

Supplementary for anomalous conductance quantization of a one-dimensional channel in monolayer WSe₂

Justin Boddison-Chouinard,¹ Alex Bogan,² Pedro Barrios,³ Jean Lapointe,³ Kenji Watanabe,⁴ Takashi Taniguchi,⁵ Jarosław Pawłowski,⁶ Daniel Miravet,¹ Maciej Bieniek,^{7,6} Paweł Hawrylak,¹ Adina Luican-Mayer,^{1,*} and Louis Gaudreau^{2,†}

¹*Department of Physics, University of Ottawa, Ottawa, Ontario, K1N 9A7*

²*Emerging Technologies Division, National Research Council of Canada, Ottawa, Ontario, K1A 0R6*

³*Advanced Electronics and Photonics, National Research Council of Canada, Ottawa, Ontario, K1A 0R6*

⁴*Research Center for Functional Materials, National Institute for Materials Science, 1-1 Namiki, Tsukuba 305-0044, Japan*

⁵*International Center for Materials Nanoarchitectonics,
National Institute for Materials Science, 1-1 Namiki, Tsukuba 305-0044, Japan*

⁶*Department of Theoretical Physics, Wrocław University of Science and Technology, Wrocław, Poland*

⁷*Institute of Theoretical Physics, Würzburg University, Würzburg, Germany*

Outline

Section 1: 2-point measurement and contact resistance

Section 2: Mobility and carrier density calculation

Section 3: Series resistance calculation

Section 4: Reproducibility at 10 mK

Section 5: Reproducibility in a different measurement setup

Section 6: Transport in the low carrier density regime

Section 7: Tight-binding parameters

* luican-mayer@uottawa.ca

† louis.gaudreau@nrc-cnrc.gc.ca

SECTION 1: 2-POINT MEASUREMENT AND CONTACT RESISTANCE

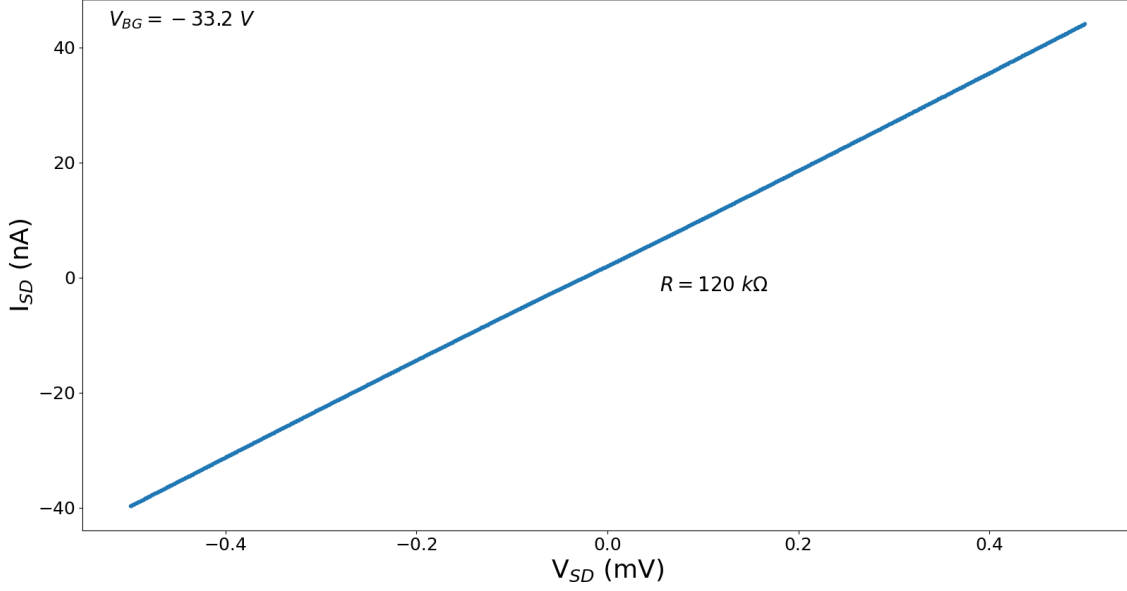


FIG. 1. 2-point measurement of the source-drain current as a function of the bias voltage indicating a total resistance of 120 k Ω . T = 4 K.

We performed 2-point IV measurements in addition to the 4-point measurements presented in the main text to obtain the contact resistance. The 2-point measurement yielded a resistance of 120 k Ω (Figure 1) which is a sum of the contact resistance (2 contacts), the RF line (connected to a single contact), and the channel resistance. From the 4-point measurement taken at a back-gate voltage of $V_{BG} = -33.2 \text{ V}$, the channel resistance is 480 Ω (Figure 2a in the main text). The RF line connected to one contact has a resistance of 100 k Ω . Therefore, the average contact resistance per contact is 9760 Ω .

$$R_C = \frac{1}{2}(R_{2\text{-point}} - R_{4\text{-point}} - R_{RF}) = 9760 \text{ } \Omega$$

SECTION 2: MOBILITY AND CARRIER DENSITY CALCULATION

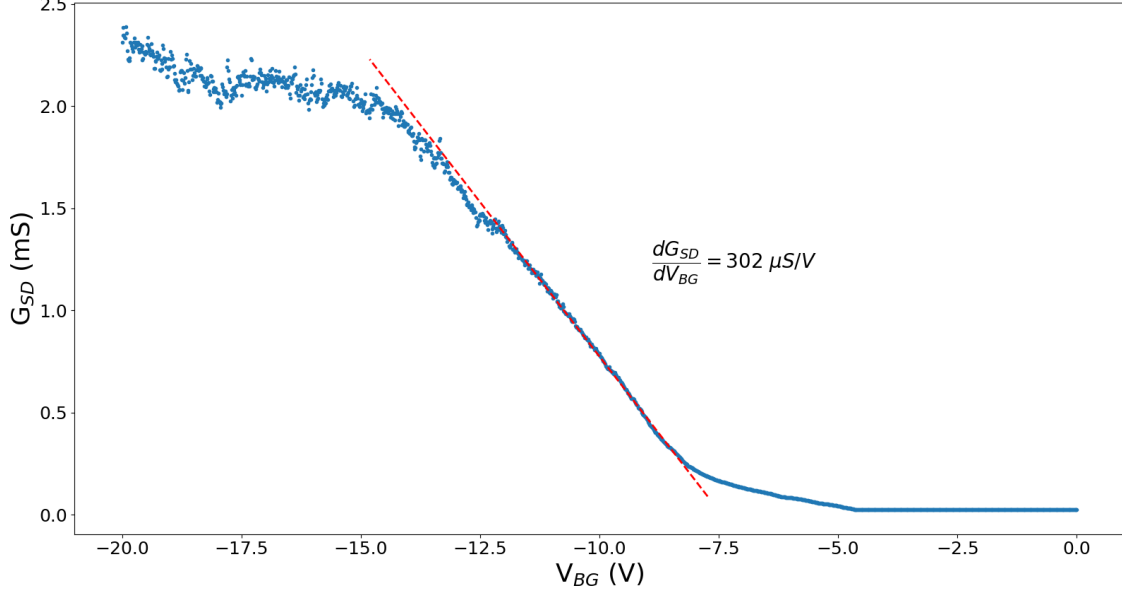


FIG. 2. 4-point measurement of the source-drain conductance as a function of back-gate voltage taken at 4K.

In a 4-point measurement scheme, we monitor the resistance as a function of back-gate voltage with the split gate turned off. The conductance (inverse of resistance) increases linearly as of $V_{BG} = -8$ V. From this linear segment, we extract a slope of $-302 \mu\text{S/V}$ and a x-intercept of $V_{th} = -7.44$ V, which corresponds to the threshold voltage. Using these values, we can estimate the field-effect mobility of our device and obtain the carrier concentrations for different values of V_{BG} . For calculating the mobility, we use:

$$\mu = \frac{dG_{SD}}{dV_{BG}} \frac{L}{w} \frac{1}{C_G}$$

where the ratio L/w is taken to be 1.3 (calculated from the geometry of the sample), and $\frac{dG_{SD}}{dV_{BG}} = -302 \mu\text{S/V}$ (Figure 2). The gate capacitance per unit area, C_G , is obtained by considering that the dielectric between the WSe_2 and the back-gate is comprised of 285 nm of SiO_2 and 26 nm of hBN (confirmed by AFM). Therefore,

$$\begin{aligned} C_G &= \epsilon_0 \left(\frac{\epsilon_{\text{SiO}_2} \epsilon_{\text{hBN}}}{\epsilon_{\text{hBN}} t_{\text{SiO}_2} + \epsilon_{\text{SiO}_2} t_{\text{hBN}}} \right) \\ &= \epsilon_0 \left(\frac{(4)(4)}{4(285 \times 10^{-9}) + 4(26 \times 10^{-9})} \right) \\ &= 1.14 \times 10^{-4} \text{ F/m}^2. \end{aligned}$$

With these values, we obtain a mobility of approximately $\mu_{FE} = 7900 \text{ cm}^2/\text{Vs}$ which is better than other high mobility values reported in WSe_2 [1–4]. Additional values were extracted from similar curves taken at room temperature and at 1 K where we obtained $\mu_{FE}(T = 300\text{K}) = 297 \text{ cm}^2/\text{Vs}$ and $\mu_{FE}(T = 1\text{K}) = 16357 \text{ cm}^2/\text{Vs}$. This trend from low mobility to high mobility as temperature decreases further suggests that a clean and high mobility device has been fabricated.

The carrier concentration at any given back-gate voltage can be estimated by

$$n(V_{BG}) = C_G \frac{V_{BG} - V_{Th}}{e}$$

For example, at $V_{BG} = -33$ V (Figure 2 a-b in main text), the hole concentration is approximately $n = 1.82 \times 10^{12} \text{ cm}^{-2}$.

SECTION 3: SERIES RESISTANCE CALCULATION

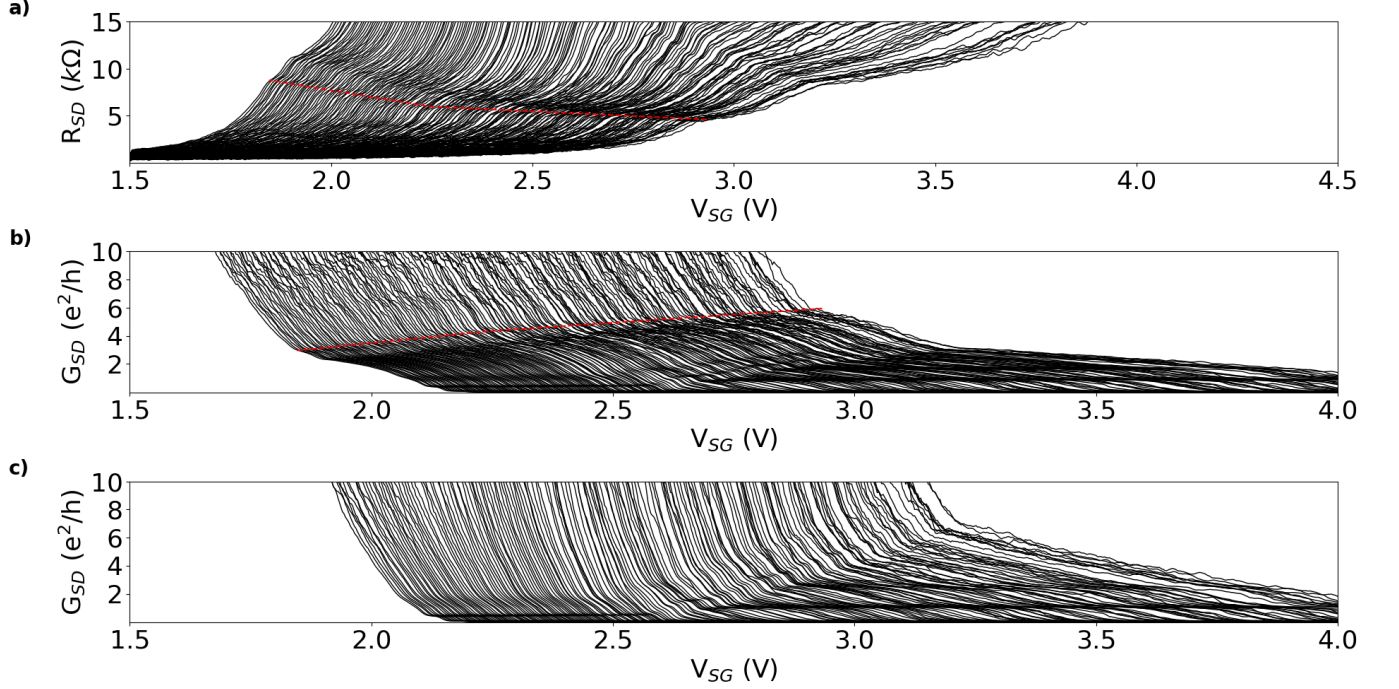


FIG. 3. (a) Resistance as a function of split gate voltage V_{SG} where each trace is taken at a different back-gate voltage V_{BG} ranging from -25 V (left) to -35 V (right). (b) Corresponding conductance curves plotted in units of e^2/h . The red lines in plots (a-b) correspond to the depletion of the split gates and consequently the series resistance. (c) The same traces as in (b) after subtracting the series resistance.

In Supplementary Figure 3(a), we plot the raw data (resistance vs. split gate voltage) for various values of the back-gate voltage. The leftmost curve corresponds to a back-gate voltage of -25 V and the rightmost curve corresponds to a back-gate voltage of -35 V. The spacing between each curve is 50 mV. In Supplementary Figure 3(b), the conductance ($\frac{1}{R_{SD}}$) is plotted as a function of the split gate voltage for the same curves as in Supplementary Figure 3(a). In both Supplementary Figure 3(a-b), a red dotted line is plotted indicating the value of the series resistance that was subtracted to obtain Supplementary Figure 3(c) (Figure 2 c-d in the main manuscript). This series resistance represents the resistance at the point where the areas beneath the split gates are depleted and was obtained in a similar fashion to Marinov *et al.*[5]. As we can see, the series resistance decreases as a function of back-gate voltage because the WSe₂ sheets on either side of the split gates have more carriers and therefore less resistance. After removing the series resistance (Supplementary Figure 3(b)), we obtain the same plot as found in the main text (Supplementary Figure 2d).

SECTION 4: REPRODUCIBILITY AT 10 MK

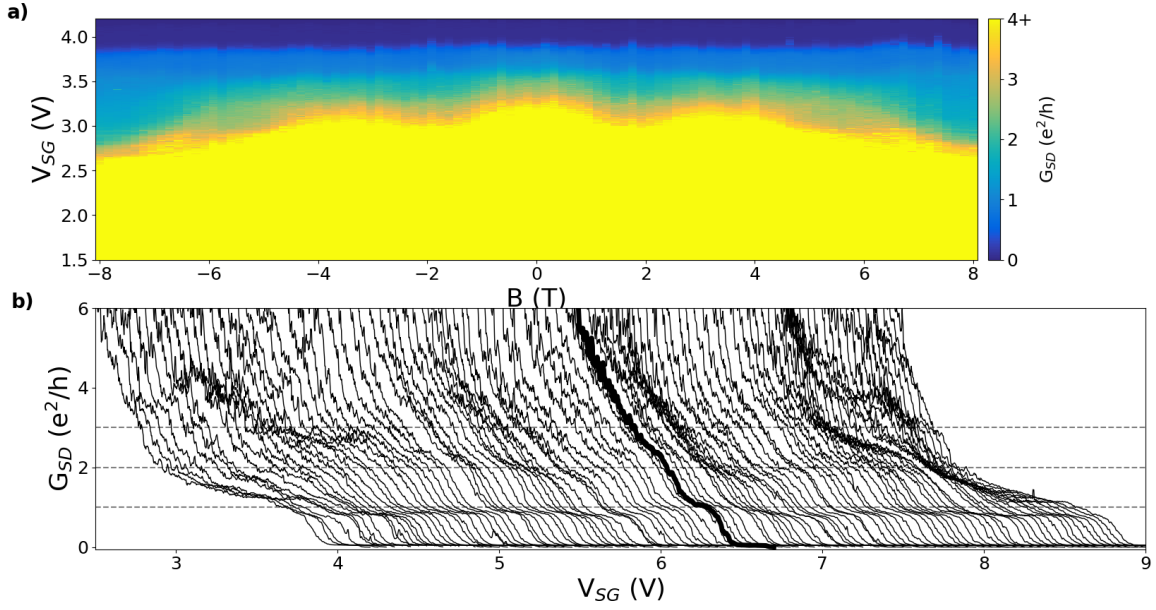


FIG. 4. (a) Dependence of the quantized conductance plateaus on a perpendicular magnetic field ranging from -8 T to 8 T. (b) Line cuts from (a) plotted in a “waterfall” style. A horizontal offset is introduced between adjacent line traces for clarity. A lead resistance of $R_L = 5083 \, \Omega$ was subtracted. $V_{BG} = -33.2 \, \text{V}$.

The same set of measurements found in Figure 3 in the main manuscript was also performed at the base temperature of the dilution refrigerator (10 mK) (Supplementary Figure 4). A first plateau appears at e^2/h for all values of the magnetic field. Another plateau appears around $2 e^2/h$ at $B = 0 \, \text{T}$ and quickly converges to $2 e^2/h$ as we turn on the magnetic field. This value away from $2 e^2/h$ at $B = 0 \, \text{T}$ is attributed to magnetoresistance effects in the leads. At approximately $\pm 5 \, \text{T}$, the $2 e^2/h$ plateau evolves towards the e^2/h plateau as seen at 4 K.

SECTION 5: REPRODUCIBILITY IN A DIFFERENT MEASUREMENT SETUP

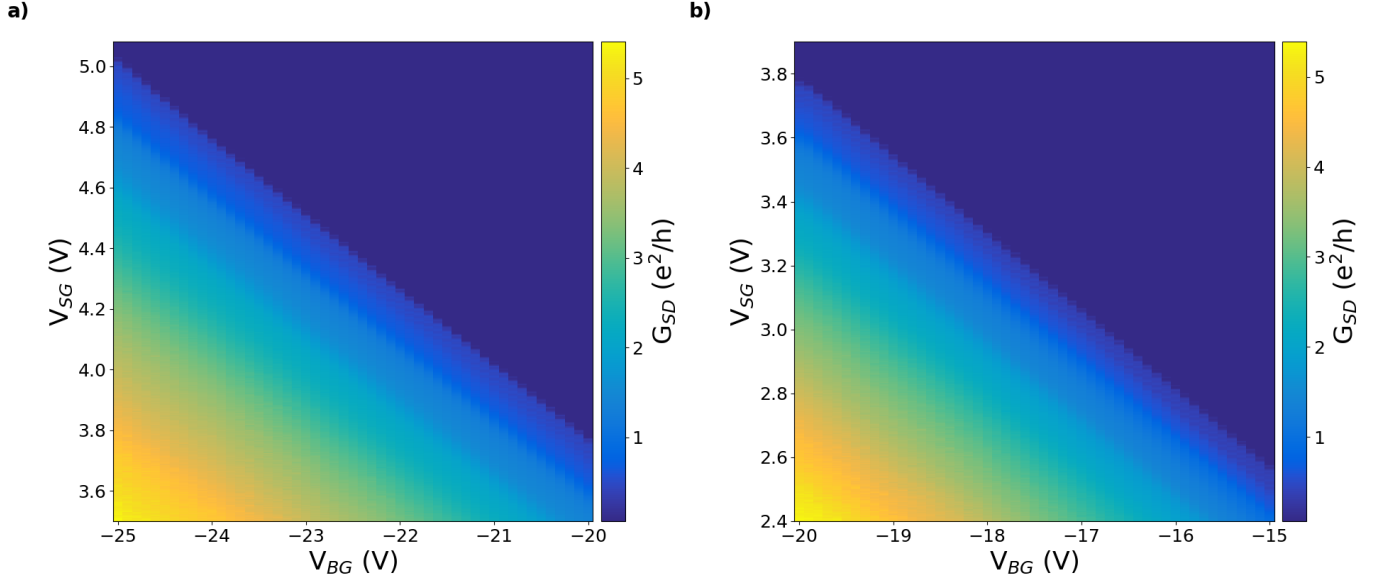


FIG. 5. Color map of conductance as a function of split gate voltage V_{SG} and back-gate voltage V_{BG} .

The device considered in the main manuscript was also studied in a 1K cryostat at 4 K. Similar results are observed where there are 3 robust plateaus each spaced by e^2/h for various carrier densities as seen in Supplementary Figure 5.

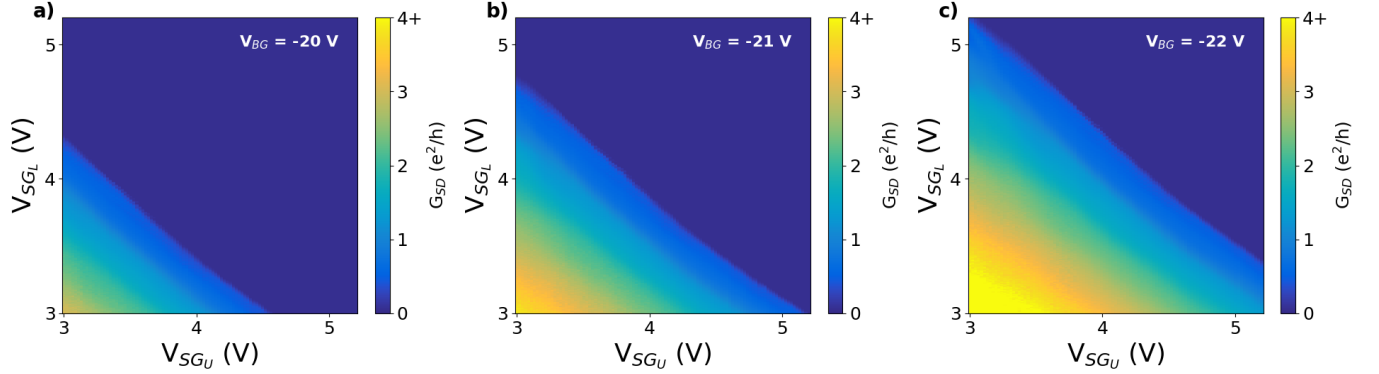


FIG. 6. Conductance as a function of individual split gates V_{SG_L} and V_{SG_U} taken at (a) $V_{BG} = -20$ V, (b) $V_{BG} = -21$ V, and (c) $V_{BG} = -22$ V

To ensure that the conductance plateaus are related to the gate-defined channel and not some resonances under the split gates, we measured the conductance as a function of each individual split gate (Supplementary Figure 6). V_{SG_L}/V_{SG_U} refer to the lower/upper split gates in the inset of Figure 1b in the main text. These plots were taken at 3 different carrier concentrations (back-gate voltages) and we observed robust plateaus that are equally influenced by both gates (a slope of approximately 45°) indicating that the origin of the plateaus is located in between the two gates, hence the channel.

SECTION 6: TRANSPORT IN THE LOW CARRIER DENSITY REGIME

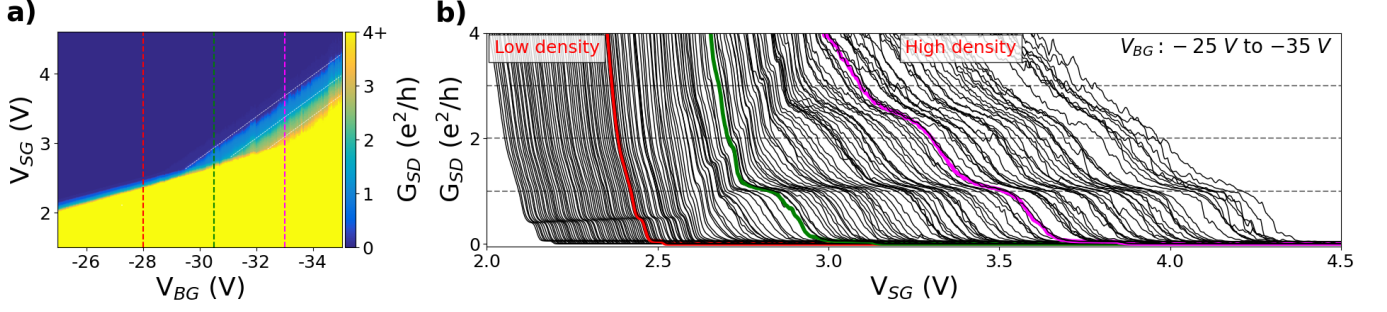


FIG. 7. (a) Color map of conductance as a function of split gate voltage V_{SG} and back-gate voltage V_{BG} as found in Figure 2c of the main manuscript. A lead resistance is subtracted. (b) Line cuts from (a) plotted in a “waterfall” style indicating a first step at e^2/h and a second step around $2e^2/h$ in the high density regime. An additional robust plateau is found at $0.5 e^2/h$ in the low density regime. The left most trace is taken at $V_{BG} = -25$ V and the right most trace is taken at $V_{BG} = -35$ V. The red, green and magenta lines are highlighted by similarly colored dashed lines in (a) and correspond to back-gate voltages of -28 V, -30.5 V, and -33 V respectively. These three curves feature the regimes where we observe the $0.5 e^2/h$ plateau (red), the $1 e^2/h$ plateau (green), and the $1 e^2/h$ and $2 e^2/h$ plateaus (magenta)

Transport through the 1D channel was studied at various back-gate voltages (-25 V to -35 V) which led to the observation of two distinct regimes as demonstrated in Supplementary Figure 7a. At higher hole concentrations ($V_{BG} < -30$ V) we observed conductance plateaus at $1 e^2/h$ and $2 e^2/h$ as discussed in the main manuscript. Furthermore, Supplementary Figure 7b reveals that there is a robust plateau located at $0.5 e^2/h$ found at lower carrier densities corresponding to a back-gate raised above -30 V. This plateau is unexpected and demonstrates that further research needs to be conducted on monolayer TMDs to fully understand their electronic properties.

SECTION 7: TIGHT-BINDING PARAMETERS

In the tight-binding atomistic calculations we chose the following structural parameters: $d_{\parallel} = 1.9188$ Å (W-Se₂ dimer center distance), $d_{\perp} = 1.6792$ Å (Se atom distance from $z = 0$ plane). The tight-binding Slater-Koster parameters are given by (all in eV): $E_d = -0.4330$, $E_{p0} = -3.8219$, $E_{p\pm 1} = -2.3760$, $V_{dp\sigma} = -1.58193$, $V_{dp\pi} = 1.17505$, $V_{dd\sigma} = -0.90501$, $V_{dd\pi} = 1.0823$, $V_{dd\delta} = -0.1056$, $V_{pp\sigma} = 0.52091$, $V_{pp\pi} = -0.16775$, together with characterising intrinsic spin-orbit couplings: $\lambda_W = 0.275$, $\lambda_{Se_2} = 0.08$. We note that these parameters are chosen to reproduce ab initio electronic band structure of two spinfull valence bands.

-
- [1] H.-J. Chuang, X. Tan, N. J. Ghimire, M. M. Perera, B. Chamlagain, M. M.-C. Cheng, J. Yan, D. Mandrus, D. Tománek, and Z. Zhou, *Nano Letters* **14**, 3594 (2014).
 - [2] H. C. P. Movva, A. Rai, S. Kang, K. Kim, B. Fallahazad, T. Taniguchi, K. Watanabe, E. Tutuc, and S. K. Banerjee, *ACS Nano*, *ACS Nano* **9**, 10402 (2015).
 - [3] Y. Jung, M. S. Choi, A. Nipane, A. Borah, B. Kim, A. Zangiabadi, T. Taniguchi, K. Watanabe, W. J. Yoo, J. Hone, and J. T. Teherani, *Nature Electronics* **2**, 187 (2019).
 - [4] K. Sakanashi, P. Krüger, K. Watanabe, T. Taniguchi, G.-H. Kim, D. K. Ferry, J. P. Bird, and N. Aoki, *Nano Lett.* **21**, 7534 (2021).
 - [5] K. Marinov, A. Avsar, K. Watanabe, T. Taniguchi, and A. Kis, *Nature Communications* **8**, 10.1038/s41467-017-02047-5 (2017).