Edge superconductivity in multilayer WTe$_2$ Josephson junction

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ABSTRACT

WTe$_2$, as a type-II Weyl semimetal, has 2D Fermi arcs on the (001) surface in the bulk and 1D helical edge states in its monolayer. These features have recently attracted wide attention in condensed matter physics. However, in the intermediate regime between the bulk and monolayer, the edge states have not been resolved owing to its closed band gap which makes the bulk states dominant. Here, we report the signatures of the edge superconductivity by superconducting quantum interference measurements in multilayer WTe$_2$ Josephson junctions and we directly map the localized supercurrent. In thick WTe$_2$ ($\sim 60$ nm), the supercurrent is uniformly distributed by bulk states with symmetric Josephson effect ($|I^+ (B)| = |I^- (B)|$). In thin WTe$_2$ (10 nm), however, the supercurrent becomes confined to the edge and its width reaches up to 1.4 $\mu$m and exhibits non-symmetric behavior $|I^+ (B)| \neq |I^- (B)|$. The ability to tune the edge domination by changing thickness and the edge superconductivity establishes WTe$_2$ as a promising topological system with exotic quantum phases and a rich physics.

Keywords: WTe$_2$, Josephson junction, Weyl semimetal, edge superconductivity, non-symmetric effect

INTRODUCTION

Layered WTe$_2$ was suggested as the first material candidate to be a type-II Weyl semimetal, where eight separated Weyl points exist in the bulk and topological Fermi arcs occur on the (001) crystal surfaces owing to the reflection symmetry [1]. An extra set of quantum oscillations arising from Weyl orbits were observed as evidence of Fermi arcs in transport [2]. Intriguingly, when the thickness is reduced to the monolayer, WTe$_2$ turns to be a quantum spin Hall insulator with edge states [3], which have been demonstrated in numerous experiments involving low-temperature transport [4,5], angle-resolved photoelectron spectroscopy [6], scanning tunneling microscopy [7,8], and microwave impedance microscopy [9]. Besides, it has also been predicted that WTe$_2$ has 1D hinge states as a higher-order topological insulator [10].

While the boundary modes of WTe$_2$ have been well studied in both the 3D and 2D limits [11,12], in multilayers these modes become rather complicated due to the intervening bulk and edge states and thus they remain largely unexplored. Unlike the monolayer WTe$_2$, the nearly-closed bandgap in multilayer WTe$_2$ results in a large density of bulk states. Therefore, it is difficult to distinguish the edge states through a gating approach. It is then necessary to make them distinct from the coexisting bulk ones. However, separating edge and bulk states in a single electrical conductance measurement may be ambiguous. In contrast, if the charge carriers condense together to form Cooper pairs, the difference can be amplified since the supercurrent properties are largely related to the coherence length [13]. A planar microscopic Josephson junction to realize superconducting TSM is feasible to elucidate the boundary states. For example, in Nb/Bi$_2$Te$_3$/Nb Josephson junctions the surface states enable the ballistic Josephson current rather than the diffusive bulk transport [14]. The supercurrent distribution in real space can be also quantitatively extracted from the superconducting quantum interference (SQI)...
measurements, where a perpendicular magnetic field induces oscillations in the amplitude of the superconducting current in Josephson junctions. This approach has been widely adopted to reveal the quantum spin Hall edge states in HgTe quantum well [15], topological surface states in TI [16] and quantum Hall edge states in graphene [17], but not yet in TSM.

Here, we report the observation of edge superconductivity in multilayer WTe₂ Josephson junctions. By varying the thickness of WTe₂ in SQI experiments, we have observed the Fraunhofer and the mixture of Fraunhofer and SQUID pattern in thick and thin WTe₂, respectively, which indicates the edge superconductivity in thin WTe₂. The non-uniform supercurrent exists in multilayer WTe₂ up to 16 nm, while the bulk supercurrent density amplitude \( I_c \) is about 1/3 of the edge in the thinnest sample. \( |I_c^- (B)| \neq |I_c^+ (B)| \) is also observed in thin WTe₂ due to the inversion symmetry breaking.

**WTe₂ JOSEPHSON JUNCTIONS**

We measure several Josephson junctions consisting of WTe₂ flakes of different thicknesses contacted by niobium (Nb) leads. The fabrication and characterization details are described in the Methods and SI Section I (Supplementary Figs 1 and 2). A scanning electron microscopy (SEM) image of the actual device and its measurement configuration are displayed in Fig. 1a (device #1, 10 nm-thick WTe₂). The length and width of the superconducting channel are \( L = 200 \text{ nm} \) and \( W = 13 \mu\text{m} \), respectively. Figure 1b shows the resistance-temperature \((R-T)\) curve of the junction with two transitions \( T_{c1} \) and \( T_{c2} \) at zero magnetic field. \( T_{c1} \sim 8 \text{ K} \) originates from the Nb superconducting transition, while the resistance continues to drop to \( 10^{-3} \) times of the normal resistance below \( T_{c2} \sim 0.72 \text{ K} \) which comes from the proximity Josephson coupling. The Josephson effect is highly reproducible across different devices, as shown in Supplementary Fig. 3. Figure 1c and its inset display the \( I-V \) characteristics and the differential resistance \( (dV/dI) \) of the junction at 45 mK, respectively. From the slope of the \( I-V \) curve in the high bias region \( (I > 10 \mu\text{A}) \) where the curve is linear, the normal-state resistance \( R_N \sim 1.7 \Omega \) is extracted. For \( |I| < 4.1 \mu\text{A} \), the voltage and \( dV/dI \) across the junction remain nearly zero, indicating a robust Josephson effect. Ten WTe₂ Josephson junctions with various \( L \) and \( W \) are studied (see Table S1 for their junction parameters), all exhibiting a finite supercurrent at low temperatures with reproducible behavior. The junction is in the long junction limit [18] (see SI Section IV and Supplementary Fig. 4 for details). Therefore it follows the \( 1/L \) dependence found from the \( I, R_N \) plot versus \( L \) in Fig. 1d. In this long junction regime, the critical current is given [18,19] by \( I_c \sim \frac{E_{Th}}{R_N} \), being determined by the Thouless energy \( E_{Th} \), which can be estimated [20] to be \( \sim \hbar v_F/L \), yielding \( I_c R_N \propto 1/L \).

**THE SUPERCONDUCTING QUANTUM INTERFERENCE MEASUREMENTS**

Having established the Josephson effect in our Nb/WTe₂/Nb junctions, we then focus on the supercurrent of WTe₂. In our experiments, the spatial distribution of the supercurrent is analyzed by applying a perpendicular magnetic field \( B \) during the SQI measurements with different thicknesses of WTe₂. The particular shape of the critical current interference pattern depends on the phase-sensitive summation of the supercurrents traversing the junction. In the case of a symmetric supercurrent distribution, this integral takes the simple form [21]:

\[
I_c^{\text{max}} (B) = \left| \int_{-\infty}^{\infty} J_c (x) \cos \left( \frac{2\pi L_{\text{eff}} B x}{\Phi_0} \right) \text{d}x \right|,
\]

where \( L_{\text{eff}} \) is the effective length of the junction along the direction of the current, accounting for the magnetic flux threading [22] through parts of the superconducting contacts over the London penetration depths. \( \Phi_0 = \hbar/2e \) corresponds to the magnetic flux quantum.

In thick WTe₂, the bulk states dominate and along the \( y \)-axis the supercurrent density has an approximately uniform distribution as shown in Fig. 2a. Thus, the uniform current density yields the single-slit Fraunhofer pattern described by [21]

\[
I_c (B) = I_{c0} \left| \sin \left( \frac{\pi L_{\text{eff}} BW}{\Phi_0} \right) / \left( \frac{\pi L_{\text{eff}} BW}{\Phi_0} \right) \right|.
\]

We have measured device #8 with 60 nm-thick WTe₂ as shown in Fig. 2b. The critical current envelope has an oscillation characteristic. We obtain a period of \( \sim 0.33 \text{ mT} \), which yields the effective length of \( L_{\text{eff}} = \Phi_0/\delta B_{\text{thr}} W \sim 1.0 \mu\text{m} \). This effective length is larger than the distance between the two Nb electrodes \( (L = 240 \mu\text{m}) \), caused by the London penetration depth and the flux focusing due to the Meissner effect [23,24]. The critical current envelope strongly resembles a single-slit pattern with \( 2\Phi_0 \) central lobe width. The corresponding supercurrent distribution is obtained by transforming the single-slit pattern to the real-space current density,

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*References and further details are provided in the original source.*
Figure 1. Josephson effect in thin WTe$_2$. (a) Top: Junctions schematic. Bottom: False-colour SEM image of the device with the measurement configuration. 120 nm-thick Nb is deposited on the top of WTe$_2$ (device #1). A four-terminal measurement across the interface was performed. The in-plane crystal axis of the WTe$_2$ flake is unknown. (b) Temperature dependence of WTe$_2$ Josephson junction resistance. Two transitions are identified: $T_c^1 = 8$ K is from the superconducting Nb, $T_c^2 \sim 0.72$ K is from the proximity Josephson coupling of WTe$_2$. Inset shows that the junction has a length of $L = 200$ nm. (c) $I$-$V$ characteristics for Josephson junction in the superconducting states with a critical current of $I_c \sim 4.1 \mu$A under zero magnetic field at 45 mK. Inset: $dV/dI$ characteristics indicate zero resistance below the critical current, the same as the $I$-$V$ curve. (d) Effect of the junction length on supercurrent for eight devices. The product $I_c R_N$ follows a general trend of $I_c R_N \propto 1/L$.

$J_z(x)$, as shown in Fig. 2c. This suggests a nearly uniform supercurrent density throughout the $y$ direction. The full details of the extraction procedure can be found in the SI section V and Supplementary Fig. 5. Furthermore, the critical currents overlap each other at different current directions as shown in Fig. 2d which indicates a symmetric Josephson effect with $|I^+_c(B)| = |I^-_c(B)|$, where + and − denote the sweep direction of the bias current and $+B$ and $-B$ are the magnetic field directions.

When the WTe$_2$ is thinned down to a few layers, the low bulk density of states coexists with the possible high density at edges as shown in Fig. 2e. The magnetic-field-dependent critical current envelope in a 13 nm-thick WTe$_2$ device (device #2) demonstrates the periodic SQI with a $1.6 \Phi_0$ central lobe width (Fig. 2f). $I_c$ decays slowly which is distinct from the Fraunhofer pattern in Fig. 2b. We use an edge-stepped nonuniform supercurrent model to directly simulate the $I_c$-$B$ relation as shown by the black line in Fig. 2f (see the model details in SI Section VI and Supplementary Fig. 6). The good fit of both the magnitude and periodicity of $I_c$ indicates the nonuniform supercurrent in
Fourier transform of the data in (b). The supercurrent density is uniform along the $y$-interference characteristics with a uniform supercurrent density. (c) The supercurrent distribution along the $y$-axis, which is calculated by the inverse Fourier transform of the data in (b). The supercurrent density is uniform along the $y$-axis, consistent with trivial bulk charge transport. (d) Critical current $I_c$ as a function of $B$ for the two sweep directions (positive as the blue line, negative as the red line). Two curves overlap with each other. (e) A schematic picture of a lateral Josephson junction with the out-of-plane magnetic field. (f) The critical current $I_c$ as a function of $B$ for the two sweep directions (positive as the blue line, negative as the red line), indicating non-symmetric behavior $I_{c+}(B) \neq I_{c-}(B)$.

To further distinguish the superconducting proximity Josephson coupling of edge/bulk, we experiment with a 16 nm-thick WTe$_2$ device (#3) to distinguish the bulk and edge contributions. Two Josephson channels are fabricated as the edge-crossing ($R_1$) and edge-untouched ($R_2$) as shown in Fig. 3a. For $R_2$, the junction is easier to be conducted by the bulk because the electrodes are closer in the central region ($L_{cb} \sim 0.4$ $\mu$m) while far at the edge. The distance on the edge side is $L_{ce} \sim 4$ $\mu$m that makes it hard to realize the Josephson effect through the edge region. Since the thickness is uniform in this sample, as indicated by the atomic force microscopy (AFM) measurement (Supplementary Fig. 2c and d), we can reasonably assume that the resistance by bulk states is isotropic and inversely proportional to the width. Figure 3b shows the $R$-$T$ curve at low temperatures. Only edge-crossing $R_1$ can reach zero to exhibit Josephson effect while $R_2$ only decreases a little. The differential resistance versus the current measurement in Fig. 3c confirms this property. Since the lengths of two junctions differ slightly, the...
coherence length of $R_1$ should be larger than that of $R_2$ to realize the Josephson effect. A similar mixture of Fraunhofer and SQUID pattern with edge-dominated supercurrent is also observed, as shown in Supplementary Fig. 7b, which is consistent with the other two thin devices (#1 and #2). On the contrary, $R_2$ does not exhibit any asymmetry and only the central lobe is observed (see Supplementary Fig. 8 for details). The width $W_2$ for $R_2$ is estimated to be 1.9 μm, which corresponds well to the actual junction width 1.7 μm as shown in Fig. 3a. The in-complete superconductivity of $R_2$ is due to the weaker superconducting combination for bulk. If the Josephson channel is further shortened, the bulk-only channel $R_2$ can also be superconducting in another device #9. However, only the Fraunhofer pattern with uniform supercurrent density is observed and corresponds well to the bulk-dominated sample #8 in Fig. 2c and d (see Figs S8 and 9 for details).

**DISCUSSION**

It is necessary to discuss whether the observed edge superconductivity originates from the edge states in WTe$_2$ or other trivial effects. All of the four different devices exhibit the sharp edge superconductivity which can exclude the accidental impurity effect. The exclusion of some trivial effects such as fluctuations and the affection by the SiO$_2$ substrate and the capping layer in thinner WTe$_2$ is also discussed in Supplementary Section VIII. However, it is difficult to exclude other trivial effects such as trivial edge states. Moreover, the other trivial mechanisms can also lead to a similar non-uniform supercurrent such as an inhomogeneous interface. A mixture of Fraunhofer and SQUID pattern was also observed in Nb-InGaAs/InP junctions with a step-shaped current density distribution [26]. Therefore, we need to point out that the edge superconductivity we observed is not equivalent to the superconductivity in the edge modes nor any evidence of topological superconducting phase. On the contrary, only the superconductivity in the edge region of samples can be concluded in our experiments.

The critical currents following $|I_{c1}^- (B)| ≠ |I_{c2}^- (B)|$ in thin WTe$_2$ are quite interesting. In general, the asymmetric crystal can induce different Fermi velocities at two sides and result in supercurrent asymmetry. Since the supercurrent density is uniform as shown in Fig. 2c with symmetric Fraunhofer pattern (Fig. 2d), the bulk WTe$_2$ does not contribute to the asymmetry. Consequently, this supercurrent asymmetry may be related to the edge which is consistent with the predicted effect of inversion-symmetry-breaking on Weyl semimetal [27]. The total Josephson current carried by the two edges can be described by [28]

$$I(\Phi, \varphi) \propto I_1 \sin(n\varphi + n\Phi) + I_2 \sin(n\varphi - n\Phi),$$

where $I_1$ and $I_2$ represent the Josephson current carried by the two edges, $\Phi$ and $\varphi$ are the phase in WTe$_2$ (the magnetic-field-related) and Nb regions (the current-related), respectively. The two edges have different energy spectra and $I_1 \neq I_2$ in thin WTe$_2$ (Fig. 2g) which results from different Fermi velocity of the two edge sides, denoted by the red and blue lines as shown in Fig. 2e. Therefore, the $I(\Phi, \varphi)$ is not symmetric for both $\varphi$ and $\Phi$ anymore. Other possibilities such as vortex trapping, vortex motion during the magnetic field sweep or
Figure 4. Summary of thickness-dependent edge-superconductivity contribution in WTe₂. The edge/bulk current amplitude is estimated by the ratio of edge/bulk \(I_{\text{edge}}/I_{\text{bulk}}\) supercurrent density. \(I_{\text{edge}}\) and \(I_{\text{bulk}}\) are estimated by the average value of the left and right peaks and the value of the central region in position-dependent supercurrent density. The dashed line shows the trend.

bulk states asymmetry may contribute. However, the \(|I^+ (B)| = |I^- (B)|\) in the thick sample in Fig. 2d helps to largely exclude the other possibility.

We note that two recent preprints [29,30] have also studied WTe₂ Josephson junction and shown evidence of edge states which is explained to be Hinge states [10]. Indeed, it is challenging to unambiguously determine the definite origin of edge superconductivity in our results, and various possibilities exist. However, from the consistent observations of high edge supercurrent density [29], the edge superconductivity is confirmed in the multi-layer WTe₂ system. Compared to the reported data, we further perform thickness-dependence experiments and provide more evidence that edge superconductivity exists in thin WTe₂ but not a thick one.

We summarize the supercurrent density amplitude ratio of the edge and bulk in Fig. 4. The edge superconductivity gradually emerges in thinner ones and the edge/bulk supercurrent amplitude reaches 2.76 in 10 nm-thick WTe₂. The critical thickness for the transition from edge to bulk-dominated superconductivity is estimated to be \(t_c = 16-20 \text{ nm}\). Moreover, various topological semimetals such as the TaAs family [31] (Fermi-arc surface states), layered MoTe₂ [32] (edge states in the 2D limit) and ZrSiS [33] (nodal-line surface states) can be further fabricated into Josephson junctions to detect the surface/edge states.

CONCLUSION

In summary, by studying the Fraunhofer interference, our measurements provide the supercurrent distribution in type-II Weyl semimetal WTe₂. In thin WTe₂, the existence of edge superconductivity is evidenced. Besides, non-symmetric behavior \(I^+ (B) \neq I^- (B)\) in WTe₂ through the edge is an intrinsic property of the inversion symmetry breaking, which is distinct from other systems by an external in-plane magnetic field [22]. Furthermore, the Josephson junctions formed from 1D edge states or 2D surface states and s-wave superconducting contacts are expected to emulate spinless p-wave superconductivity [34] and Majorana flat bands [35] via a.c. Josephson effect by Shapiro response measurements. Edge superconductivity establishes WTe₂ as a promising platform for the future realization of topological superconductivity and Majorana bound states.

METHODS

WTe₂ crystal growth

High-quality bulk WTe₂ crystals were grown by chemical vapor transport (CVT) method as reported before [36]. Single crystals of WTe₂ were grown by a high-temperature self-flux method. High-purity tungsten powders (99.9%) and Te pieces (99.999%) were inserted into alumina crucibles with a molar ratio of 1:30 in a glove box filled with pure argon then sealed in quartz tubes under high vacuum. The tubes were heated to 1100°C in 20 hours and maintained for 10 hours. Then the furnace was slowly cooled down to 650°C with a rate of 2°C/h followed by separating the Te flux in a centrifuge at 650°C.

Device fabrication

The WTe₂ flakes were mechanically exfoliated onto a Si substrate capped with a 280 nm-thick SiO₂ layer and the thickness of WTe₂ was identified by optical contrast and atomic force microscopy. The WTe₂ Josephson junctions were fabricated by an e-beam lithography technique and wet-etched by standard buffered HF solution for 5 s in the electrode regime. We deposited 120 nm-thick Nb electrodes using magnetic sputtering. Then, 40 nm-thick SiO₂ was deposited on top to prevent the WTe₂ oxidization.

Transport measurements

Four-terminal temperature-dependent transport measurements were carried out in a Physical Property Measurement System (PPMS, Quantum Design) with a dilution refrigerator, which achieves a base temperature of 35 mK. The transport
properties were acquired using lock-in amplifiers (SR830) and Agilent 2912 meters. We used an excitation current of <50 nA. In differential resistance (dV/dI) measurements, a small a.c. current bias (10 nA to 100 nA) is generated by the lock-in amplifier output voltage in combination with a 10 MΩ bias resistor. This small a.c. current is added on top of the larger d.c. current bias by Agilent 2912, and the induced differential voltage is measured using the lock-in technique with a low frequency (<50 Hz).

DATA AVAILABILITY
The data that support the plots within this paper and other findings of this study are available from the corresponding author upon reasonable request.

SUPPLEMENTARY DATA
Supplementary data are available at NSR online.

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AUTHOR CONTRIBUTIONS
F.X. conceived the ideas and supervised the overall research. Y.S. and C.Y. synthesized high-quality WTe$_2$ bulk samples. C.H. and E.Z. fabricated the nanodevices. C.H., L.A. and S.L. carried out the PPMS measurements. A.N. and S.S. provided theoreti-
cal support. X.X. provided the curve fitting. C.H. and F.X. wrote the paper with assistance from all other authors.

Conflict of interest statement. None declared.

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