One-dimensional states residing on edges and steps in few-layer WTe₂

Artem Kononov¹,*, Gulibusitan Abulizi¹, Kejian Qu², Jiaqiang Yan³,², David Mandrus²,³, Kenji Watanabe⁴, Takashi Taniguchi¹, and Christian Schnenberger¹,⁵,*

¹Department of Physics, University of Basel, Klingelbergstrasse 82, CH-4056 Basel, Switzerland
²Department of Materials Science and Engineering, University of Tennessee, Knoxville, TN 37996, United States
³Materials Science and Technology Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831, United States
⁴National Institute for Material Science, 1-1 Namiki, Tsukuba 305-0044, Japan
⁵Swiss Nanoscience Institute, University of Basel, Klingelbergstrasse 82, CH-4056 Basel, Switzerland

*Correspondence and requests for the materials should be addressed to A.K. (email: Artem.Kononov@unibas.ch) and C.S. (email: Christian.Schoenenberger@unibas.ch)

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Abstract

WTe₂ is a layered transitional metal dichalcogenide (TMD) with a number of intriguing topological properties. The bulk crystal is a Weyl semimetal with Fermi arc surface states and the monolayer is a two-dimensional (2D) topological insulator. Recently, WTe₂ has also been predicted to be a higher-order topological insulator (HOTI) with hinge states along the edges. The gapless nature of WTe₂ complicates the observation of one-dimensional (1D) topological states in transport due to their small contribution relative to the bulk. Here, the Josephson effect can help to detect the edge transport, since the evolution of the critical current in magnetic field is sensitive to the spatial current distribution. Here, we employ superconducting contacts in WTe₂ that emerge when Pd is placed in contact with the TMD to define Josephson junctions. Using the Josephson effect, we demonstrate the presence of 1D current carrying states residing on the edges and steps of few-layer WTe₂ crystals. The width of the 1D current-carrying states is deduced to be below 80 nm. A supercurrent $I_c$ is measured over distances up to 3 µm and persisting in magnetic fields up to $B = 2$ T. This observation is in good agreement with the recent prediction of HOTI states in WTe₂. Moreover, the observed dependencies of $I_c(B)$ on magnetic field demonstrate a particular symmetry with the direction of the current and the magnetic field, which matches the prediction for topological states in systems with broken inversion symmetry. Our observation adds another effect to a plethora of intriguing properties of WTe₂ and potentially provides a new platform for obtaining Majorana zero modes.
Introduction

Materials with non-trivial topology attract a lot of attention due to their intriguing properties and potential to harness them for quantum computing. Non-abelian excitations, occurring when topology meets superconductivity, are especially interesting for applications [1]. Many realizations of these excitations have been proposed and implemented recently, including designing topological superconductivity by combining spin-orbit interaction and Zeeman effect with normal s-wave superconductors [2], or by proximity inducing superconductivity in topological insulators [3]. Recently, it has also been demonstrated that one can engineer them in hinge states of a higher-order topological insulator (HOTI) combined with proximity induced superconductivity [4]. The layered TMD WTe$_2$, which in the form of a 3D crystal is a Weyl semimetal [7, 8] and a 2D topological insulator in the form of a monolayer [5, 6], has been predicted to be a HOTI [9], hosting topological hinge states on the edges and steps of the crystal. However, the bulk conductivity of WTe$_2$ complicates the observation of these states. One way to overcome bulk conductivity is to use local measurement techniques such as scanning tunneling spectroscopy. Another possibility is to employ the Josephson effect [10, 11, 12]. Here, the evolution of the critical current $I_c(B_\perp)$ with perpendicular magnetic field $B_\perp$ is connected with the current distribution in the plane by a Fourier transform [13]. It has been recently predicted that topological states in systems with broken inversion symmetry show a distinctive lack of symmetry in the critical current $|I_c^+(B_\perp)| \neq |I_c^-(B_\perp)|$, where the two signs denote the two different current directions [14]. This effect is known as the asymmetric Josephson effect. It has previously been observed in a 2D topological insulator coupled to a superconductor [15]. Hence, the observation of the asymmetric Josephson effect may provide additional evidence of a topological origin.

Here, we reveal 1D states along edges and steps in few-layer WTe$_2$ by studying the Josephson effect in a perpendicular magnetic field. The superconducting contacts required for Josephson junctions are realized by a lithographically patterned Pd film that is in contact with clean WTe$_2$ and induces superconductivity therein. This allows in principle to define junctions of arbitrary shape. We found that a Josephson current can be measured over distances up to 3 $\mu$m and it withstands magnetic fields up to 2 T, suggesting its 1D nature with a very tight lateral confinement. Moreover, transport through these 1D states shows signatures of the asymmetric Josephson effect.

Superconductivity induced in WTe$_2$ by normal leads

A few-layer WTe$_2$ device covered with hBN and shaped in a Hall bar geometry has been fabricated by placing a stripe-shaped WTe$_2$ flake on prepatterned Pd leads, as demonstrated in Fig. 1(a). We measured the longitudinal resistance $R_{xx}$ of the WTe$_2$ flake in a four-probe setup. At 4 K the device demonstrates a non-saturating magnetoresistance in perpendicular magnetic field $B_\perp$ up to 8 T, which is a signature of a high quality WTe$_2$ crystal [16] (see Fig. S1 in the supplementary). However, upon cooling down to below 1.1 K the behavior of $R_{xx}$ changes drastically (Fig. 1(b)): at low magnetic fields the resistance is zero, then there is a rapid transition where $R_{xx}$ increases to an intermediate state with approximately half of the 4 K resistance value. At even higher magnetic fields, a second rapid increase occurs
where the normal state resistance of the device is restored. Besides, both increases of the resistance are moving towards zero field when the temperature is increased. The zero $R_{xx}$ state disappears completely above 600 mK and the intermediate resistance disappears above 1.1 K. A similar behavior is obtained at zero magnetic field as a function of current: $R_{xx}$ first switches to the intermediate state, followed by a switch to the normal-state resistance. This behavior is typical for Josephson junctions, where the change of the resistance from zero to a finite value corresponds to the disappearance of the Josephson current and the second increase of the resistance reflects the transition to the normal state of the superconducting leads.

The observation of superconductivity in our samples is an interesting phenomenon on its own and it requires a separate study [17]. Our WTe$_2$ crystals are not intrinsically superconducting. In the samples described below we observe superconductivity only with shorter junctions. For a superconductor no dependence on the contacts separation is expected. We can also exclude the possibility that the Pd leads are superconducting and induce the superconductivity in WTe$_2$ by the proximity effect. In this case, the interface resistance between Pd and WTe$_2$ is expected to be zero, but in our samples this resistance is measured to be $\sim 500 \, \Omega$.

There are several possibilities, why superconductivity is induced in the layered stack. One can imagine that Te and Pd inter-diffuse when Pd is in contact with WTe$_2$, leading to the formation of superconducting PdTe [18] or PdTe$_2$ [19] at the interface between WTe$_2$ and Pd. If this is the case, the inter-diffusion should take place at quite low temperatures, since we do not heat our samples above 180 $^\circ$C. The formation of superconductivity in WTe$_2$ in contact with Pd is another plausible explanation, since WTe$_2$ is prone to becoming superconducting. It is a superconductor under pressure [20, 21] or at moderate electron doping [22] and a monolayer can be tuned into a superconducting state by electrostatic gating [23, 24]. Hence, a moderate increase in the electron concentration can lead to superconductivity in WTe$_2$. Such an increase can occur at the contact of two materials due to charge transfer [25] or due to flat-band formation in WTe$_2$, as has recently been reported in another Weyl semimetal Cd$_3$As$_2$ [26]. Our experimental curves in Fig. 1(b) support the situation depicted in Fig. 1(c): superconductivity is locally induced in WTe$_2$ above the Pd leads. The superconducting regions themselves are connected by a Josephson current that flows in WTe$_2$.

After having established the presence of the Josephson effect, we can use it to obtain information about the current distribution in our WTe$_2$ devices. The evolution of the critical current as a function of the flux through the Josephson Junction (JJ) strongly depends on the spatial supercurrent distribution. When the supercurrent is uniformly distributed through the JJ, the critical current $I_c(B_\perp)$ as a function of perpendicular magnetic field $B_\perp$ shows oscillations with a rapidly decaying amplitude (top in Fig. 1(d)). Measured from minimum to minimum, the central lobe has twice the width of the other lobes. This dependence of $I_c(B_\perp)$ is known as the Fraunhofer pattern and it is analogous to the intensity distribution caused by the diffraction of monochromatic light through a single slit. If, on the other hand, the supercurrent flows only along the sample edges, as indicated in Fig. 1(d), $I_c(B_\perp)$ displays slowly decaying oscillations. This situation is similar to the two-slit interference pattern in optics and is typical for SQUIDs. The period of oscillations corresponds a single flux quantum $\Phi_0 = h/2e$ through the area enclosed by the SQUID.

Fig. 1(e) displays the critical current of the device shown in Fig. 1(a). The critical current
Figure 1: Superconductivity and Josephson effect in a few-layer WTe$_2$ device in a Hall bar geometry. (a) Optical image of the device (scale bar 10 µm) with a sketch of the four-terminal measurement setup. (b) The longitudinal differential resistance $R_{xx}$ of the device as a function of perpendicular magnetic field $B_\perp$ (left) and current $I$ (right) at different temperatures. $R_{xx}$ assumes a zero value below a certain temperature, magnetic field or current value. This is a clear sign of superconductivity in the sample. (c) Schematic side view of the sample illustrating its state: above the Pd leads WTe$_2$ is superconducting and the current between these regions is mediated by the Josephson effect. (d) Illustration showing the expected dependence of the critical current of a 2D Josephson junction on $B_\perp$ for two different supercurrent distributions: for a uniform current distribution, $I_c(B_\perp)$ shows rapidly decaying oscillations (Fraunhofer behaviour), whereas for two narrow edge states, the $I_c(B_\perp)$ oscillations do not (or only weakly) decay in amplitude (SQUID behavior). (e) The critical current $I_c$ as a function of perpendicular magnetic field $B_\perp$ measured at 60 mK. $I_c$ is extracted from the position where the two-terminal differential resistance $R(I)$ as a function of bias current shows a sharp increase, associated with the transition to the intermediate state. The inset shows the oscillation of the critical current in more details. The period of oscillations is 0.2 mT.
is determined by the current value where the two-terminal resistance $R$ jumps from the zero-state to the intermediate-state value discussed before and shown in Fig. 1(b). The $I_c(B_{\perp})$ dependence is seen to be a convolution of a SQUID-like behavior with many rapid oscillations and a Fraunhofer pattern with a much lower frequency. The period of the fast oscillation $\Delta B \sim 0.2$ mT roughly corresponds to a single flux quantum $\Phi_0$ through the area $S$ of the sample ($S \sim 12 \mu m^2$), indicating that the supercurrent flows along the edges of the WTe$_2$ flake. The Fraunhofer shape of the envelope of oscillations reflects the finite width of states hosting the supercurrent. Although $I_c(B_{\perp})$ strongly suggests the presence of supercurrent carried by edge modes, one cannot exclude a non-uniform current distribution caused by the contact geometry in this device. The voltage probes in the employed Hall bar geometry are in contact with the WTe$_2$ flake only $\sim 0.5 \mu m$ from the edges. So they can locally enhance superconducting correlations near the edges, giving rise to the edge supercurrent. We will address this issue with the devices described below.

**Spatial distribution of supercurrent**

The second device, device 2, in Fig. 2(a) allows to investigate the intrinsic spatial distribution of the supercurrent, since here all the Pd leads have a constant width of 1 $\mu m$ and are placed uniformly across the WTe$_2$ flake. Several junctions with different lengths along the flake are defined by the leads. Here, we present the measurements of two 1 $\mu m$ and one 2 $\mu m$ long junctions. The measurements were performed in a four-probe method as indicated schematically in Fig. 2(a). The current was supplied through leads outside of the studied junctions. Fig. 2(b) shows the obtained differential resistance $dV/dI$ as a function of the current $I$ at zero magnetic field and a temperature of 50 mK. For both 1 $\mu m$ long junctions $dV/dI$ goes to zero at small currents, indicating Josephson coupling. For the 2 $\mu m$ long junction, $dV/dI$ does not go to zero, but has a small dip at $I = 0$, which is a result of the proximity effect. The absence of a zero resistance state for longer junctions additionally confirms our conclusion that superconductivity is induced locally by the leads and is not intrinsically present in WTe$_2$.

Fig. 2(c) shows the measured $I_c(B_{\perp})$ dependence for the two 1 $\mu m$ long JJs. The critical current oscillates with the perpendicular magnetic field. The central peak of $I_c$ has a width bigger than a single period of oscillation, but smaller than two periods. The amplitude of these oscillations is decaying faster at smaller fields and slower at larger ones. The measured $I_c(B_{\perp})$ is a combination of a Fraunhofer pattern creating a peak of critical current at zero magnetic field and a SQUID-like pattern with more than 50 visible oscillations. The period of these oscillations is $\Delta B \sim 0.27$ mT, which corresponds to an effective junction length $L_{\text{eff}} = L + 2\lambda_L$ of $\Phi_0 / \Delta B \cdot W \sim 1.75 \mu m$. Here, $W \sim 4.3 \mu m$ is the sample width and $\lambda_L$ is the London penetration depth. Adding the flux that penetrates the contacts is also known as “flux focusing”. It accounts for the penetration of magnetic field into the superconducting region. It is also seen that the minima of the oscillation pattern are not reaching zero. Such a behavior is consistent with a situation where the current distribution is not symmetric over the width of the junction [13], but it can also emerge from a non-sinusoidal current-phase relation [27].

To obtain a more quantitative measure of the supercurrent distribution, we performed a
Figure 2: Spatial distribution of supercurrent. (a) Optical image of device 2 (scale bar 10 µm) with a sketch of the measurement setup. (b) Four-terminal differential resistance \( dV/dI \) of three junctions 1-3 with lengths 1, 1 and 2 µm, respectively. The 1 µm long junctions demonstrate zero differential resistance at small currents as a result of the Josephson effect. (c) Critical current \( I_c(B_{\perp}) \) of junctions 1 and 2 as a function of \( B_{\perp} \). A combination of a SQUID- and Fraunhofer-like behavior is observed, indicating a significant amount of edge supercurrent. (d) Supercurrent density distribution of junction 2 extracted from \( I_c(B_{\perp}) \). Two distinctive edge states, each having a width of \( \sim 75 \) nm, are observed.

Fourier transform of \( I_c(B_{\perp}) \) by following the Dynes-Fulton approach [13]. With the rise of 2D topological insulators, this approach has become a standard method to confirm the presence of supercurrent carrying edge states. This method is based on a sinusoidal current-phase relation, and one of its underlying assumption is a nearly symmetric supercurrent distribution across the width of a junction. For a symmetric current distribution the minima of \( I_c(B) \) should approach zero. However, this is not quite correct in our case, as we have pointed out before. The result of the Fourier transform should therefore be more accurate for junction 2, since the \( I_c(B) \) minima are found to be much closer to zero. Fig. 2(d) shows the result of
such a transformation for junction 2. As expected from the qualitative analysis above, there is supercurrent flowing through the whole width of the junction, but there are also two sharp peaks of supercurrent density at the edges of the sample. The two supercurrent peaks are very narrow, suggesting a strong edge localization. The full width at half maximum of these supercurrent density peaks obtained from the Gaussian fit is below 80 nm. The presence of sharp peaks of supercurrent on the edges of few-layer WTe$_2$ is consistent with the recent prediction of bulk WTe$_2$ being a HOTI with hinge states residing on the edges [9].

1D states on the steps of few-layer WTe$_2$

We have found before that the supercurrent in few-layer WTe$_2$ is of 1D nature, flowing predominately along the edges. With the third sample we demonstrate that 1D conducting states are present not only on the physical edges of WTe$_2$ flakes, but can also reside at step edges of WTe$_2$. This observation is consistent with the reported hinge states in bismuth [11] and with the results of scanning tunneling spectroscopy of WTe$_2$ [28]. Device 3, shown in Fig. 3(a), is as before a hBN-covered few-layer WTe$_2$ flake placed on top of Pd leads. In comparison to the previous devices, there are two major differences in the design. In the first place, the flake has steps along the junctions. The central part of the flake is 5 layers thick, while the outer parts are bilayers. We do not expect any contribution in transport from a bilayer, since in previous studies it has been shown to be an insulator without edge conductivity [5, 29]. In the second place, each Pd lead is split into two by a 100 nm gap. This provides an opportunity to measure the resistance in a four-probe manner using only contacts on a studied junction, as shown by the top schematic in Fig. 3(b). This is different from the measurements employed in device 2, as depicted in the bottom schematic. We made sure that such measurements are correct through the direct comparison of $dV/dI(I)$ and $I_c(B_{\perp})$ obtained for JJs, where both types of measurements are available. However, the presence of gaps in the Pd leads can complicate the interpretation of $I_c(B_{\perp})$, since these gaps may form additional JJs as will be discussed below in more details.

Fig. 3(c) demonstrates the $dV/dI(I)$ traces for different junctions normalized by the length of the junction. The differential resistance goes to zero for 1, 2 and 3 $\mu$m long junctions, indicating the presence of Josephson current. The normal state resistance per unit length is comparable for all junctions, yielding $\sim 100 \ \Omega \mu m^{-1}$. For this sample, the product $I_cR_N \sim 150 - 380 \ \mu V$ depending on the junction and the way $R_N$ is defined. This value is comparable to the result obtained by the Ambegaokar-Baratoff formula: $I_cR_N = \pi \Delta/2e \sim 270 \ \mu V$ [30]. Here, we estimate the energy gap by following the formula $\Delta(T = 0) = 1.76k_BT_c$ [31] with $T_c = 1.1 \ \text{K}$ defined as the maximal temperature where signs of superconductivity in the samples are still present. The ratio of the measured $I_cR_N$ relative to the predicted Ambegaokar-Baratoff value is often used as a figure of merit of a JJ. The agreement between them implies that there is a strong proximity effect and the JJs are in a regime which is close to the short ballistic limit.

The Josephson current for all junctions survives magnetic fields above 1 T, see Fig. 3(d). This is inconsistent with a uniform supercurrent, since even for the shortest junction it corresponds to $BS/\Phi_0 \sim 2000$ flux quantum through the JJ area, which means that the supercurrent is carried by extremely narrow states. At a closer look, oscillations of $I_c(B_{\perp})$
Figure 3: **Supercurrent along the steps in thin WTe$_2$.** (a) Optical image of device 3 (scale bar 10 µm). Each Pd lead has a 100 nm gap in the middle, which is located below the thicker part of the WTe$_2$ flake. (b) Schematics of the two measurement setups that were employed. Top: the current is passed through two neighboring leads, while the voltage is measured across the two leads that reside on the opposite side and are separated by a small gap. Bottom: the current is injected through two leads outside the studied junction, one on the left and the other on the right side, while the voltage is measured across the studied junction. Similar results are obtained with both setups. (c) Four-terminal $dV/dI$ of junctions with different lengths divided by the length of corresponding junctions in µm. The Josephson effect is present in junctions that are up to 3 µm long. (d) Critical current $I_c(B_\perp)$ of junctions as a function of perpendicular magnetic field $B_\perp$. (Note: $I_c$ is here multiplied by the length of corresponding junctions in µm). The arrows highlight the periodic low-frequency modulation of $I_c$ for the 2 µm long junction. Inset: $I_c(B_\perp)$ for the 2 µm long junction zoomed in to small magnetic fields. A fast periodic oscillation with an amplitude of $\sim 1\%$ is clearly discerned.
are visible for the 2 µm long junction, see the inset to Fig. 3(d). The oscillations are clearly of a SQUID character with a period $\Delta B \sim 0.33$ mT, corresponding to a junction area $S = \Phi_0/\Delta B \sim 6.1$ µm$^2$. This area is smaller than the area 9 µm$^2$ of the 5-layer thick WTe$_2$ part in the junction. However, it is comparable with the area of the neighboring 1 µm long JJ taking into account the flux focusing: $L_{eff} = (L + 2\lambda_L) = S/W = 1.4$ µm. It is possible that the 100 nm wide slits in the Pd leads act as additional JJs. Together with the JJs formed by the edge states, a network of JJs is formed, as schematically shown in Fig. 4(a). In this case, the distribution of supercurrent across the whole network defines $I_c(B_\perp)$ for each pair of Pd leads. The formation of a network of JJs can complicate the observation and the interpretation of $I_c(B)$ oscillations, but does not affect the conclusion that 1D supercurrent carrying states are present at the steps of our flake. In this picture, a small amplitude of SQUID-like oscillations, as we observe here, would mean that the slit JJs are relatively weak compared to the JJs defined by the 1D transport channels. Although the slit junctions are shorter, their critical current must be small, suggesting that bulk states in WTe$_2$ have a much smaller mobility than the 1D states.

![Figure 4: Supercurrent in sample 1. (a) Electrical circuit that resembles the main current distribution in device 3. Only junctions neighboring to the studied junction are shown. There are two different kinds of JJs: edge states between SC regions above the Pd leads form JJs (red), but also the short slits in the Pd leads define JJs (blue). When a current is passed between a pair of Pd leads, the supercurrent is redistributed across the network of JJs. (b) Sketch of a cross section of the sample near the step from 5L to 2L, illustrating the possibility that multiple 1D channels along the step appear.](image-url)

The measurement of $I_c(B_\perp)$ of the 2 µm long junction shows additional oscillations with a larger period of $\delta B \sim 0.3$ T (red arrows in Fig. 3(d)). The period of these oscillations is too big to link them to the slits in the Pd leads which act as Josephson junctions. The area corresponding to these oscillations $S = \Phi_0/\delta B \sim 7 \cdot 10^{-3}$ µm$^2$ is much smaller than the slit area $S_{sl} \sim 100$ nm $\times$ 1 µm $\sim 10^{-1}$ µm$^2$. The nature of these oscillations is not clear yet, but there are two plausible explanations within the framework of 1D states residing on the steps of WTe$_2$ flakes.

First, slow oscillations can emerge from a slight difference in wavevectors of electrons and
holes that are forming the Andreev pairs. This mechanism has been previously observed for
topological hinge states in bismuth [32]. The observed period of oscillations is in good
agreement with the expected value \( \delta B \sim 2\pi \hbar v_F / g_{\text{eff}} \mu_B L \sim 0.15 - 0.7 \) T, where \( L = 2 \) µm is
the length of the junction, \( v_F \sim 2 \cdot 10^5 \) m s\(^{-1}\) [33] the Fermi velocity and \( g_{\text{eff}} \sim 10 - 50 \) [34]
the Landé \( g \)-factor. Second, a slower oscillation can result from a beating pattern between
two fast oscillations with similar frequencies. Such a situation can occur if there are several
1D states residing on the WTe\(_2\) step from 5 to 2 layers, as indicated in Fig. 4(b). The
distance between these states \( w \) can be estimated from the ratio of periods of the slow
\( \delta B \sim 0.3 \) T and fast oscillations \( \Delta B \sim 0.33 \) mT and the width of the junction \( W \sim 4.5 \) µm:
\( w \sim W \delta B / \Delta B \sim 5 \) nm. The very small difference of only 5 nm suggests that these 1D
states may be localized at the edges of different layers as indicated in Fig. 4(b).

**Symmetry of the supercurrent**

![Figure 5: Symmetry of the critical current.](image)

(a) Absolute value of critical currents for device 2 as a function of perpendicular magnetic field for positive and negative currents. \( I_c(B) \) lacks a symmetry to the change of current direction. (b) Same data as in (a) but with a reversed magnetic field for negative currents. Symmetry is preserved when both current and magnetic field are reversed. (c) Critical currents for device 1 as a function of perpendicular magnetic field for positive and negative currents also demonstrating \( |I^+(B)| \neq |I^-(B)| \).

For a conventional Josephson junction with a sinusoidal current-phase relation (CPR) \( j(\phi, x) = j_c(x) \cdot \sin(\phi) \) certain symmetries in the dependence of \( I_c(B) \) as a function of perpendicular magnetic field \( B \) are expected. First, the magnitude of the critical current at a fixed field is the same for opposite current directions: \( |I_c^+(B)| = |I_c^-(B)| \), where \( I_c^+(B) = \max_\phi I(B, \phi) \) and \( I_c^-(B) = \min_\phi I(B, \phi) \). Second, the critical current is an even function of perpendicular magnetic field: \( I_c(-B) = I_c(B) \). Furthermore, these symmetries are holding for a JJ with any odd CPR, if the distribution of the supercurrent \( j_c(x) \) is symmetric over the width of the junction. There is a more general constrain that only relies on the time-reversal symmetry: \( I_c^\pm(B) = -I_c^\mp(-B) \). Breaking of these symmetries has been recently connected with the inversion symmetry breaking in topological systems [14].

As apparent from Fig. 2(c) and Fig. 5(a), \( I_c^\pm(B) \) is not symmetric, i.e. not an even function in \( B \), for sample 2. The observation of an asymmetry in \( I_c(B) \) is not uncommon and is usually connected to a flux trapping in the JJ [35]. In this case, the asymmetry is
merely a result of the magnetic flux through the junction not being reversed when the external magnetic field is reversed. In contrast, the symmetry in current inversion is preserved in this case. It may therefore appear more surprising when the symmetry relative to the change of the current direction is lost, as demonstrated in Fig. 5(a). The symmetry is restored when both current and magnetic field are reversed, see Fig. 5(b), excluding that vortex trapping matters here. This experimental observation is in agreement with the recent prediction of the asymmetric Josephson effect (AJE) in materials with broken inversion symmetry [14].

Device 1 also demonstrates \( |I_c^+(B)| \neq |I_c^-(B)| \), as shown in Fig. 5(c). In this case, we observe a seeming lack of the symmetry when both current and magnetic field are reversed. It results from an uncompensated residual field of the superconducting solenoid used to set the field. Hence, zero of magnetic field on the plot does not correspond to the absence of magnetic field. The non-symmetric behavior of this sample is also consistent with the predicted AJE [14]. However, we want to point out here that the \( I_c(B) \) dependence seen in Fig. 5(c) is also consistent with the picture of an asymmetric SQUID [36]. Here, the critical current in the weaker junction defines the amplitude of the oscillations \( I_w = (\max(I_c) - \min(I_c))/2 \), and the critical current of the stronger junction defines the average value \( I_s = (\max(I_c) + \min(I_c))/2 \). Thus, the SQUID asymmetry is given \( \alpha = I_s/I_w \sim 5 \) for device 1. In a highly asymmetric SQUID with \( \alpha \gg 1 \), the \( I_c(B_\perp) \) dependence is determined by the current-phase relation of the weak junction [36]. So if the CPR is skewed, i.e. non-sinusoidal, as expected for a transparent short ballistic junction, the \( I_c(B) \) of the SQUID will also be asymmetric [36]. This asymmetry has nothing to do with a topology and broken inversion symmetry, although it does look similar to the prediction of the AJE [14]. Moreover, a self-flux through the JJ, caused by the kinetic inductance of the junction \( L_K \), skews the SQUID - \( I_c(B) \) pattern in a similar manner [37]. \( L_K \) can be significant if the concentration of Cooper pairs is low and the current carrying states are narrow and long, as is the case here.

We want to emphasize that while the absence of AJE can be used as an argument against the presence of supercurrent carried by topological states in materials with broken inversion symmetry, the opposite is not correct. From a measured asymmetry of \( I_c(B_\perp) \) as a function of magnetic field \( B_\perp \) one cannot conclude that there are edge states of topological origin. The AJE can arise from edge states that carry different currents due to different lead couplings. It can also arise from the self-inductance and from the non-sinusoidal nature of the current-phase relation in ballistic systems.

**Conclusion**

During the preparation of this manuscript we became aware of two recent preprints [38, 39] with similar results, but with Josephson junctions in WTe\(_2\) obtained by proximity effect from superconducting Nb leads. The experimental results in these preprints are in good agreement with our results and our interpretation of the data. Compared to the reported data, our samples are in the thin limit and they additionally demonstrate a stronger Josephson coupling over longer distances and thereby provide strong evidence for Josephson coupling through highly localized narrow 1D states residing on the steps of WTe\(_2\).

In conclusion, we present an experimental study of Josephson transport in encapsulated few-layer WTe\(_2\) samples. Our data strongly suggest the presence of 1D states residing on the steps and edges of WTe\(_2\). The Josephson current in these 1D states is extremely robust that
they survive magnetic fields up to 2 T and extend over distances up to 3 µm. Moreover, the supercurrent demonstrates a particular asymmetry consistent with the asymmetric Josephson effect predicted to occur in topological materials with a broken inversion symmetry. Our findings fit well with the recent prediction of higher-order topological insulator states in WTe$_2$ [9] and demonstrate many features previously observed [10, 32] in another HOTI - bismuth.

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Authors contributions

A.K. fabricated the devices 2, 3, performed the measurements and analyzed the data. G.A. optimized the fabrication recipe, developed the thickness determination method by optical contrast and together with A.K. fabricated and measured device 1. K.Q., J.Y. and D.M. provided WTe$_2$ crystals. K.W. and T.T. provided hBN crystals. A.K prepared the manuscript. C.S. initiated and supervised the project and participated in all discussions. All authors contributed to the manuscript.

Methods

Fabrication

Contacts were patterned by the standard e-beam lithography on p-doped Si substrates with 295 nm thick SiO$_2$ layer on top. 3 nm of titanium and 12 nm of palladium were deposited in an e-beam evaporator system, followed by a lift-off in hot acetone. hBN flakes were mechanically exfoliated on similar substrates under ambient conditions and 10 – 30 nm thick flakes without visible steps and signs of residues were preselected. WTe$_2$ flakes were exfoliated from flux grown WTe$_2$ [40] in a N$_2$ filled glovebox with an oxygen level below 0.5 ppm. We optically identified thin (below 15 layers) elongated flakes that are oriented along the $a$-axis without visible steps, except for device 3. The thickness of WTe$_2$ flakes was
identified using the optical contrast method [41]. We picked up exfoliated hBN using the polymer dry transfer technique [42]. This was then used to pick up selected WTe$_2$ flakes and place the stack on the prepatterned leads. Thus, WTe$_2$ flakes were always protected from oxidation, initially by keeping the exfoliated flakes in the oxygen-free environment of the glovebox and later by the hBN cover.

**Measurements**

The low temperature measurements were done in a dilution refrigerator with a base temperature of 30 mK. The insert of the cryostat was fitted with low temperature line filters. Additional 10 nF $\pi$-filters were attached at room temperature. We determined the differential electrical resistance by current biasing the sample with both DC and AC components and measuring the voltage over the sample using an $SR - 830$ lock-in amplifier. The DC current is obtained from a voltage source connected to the device through a series resistor with a resistance value of 100 k$\Omega$. The AC component is added through a transformer. The voltage over the sample was amplified by a home-built low noise differential amplifier. We used AC frequencies ranging from 77 Hz to 277 Hz. All measurements were done in the linear response regime with an AC excitation current below 4 nA.

For device 3 with a high $I_c R_n$ product of $\sim 200 \mu$V we also employed statistical measurements of the switching current to obtain $I_c$. We bias the sample with a time-dependent current ramp for which the current increases at a constant rate. The time before the JJ switching from the superconducting to the normal state is measured with a counter which is stopped by a trigger signal obtained from the sharp increase of the voltage across the junction from 0 to $\sim I_c R_n$. This time is averaged over 200 current ramps and used as the value for the critical current $I_c$. In reality, the switching current is smaller than the "true" critical current $I_c$. To set current, we used a signal generator creating a saw-tooth signal at frequencies between 177 and 277 Hz connected through a 10 k$\Omega$ resistor in series with the sample. The voltage drop across the junction was amplified 1000 times before reaching the trigger input of the counter set to a threshold value of 15 mV.

**Data availability**

All data in this publication are available in numerical form in the Zenodo repository at https://doi.org/10.5281/zenodo.3526560.

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