘re-entrant quantum Hall effect’ in an inverted device: \(E_F\) was thought to stay constant with fixed gate voltage and thus if resides in the gap at zero field the insulating region expanding linearly with field. MIM scans of the 5.5 nm device agree well with expectation (Fig. 2a–e). The observed behaviour can be well understood by assuming that the mobility edge is at a fixed LL filling factor \(v\) (~ +0.15/−0.2) in this particular device, orange and blue lines in Fig. 2c–e).

**Magnetic field dependence of 5.5 nm QW.** The field dependence of the 5.5 nm device agrees well with expectation (Fig. 2a–e). Gate- and field-dependent two-terminal resistance (Fig. 2d) shows a simple metal–insulator transition at low densities, with the insulating region expanding linearly with field. MIM scans of a 7.2-\(\mu\)m long section of the mesa confirm that the mesa stays mostly homogeneously conductive or insulating with smooth transitions (Fig. 2e). The observed behaviour can be well understood by assuming that the mobility edge is at a fixed LL filling factor \(v\) (~ +0.15/−0.2) in this particular device, orange and blue lines in Fig. 2c–e).

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**Discussion**

These results in HgTe QWs represent an opportunity to learn physics beyond the simple textbook QSH theory—a rare
occurrence in the field of topological insulators where so far theoretical predictions are routinely confirmed. One might naively attribute the observed edge conduction in moderate to high fields to trivial edge states, possibly to mesoscopic lengths. In fact, both scenarios can account for our observations near the p-type side: Fermi level pinning would predict that the edge remains insulating when the bulk becomes conductive; fringing field effect would predict ed conduction turned on before the bulk becomes conductive; whereas experimentally the conductivity of edge and bulk evolve similarly upon entering the p-type side (for example, Vg = 0 to −1.5 V in Fig. 3d).

Moreover, the edge conduction, expected and unexpected, only appears in the 7.5 nm device—suggesting that it cannot be completely ‘trivial’, but is related to the thickness-induced band inversion. Additional crucial ingredients may include many-body effects and material specifics of HgTe QW, including its strong spin-orbit coupling, n-p asymmetry, mercury.
Methods

Contributions and understanding QSH in real systems.

Vacancies\textsuperscript{21,29,30} and intrinsic surface effect\textsuperscript{22,23}.

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Methods

**Figure 3** | Transport and MIM line-cut analysis for the 7.5 nm device at 3 and 7 T. (a) Averaged line-cuts of the centre \( \frac{1}{2} \) section of the real-space MIM-Im images in the 3 T column of Fig. 2g, with a 1.0 V offset in MIM signal between each gate voltage. Gate voltage is from \(-1.5\) to 3.0 V in 0.5 V steps. (b) Edge and bulk MIM-Im signal (at the red and blue dashed lines in a) and two-terminal resistance plotted against gate voltage. (c,d) Same plots for the 7 T column. Transport is clearly dominated by edge conduction in the bulk gapped regime in both fields, confirming the extended nature of the edge conduction observed by MIM.

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Author contributions

E.Y.M. did MIM and transport measurements. M.R.C. and M.M. developed the fabrication process and fabricated the devices. C.A., P.L. and M.R.C. characterized the material. C.A. and P.L. grew the QW wafers. J.W. and B.L. did the theoretical calculations. M.B. fabricated devices used for preliminary measurements. Data analysis, interpretation and manuscript preparation were done by all authors.

Additional information

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Competing financial interests: M.A.K and Z.X.S are co-founders of PrimeNano Inc. which licensed the sMIM technology from Stanford for commercial instrument.

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