Edge conduction in monolayer WTe$_2$

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2D Topological Insulators

2D topological insulator $\implies$ Helical 1D edge mode

Quantum wells of Hg/CdTe and InAs/GaSb

Edge conductance not quantized
mesoscopic fluctuations as a function of gate voltage

Existence/Absence of elastic backscattering?
Conductance at high magnetic field
Tungsten Ditelluride WTe$_2$

- $a = 3.48$ Å
- $b = 6.25$ Å
- $c = 14.02$ Å

Helical modes

Bulk

5µm

Top Graphite

Pt/Pd

hBN

Si
WTe$_2$

100 µV a.c. Excitation
3 mV d.c. bias
Effects only 1.6K, suppresses ZBA

3Layer
Stays metallic

2Layer
Sharp dip at around $V_G=0$
Stays metallic for $V_G>>1$

1 Layer
Wider minimum
100>T plateau of conductance

100>T → Bulk is insulating
⇒ Edge conduction
Edge Conduction

\[ \frac{V_{nl}}{V_0} \approx 1 \rightarrow \text{Edge Conduction} \]

Bulk is insulating

\( \text{(Black)} \) – \( \text{(Blue)} \)

Constant edge contribution

Independent of \( V_G \)
Edge Conduction

Negligible bulk contribution

\[ G_{\text{edge}} = G_0 e^{-\alpha B_{\parallel} / T} \]
\[ \Delta_B = g \mu_B B_{\parallel} \]
\[ g = \alpha k_B / \mu_B \approx 7.5 \]

Possibility of Edge Conductance
- \( G_{\text{edge}} \) is independent of gate voltage
- No Edge conduction in bilayer
- \( B_{\parallel} \) suppresses \( G_{\text{edge}} \) \( \iff \) TR symmetry is broken
Zero Bias Anomaly

All edges show dip at 1.6K

ZBA ↔ mesoscopic fluctuation

B field ⟹ suppresses ZBA and mesoscopic fluctuations
Value of $G_{\text{edge}}$

Expected $G_{\text{edge}} = 1 \frac{e^2}{h} = 38.7 \ \mu S$

Possible reasons:
- Imperfect transmission between edge and the metal contacts.
- Backscattering from multiple magnetic impurities*
- Puddles in disorder potential*

If some form of backscattering is allowed in a quantum wire, ZBA can develop due to interaction effects*

We do not observe the quantized conductance that would be a definitive signature of a 2DTI
Discussion

Suppose single helical edge in disorder potential

If backscattering, stronger at weak points

\[ B_\parallel = 0 \Rightarrow \frac{1}{2} e^2/h \]

\[ \Rightarrow \text{Rapid mesoscopic fluctuations} \]

If the reason is quantum interference, no \( B_\perp \) dependence

As \( T \) lower \( \Rightarrow \) stronger scattering \( \Rightarrow \) ZBA

Long edges \( \Rightarrow \) smaller conductance

As \( T \) higher \( \Rightarrow \) coherence length decreases

\[ \Rightarrow \text{G}_{\text{edge}} \text{ decrease (above 6K)} \]

Magnetic field opens gap \( \Delta_B \)

\[ \Rightarrow \text{G}_{\text{edge}} \text{ has factor } e^{-\Delta_B/k_B T} \]
Conclusions

Monolayer WTe2 is a possible 2D Topological Insulator

Nonlocal measurements / Pincer shaped contacts to show edge conductance

Dependece of $G_{\text{edge}}$ on $B_\parallel$, $B_\perp$ and $T$

Zero Bias Anomaly

$G_{\text{Edge}} < 1 \, e^2/h = 38.7 \, \mu\text{S}$

Discussion on the scenerio of a single helical edge mode

Outlook

- Excitonic insulator: electron-hole correlations below 100K
- Edge of exfoliated monolayer: orientation, roughness, chemical details
- Band structure tuning: chemical substitution, strain

Thank you
In studying the edges in the main text (Figure 3 and 4), we focused on two-terminal measurements. Four-terminal measurements were not presented because they yield the same results, implying the contacts to the edge were "perfect" in the sense that the current can only pass between adjacent edges via the metal of the contact in between. To illustrate this, Fig. S4a shows the parallel field dependence of the conductance at $V_g = 0$ in device MW2, in which the black and red curves were measured with two- and four-terminal configurations respectively as defined in the inset ($G_{23} = I_{23}/V_{23}$, $G_{14,23} = I_{14}/V_{23}$). Even as the magnetic field suppresses the edge conductance, both two and four-terminal measurements give almost identical conductance values.

Figure S4 | **Comparison of two-terminal and multi-terminal measurements in device MW2.** a, Perpendicular magnetic field dependence of the conductance of a particular edge at 6.5 K, $V_g = 0$; black and red curves are two- and four-terminal measurements respectively as labeled, with 2 and 3 the voltage contacts in both cases. b, Gate dependence of direct two-terminal conductance $G_{36}$ (black) and series conductance $(G_{32}^{-1} + G_{26}^{-1})^{-1}$ (red), at 1.6 K and $B = 0$.

Figure S4b compares the gate dependence of $G_{36}$ with $(G_{32}^{-1} + G_{26}^{-1})^{-1}$ in device MW2 with contact 4 grounded, here $G_{36}$, $G_{32}$, $G_{26}$ are two-terminal conductances. On the plateau region, there is minimal difference between the two, even for the mesoscopic fluctuations. This implies a strong contact coupling and, again, that the conductance is determined entirely by the edge in this regime, since bulk current flow would violate this equivalence.
SI-4. Length dependence of the monolayer 2D bulk conduction

Above 100 K, two-terminal conduction is dominated by the 2D bulk. Fig. S5 shows the two-terminal resistance as a function of aspect ratio $L/W$ for device MW1 at $V_g = 0$. If the edge contribution is small, the two-terminal resistance is given roughly by $R = \rho_s \frac{L}{W} + 2 R_c$. From the linear fit (for large aspect ratio a deviation from the linear fit is expected due to current spreading) we extract the sheet resistivity $\rho_s$, which increases from 20 kΩ at room temperature to 125 kΩ at 155 K, consistent with the insulating behavior for zero gate voltage. The extracted contact resistance $R_c$ is approximately 2 kΩ per contact.

![Figure S5](image)

**Figure S5 | Length dependence of two-terminal resistance in device MW1.** Resistance as a function of aspect ratio at $V_g = 0$ for $T = 300$ K, 200 K, and 155 K.
SI-5. Temperature dependence of the monolayer 2D bulk conduction

Figure S6a shows two-terminal linear-response conductance measurements in device MW2 made in a similar way to the measurements on the pincer-shaped device (MW3) in the main text (Fig. 2). Again a conductance plateau is seen at 4.2 K with mesoscopic fluctuations, indicating there is only edge conduction in this region. The conductance of the plateau is relatively low because of the combination of longer edges and ZBA. When we short out all the edge current, as shown in the insets, the conductance $I/V$ is suppressed to an unmeasurably small level in the plateau region implying that the conductance through the bulk is negligible at this temperature. Figure S6b shows its temperature dependence at $V_g = 0$. Above ~100 K, the conductance rises roughly linearly with temperature. At lower temperatures, it is approximately activated with activation energy ~5 meV (red trace in the right inset). This illustrates the sense in which the bulk becomes insulating below 100 K.

Figure S6 | Gate and temperature dependence of bulk conductance in device MW2. a, Comparison of $I/V$ as a function of gate voltage for the two experimental configurations shown. Analogous to Fig. 2c in the main text, the red trace is the total two-terminal resistance which contains both edge and bulk contributions, while the black trace only contains a bulk contribution. b, Temperature dependence of the bulk measurement at $V_g = 0$. Inset: Arrhenius plot, showing approximately activated behavior below ~100 K (red trace, 5 meV). No signal was detectable above the background noise at temperatures below the lowest one shown here (20 K).