Counterpropagating topological and quantum Hall edge channels

Saquib Shamim\textsuperscript{1,2} \textsuperscript{✉}, Pragya Shekhar\textsuperscript{1,2}, Wouter Beugeling\textsuperscript{1,2}, Jan Böttcher\textsuperscript{3}, Andreas Budewitz\textsuperscript{1,2}, Julian-Benedikt Mayer\textsuperscript{3}, Lukas Lunczer\textsuperscript{1,2}, Ewelina M. Hankiewicz\textsuperscript{3}, Hartmut Buhmann\textsuperscript{1,2} \& Laurens W. Molenkamp\textsuperscript{1,2} \textsuperscript{✉}

The survival of the quantum spin Hall edge channels in presence of an external magnetic field has been a subject of experimental and theoretical research. The inversion of Landau levels that accommodates the quantum spin Hall effect is destroyed at a critical magnetic field, and a trivial insulating gap appears in the spectrum for stronger fields. In this work, we report the absence of this transport gap in disordered two dimensional topological insulators in perpendicular magnetic fields of up to 16 T. Instead, we observe that a topological edge channel (from band inversion) coexists with a counterpropagating quantum Hall edge channel for magnetic fields at which the transition to the insulating regime is expected. For larger fields, we observe only the quantum Hall edge channel with transverse resistance close to $h/e^2$. By tuning the disorder using different fabrication processes, we find evidence that this unexpected $\nu = 1$ plateau originates from extended quantum Hall edge channels along a continuous network of charge puddles at the edges of the device.
Results

Material and devices. We have fabricated and measured multiple devices from (Hg,Mn)Te and HgTe quantum wells with varying layer thickness and composition. While the results reported here have been reproduced in nine devices, in this work, we present a representative subset of measurements on devices fabricated from the following quantum wells: (1) Two (Hg,Mn)Te quantum wells which are 11 nm thick with a Mn concentration of 2.4% and 1.2% labelled as QW1 and QW2, respectively. (2) A 7.5 nm thick HgTe quantum well labelled as QW3. All three quantum wells have an inverted band structure. The topological phase space of (Hg,Mn)Te quantum wells identified by \( k \cdot p \) band structure calculations have been discussed in detail in Ref.\(^1\). QW1 is a direct gap topological insulator with a band gap \( ~4.6 \) meV\(^1\). QW2 and QW3 have an indirect band gap of \( ~11 \) and \( ~23 \) meV respectively (as determined from \( k \cdot p \) band structure calculations). While the low field transport properties are sensitive to the nature of the band gap (direct or indirect)\(^1\), the high field transport properties are nominally identical for both direct and indirect gap devices as will be shown here. The devices fabricated from QW1 are labelled as Dev 1.d1 and Dev 1.d2; from QW2 are labelled as Dev 2.d and Dev 2.w; from QW3 are labelled as Dev 3.d, where d and w are used to indicate the dry- and wet-etching process respectively. The devices fabricated by dry etching use 110 nm of SiO\(_2\)/Si\(_3\)N\(_4\) (grown by plasma enhanced chemical vapor deposition at 80 °C) as gate dielectric while the wet-etched devices use 14 nm of HfO\(_2\) grown by atomic layer deposition at 30 °C as the gate dielectric layer. We have verified that the results presented in this work do not depend on the gate dielectric (Supplementary Note 1 and Supplementary Fig. 1).

In Table 1, we list the devices with their relevant properties, in particular device dimensions and etching method. Unless otherwise mentioned, all magnetotransport measurements have been performed in a magnetic field \( B \) perpendicular to the quantum well at a base temperature of \( T = 20 \) mK.

Magnetotransport: Landau level spectrum. Figure 1 shows the magnetotransport characteristics of Dev 1.d1 in a Hall bar geometry of length \( L = 30 \) μm and width \( W = 10 \) μm. The gate voltage characteristics (inset of Fig. 1a) show that we can tune the chemical potential from \( n \)- to \( p \)-conduction regime (carrier type identified by classical Hall effect measurements) by decreasing the

| Device label | quantum well | thickness \( d_{QW} \) (nm) | Mn conc. \( x \) | Dimensions \( L \times W \) (μm × μm) | Fabrication method | \( V_0 \) (V) | \( R_{xx}^{\text{max}} \) (Ω) | \( B^* \) (T) |
|-------------|--------------|-----------------|------------|-----------------|-----------------|------------|-------------|----------|
| Dev 1.d1    | QW1          | 11              | 2.4%       | 30 × 10         | dry etch       | −1.75      | 2.7 × 10\(^6\) | 3.1      |
| Dev 1.d2    | QW1          | 11              | 2.4%       | 600 × 200       | dry etch       | −2.45      | 3.0 × 10\(^5\) | 6.7      |
| Dev 2.d     | QW2          | 11              | 1.2%       | 30 × 10         | dry etch       | −1.45      | 70 × 10\(^3\)  | 6.7      |
| Dev 2.w     | QW2          | 11              | 1.2%       | 30 × 10         | wet etch       | −0.45      | 170 × 10\(^3\) | 6.7      |
| Dev 3.d     | QW3          | 7.5             | 0          | 30 × 10         | dry etch       | −0.61      | 47 × 10\(^3\)  | 6.4      |

The values are given at temperature \( T = 4.2 \) K for devices Dev 2.d and Dev 2.w, and at \( T = 20 \) mK for all other devices.
Landau level crossing at a function of perpendicular magnetic conductivity. Numbers indicate quantum Hall dashed line shows a transition from low magnetic fields emerge from the quantum spin Hall states enhanced by the band inversion-induced van Hove singularity in the valence band of topological (Hg,Mn)Te quantum wells. For $V_g^* = 0$, the $\nu = -1$ plateau persists up to $B \sim 5$ T. This value increases for more negative $V_g^*$, cf. Fig. 1a.

As $B$ increases further, $R_{xy}$ increases, changes sign and saturates to a $\nu = 1$ quantized plateau characterized by $R_{xy} = h/e^2$ (dashed gray line in Fig. 1a). The sign of $R_{xy}$ and $\nu$ is normally associated with the charge carrier type (electrons or holes) in the system and hence a change in the sign as a function of $B$ (at constant $V_g^*$) is intriguing. Interestingly, in the transition regime from $\nu = -1$ to $\nu = 1$ plateau, $R_{xx}$ is quantized to $h/2e^2$ (dotted black line in Fig. 1a) and decreases to a low value (few kΩ depending on $V_g^*$) at large $B$ when $R_{xy}$ is quantized to $h/e^2$. In addition, the $\nu = 1$ plateau at high $B$ exhibits significant fluctuations (in $R_{xy}$) and $R_{xx}$ is still finite, in contrast to the emergent $\nu = -1$ and the regular quantum Hall plateaus of two-dimensional systems where $R_{xy}$ is essentially flat and $R_{xx} = 0$ within the limits of experimental accuracy. The observed fluctuations in $R_{xy}$ at high $B$ are reproducible between measurements of the same device and result from quantum interference. The transition from $\nu = -1$ to $\nu = 1$ is prominently visible in the Landau fan (Fig. 1b), where we show $d\sigma_{xy}/dV_g^*$ as a function of $B$ and $V_g^*$. Similar eye-catching is the complete absence of the insulating regime that we would expect from the calculated Landau fan shown in Fig. 1c (calculation details in Methods section).

**Counterpropagating edge channels.** The quantization of $R_{xx}$ at $h/2e^2$ is a clear indication of presence of counterpropagating edge channels. Further convincing proof of the existence of counterpropagating edge channels can be obtained from nonlocal transport experiments. A schematic of such a nonlocal measurement setup in a six terminal Hall device is shown in the inset of Fig. 2. A current $I$ flows through the contacts 1 and 6 while the nonlocal voltages $V_{45}$ and $V_{35}$ are measured across contacts 4 & 5 and 3 & 5 respectively, which are spatially separated from the current path. The nonlocal resistances $R_{16,35} = V_{35}/I$ as a function of $B$ for $V_g^* = 0.25$ V are shown in Fig. 2. The nonlocal resistance is zero till $B \sim 4$ T, beyond which it increases, reaches the maximum at $B \sim 6$ T and finally decreases, approaching zero at high $B$. For a pair of counterpropagating edge channels, the Landauer-Büttiker formalism predicts $R_{16,35} = (1/3)h/e^2$ and $R_{16,45} = (1/6)h/e^2$, shown by the dashed lines in Fig. 2. The agreement between the experimentally measured nonlocal resistance and the theoretically expected value confirms the existence of counterpropagating edge channels in the transition regime from $\nu = -1$ to $\nu = 1$ plateau. In contrast to the situation for the helical edge channels of the quantum spin Hall effect at zero field, there is no time-reversal symmetry between the edge channels at these high fields. Here, the two edge channels have fundamentally different origins: the topological channel, associated to the $\nu = -1$ plateau, originates from the band inversion, while the quantum Hall channel, associated to the $\nu = 1$ plateau,
is generated by the magnetic field. Due to their distinct nature, their localization properties are different. The resulting spatial separation is key to the survival of the topological edge channel up to large magnetic fields and can be viewed as a manifestation of the parity anomaly in condensed matter physics.18,19.

A typical band structure calculated with the $\mathbf{k} \cdot \mathbf{p}$ method at $B = 5$ T in a disorder-free sample is illustrated in Fig. 3a. The topological and quantum Hall edge channel, coming from the same block (blue in Fig. 3a), gap out as a result of hybridization. Thus, in absence of edge channels at the chemical potential $\mu$, a trivially insulating state would be expected. However, its absence in experiments indicates that disorder must not be neglected.

**v = 1 quantum Hall edge channel due to charge puddles.** In narrow gap semiconductors, the defects at the interface of the semiconductor and insulator lead to local fluctuations in carrier density. When the gate voltage is used to tune the chemical potential, small charged regions form, known as "charge puddles."6,7 It has been shown previously that such charge puddles are the dominant disorder for HgTe devices.20 Figure 3b shows a schematic of the potential fluctuations along the width of the device (cross section from one edge to the other edge). The dry-etched devices (like Dev 1.d1) are patterned using lithography and subsequent physical etching using high energy ions. For such devices, the magnitude of the potential fluctuations is expected to be largest near the edges, where the etching takes place. Previous investigations of HgTe quantum wells (fabricated using a similar technology as in Ref. 8) showed that p-type charge puddles (regions in bulk that locally contain p-type charge carriers) are prevalent in these structures because of the large density of states near the top of the valence band.21 The formation of p-type puddles for a dry-etched device is schematically shown in Fig. 3b. In Fig. 3c we illustrate the high density of puddles near the physical edge of the device (gray areas). The edges of the dry-etched devices are formed by physically removing material using Ar ions. Hence the amount of disorder (density of puddles) is maximal near the edges. In strong magnetic fields, the quantum...
Hall edge channel (violet in Fig. 3c) propagates along an equipotential line of the disorder potential, facing the interior of the device, resulting in a propagation direction consistent with $\nu = 1$. Isolated charge puddles exist in the bulk of the material as well, that may host localized channels that do not contribute to transport at a macroscopic level. In contrast, the exterior edge of the device hosts the topological edge channel (bright blue line), i.e., the single component of the quantum spin Hall edge channels that survives in strong magnetic fields, with opposite direction of propagation ($\nu = -1$). This topological edge channel is localized at the exterior edge regardless of disorder, because the localization is independent of momentum (see Methods). The spatial separation, a result of the distinct fundamental nature of the topological and quantum Hall edge channels in combination with disorder at the edge, suppresses scattering between them, and is thus a key ingredient for their coexistence.

In order to confirm our hypothesis that charge puddles are essential for the observation of counterpropagating edge channels, we have performed two further experiments: Firstly, since a continuous network of charge puddles along the entire edge of the device is essential to observe the quantum Hall edge channel, we perform magnetotransport measurements in devices of dimensions $600 \times 200 \mu m^2$ (Dev 1.d2) which are much larger than the dimensions $30 \times 10 \mu m^2$ of Dev 1.d1 presented in Fig. 1. At larger length scales, the possibility of formation of a continuous network of charge puddles is drastically reduced and we do not expect to observe the same signature of counterpropagating edge channels and the transition from $\nu = -1$ to $\nu = 1$ quantum Hall plateau as a function of magnetic field$^{9}$. Indeed, we observe a weak signature of the transition from topological to quantum Hall plateau and an insulating state (region where $\sigma_{xy} = 0$ at high magnetic fields) is distinctly visible in the $600 \times 200 \mu m^2$ device (Fig. 4b), unlike the small device (Fig. 4a). Secondly, we have compared devices fabricated using two different techniques: dry- and wet-etching. Since the wet-etching process is known to maintain the high quality of the material and the influence of charge puddles is expected to be significantly reduced as compared to dry-etched devices, we do not expect to observe the counterpropagating edge channels in the wet-etched devices (see calculated band structure and wave functions in Fig. 3a, b). Figures 4c, d show the transverse conductivity $\sigma_{xy}$ as a function of magnetic field for dry- (Dev 2.d) and wet-etched (Dev 2.w) devices, respectively for various $V_{g}/C_3$.

The dry-etched devices show a transition from $\nu = -1$ to $\nu = 1$ plateau as a function of applied magnetic field for $V_{g} \leq 0$ V. Importantly, the edge conduction is observed in the dry-etched devices in the entire range of the gate voltage and magnetic field investigated in the experiments, indicating the absence of a gap. In contrast, the wet-etched device shows that $\sigma_{xy} = 0$ at high $B$ for various $V_{g}$, close to 0 V (Fig. 4d). We identify this $\sigma_{xy} = 0$ region as a non-topological insulating state, characterized by the absence of any edge channel, since the current through the device is zero and we do not observe any quantization of $R_{xx}$ to $h/2e^2$ (see Supplementary Fig. 3). From this we conclude that the counterpropagating edge channel is essential for the observation of counterpropagating edge channels.
channels are formed only in the dry-etched devices, while they are absent in the wet-etched ones. Thus, the amount of disorder (density of charge puddles) plays a crucial role in the formation of the extended quantum Hall edge channels.

Discussion
The presence of Mn is not at all essential for the transition from \( \nu = -1 \) to \( \nu = 1 \) quantum Hall plateau and the associated coexistence of topological and quantum Hall edge channels to occur. The HgTe and (Hg,Mn)Te quantum wells are identical in view of fundamental symmetry properties\(^{22}\) and Mn merely facilitates the observation of a \( \nu = -1 \) quantum Hall plateau at very low fields\(^{13}\). In Dev 3.d, a Mn-free HgTe two-dimensional topological insulator, we have observed the transition from \( \nu = 1 \) to \( \nu = 1 \) quantum Hall plateau (Fig. 5). The previous observation of edge conduction in HgTe quantum wells at high magnetic fields\(^{8}\) is likely due to the high density of charge puddles caused by lithographic and etching processes. Though a second chemical wet-etch process is now available to mitigate the in

Device fabrication.

The quantum wells are fabricated into Hall bars with different dimension using optical lithography and etching. We use two distinct etching techniques: conventional dry etching using high energy argon ions and chemical wet etching. The devices fabricated by dry etching use a 110 nm of SiO\(_2\)/SiN\(_x\) (grown by plasma enhanced chemical vapor deposition at 80 °C) as gate dielectric while the wet-etched devices use a 14 nm of HfO\(_x\) grown by atomic layer deposition at 30 °C as the gate dielectric layer. The gate electrode is formed by deposition of 5/200 nm of Ti/Au onto the dielectric. The ohmic contacts to the quantum well are realized by deposition of 50 nm AuGe and 50 nm Au by e-gun evaporation.

Magneto-transport measurements.

The magnetotransport measurements have been performed in a He\(_2\)/He\(_4\) dilution refrigerator of base temperature 20 mK. The longitudinal and transverse resistance, \( R_x \) and \( R_y \), respectively, have been measured using low frequency (~13 Hz) lock-in techniques in a four probe configuration. The current flowing through the device was in the range 2–20 nA.

Band structure calculations with the \( k \cdot p \) model.

We have used a \( k \cdot p \) model with a basis of eight orbitals\(^{23}\): \(| \Gamma_x, 1/2 \rangle, | \Gamma_x, -1/2 \rangle, | \Gamma_y, 1/2 \rangle, | \Gamma_y, -1/2 \rangle, | \Gamma_z, 1 \rangle, | \Gamma_z, -1 \rangle, | \Gamma_z, 0 \rangle, | \Gamma_z, 0 \rangle \). We have modelled the Hall bar geometry as a 500 nm wide strip with the layer stack as described in “Material growth and characterization”. The system is spatially discretized in two dimensions, with the remaining (longitudinal in-plane) direction being represented as momentum \( k \). The reduced width compared to the physical device does not affect the physics of the edge channels. The Hamiltonian matrices of dimension ~10\(^6\) are diagonalized using sparse matrix algorithms available from the SciPy package for Python. The calculations were performed at the Julia-HPC cluster at the University of Würzburg.

To conclude, we have observed the absence of the theoretically predicted transport gap in the Landau level spectrum of disordered two-dimensional topological insulators at high magnetic field. We have shown the significant impact of the fabrication processes on the observed transport properties, in particular how the dry-etching process can lead to the observation of edge channels at high perpendicular magnetic fields where usually one would expect an insulating state. The observations confirm the crucial role of the charge puddles for the formation of a quantum Hall conductance channel, while also underlining the significance of the distinct fundamental nature of topological versus quantum Hall edge channels. Our findings further demonstrate that, in HgTe, sufficient lithographic control is now available to mitigate the influence of charge puddles on quantum transport. The simultaneous occurrence of counterpropagating topological and quantum Hall edge channels is a novel signature of materials with an inverted band structure.

Methods

Material growth and characterization.

We use commercial (Cd,Zn)Te substrates to grow HgTe and (Hg,Mn)Te quantum wells. Using molecular beam epitaxy, we grow a CdTe buffer layer of thickness 50 nm, followed by a (Hg,Cd)Te barrier, a HgTe or (Hg,Mn)Te quantum well, and another (Hg,Cd)Te barrier. X-ray diffraction measurements are used to determine the thickness of the quantum wells and the Mn concentration. The quantum wells show a typical mobility \( \mu = 2 \times 10^6 \text{cm}^2\text{V}^{-1}\text{s}^{-1} \) for carrier density \( n = 5 \times 10^{11} \text{cm}^{-2} \).

Device fabrication.

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Acknowledgements

We thank C. Gould, C. Morais Smith and C. Brune for useful discussions. We thank P. Mandal for providing the data for Supplementary Fig. 2b. We acknowledge financial support from the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) in the Leibniz Program (L.W.M.) and in the projects SFB 1170 (Project ID 258499086; L.W.M., H.B., E.M.H.) and SPP 1666 (Project ID 22018735; L.W.M., H.B.), from the EU ERC-AdG program (Project 4-TOPS; L.W.M.), from the Würzburg-Dresden Cluster of Excellence on Complexity and Topology in Quantum Matter (EXC 2147, Project ID 39085490; L.W.M., H.B., E.M.H.), and from the Free State of Bavaria [Elitenetzwerk Bayern IDK ’Topologische Isolatoren’ (L.W.M., H.B., E.M.H.) and the Institute for Topological Insulators (L.W.M.)].

Author contributions

S.S., H.B. and L.W.M. planned the experiments. S.S., P.S. and A.B. conducted the measurements and analyzed the data. The band structure analysis was performed by W.B., J.B. and J.B.M. The material was grown by L.L. The devices were fabricated by P.S. All authors contributed to interpretation of the results. L.W.M., H.B. and E.M.H. supervised the project. S.S. and W.B. wrote the article with input from all authors. S.S., P.S., and W.B. contributed equally to this work.

Funding

Open Access funding enabled and organized by Projekt DEAL.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41467-022-29815-2.

Correspondence and requests for materials should be addressed to Saquib Shamim or Laurens W. Molenkamp.

Peer review information Nature Communications thanks the anonymous, reviewer(s) for their contribution to the peer review of this work.

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