Proximity-induced superconducting gap in the quantum spin Hall edge state of monolayer WTe$_2$

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The quantum spin Hall insulator is characterized by a band-gap in the two-dimensional (2D) interior and helical 1D edge states$^{1-3}$. Inducing superconductivity in the helical edge state results in a 1D topological superconductor, a highly sought-after state of matter at the core of many proposals for topological quantum computing$^2$. In the present study, we report the coexistence of superconductivity and the quantum spin Hall edge state in a van der Waals heterostructure, by placing a monolayer of 1T'-WTe$_2$, a quantum spin Hall insulator$^{1-3}$, on a van der Waals superconductor, NbSe$_2$. Using scanning tunnelling microscopy and spectroscopy (STM/STS), we demonstrate that the WTe$_2$ monolayer exhibits a proximity-induced superconducting gap due to the underlying superconductor and that the spectroscopic features of the quantum spin Hall edge state remain intact. Taken together, these observations provide conclusive evidence for proximity-induced superconductivity in the quantum spin Hall edge state in WTe$_2$, a crucial step towards realizing 1D topological superconductivity and Majorana bound states in this van der Waals material platform.

Contemporary interest in topological superconductors has been driven by potential applications of their gapless boundary excitations, which are thought to be emergent Majorana quasiparticles with non-abelian statistics$^{4-9}$. One path toward topological superconductivity is to realize an intrinsic spinless $p$-wave superconductor$^{10}$. A powerful alternative is to use a conventional $s$-wave superconductor to induce Cooper pairing in topologically non-trivial states via the superconducting proximity effect, resulting in an effective $p$-wave pairing$^{11}$. This approach has recently been employed to engineer two-dimensional (2D) topological superconductivity in epitaxial 3D topological insulator films grown on a superconducting substrate$^{12,13}$ and 1D topological superconductivity by proximitizing a 2D quantum spin Hall system in buried epitaxial semiconductor quantum wells$^{14,15}$. Although such demonstrations mark important milestones, there are clear advantages for exploring topological superconductivity in the van der Waals material platform. Using layered 2D materials allows the 2D quantum spin Hall edge to be proximitized in vertical heterostructures, circumventing the length restrictions of lateral proximity-effect geometries. Furthermore, the surfaces and edges are readily available for surface probes, allowing the detection and fundamental study of signatures of the 1D topological superconducting state. An intrinsic quantum spin Hall state has been demonstrated experimentally in monolayers of 1T'-WTe$_2$ (refs. 1-3,15-17), following earlier theoretical predictions$^{18}$. WTe$_2$ is attractive for studying the quantum spin Hall edge modes because it can be readily incorporated in van der Waals heterostructures and has shown quantized edge conductance up to 100 K (ref. 1). Furthermore, monolayer WTe$_2$ was recently also shown to host intrinsic superconducting behaviour below ~1 K when electrostatically gated into the conduction band$^{18,19}$.

In the present work, we study mechanically exfoliated single- and few-layer WTe$_2$, which are transferred onto the van der Waals $s$-wave superconductor NbSe$_2$. We show that this approach induces a superconducting gap in the WTe$_2$ without the need for electrostatic doping and yields a critical temperature much higher than that of the intrinsic WTe$_2$ superconductivity, an experimental advantage that facilitates studies of the interplay of superconductivity and the quantum spin Hall edge modes. We employ scanning tunnelling microscopy (STM) and spectroscopy (STS) to investigate the proximity-induced superconducting gap as a function of temperature, magnetic field and WTe$_2$ thickness. By spatially resolving the spectroscopic features of the WTe$_2$, we find that the superconducting gap coexists with the quantum spin Hall signature at the monolayer WTe$_2$ edge.

We have developed a novel fabrication technique that enables the assembly and deterministic placement of van der Waals heterostructures in a glovebox (Fig. 1a). Although similar methods have been used to fabricate complex encapsulated mesoscale devices$^{20}$, critically, our technique produces atomically clean surfaces of air-sensitive materials suitable for high-resolution scanning probe measurements (for details see Supplementary Section 1). Figure 1b presents an STM image of the resulting heterostructure, where the WTe$_2$ monolayer edge and the underlying NbSe$_2$ are visible, showing atomically clean surfaces on each material. The profile across the step edge shows a step height of ~7 Å, which corresponds to one WTe$_2$ layer$^{17}$, indicating an atomically clean interface between the WTe$_2$ and NbSe$_2$. In Fig. 1b a weak moiré pattern can be seen; this is analysed in more detail in Supplementary Section 2. Atomically resolved STM images of the NbSe$_2$ surface (Fig. 1c) show the well-known $3 \times 3$ charge density wave$^{21}$, indicating the pristine quality of the NbSe$_2$ flake. Atomically resolved STM images of the WTe$_2$ (Fig. 1d) are characterized by vertical atomic rows parallel to the axis of the WTe$_2$ unit cell.

Turning now to spectroscopic analysis of these surfaces, Fig. 2a shows a series of $dI/dV$ spectra taken along a line perpendicular to the WTe$_2$ monolayer step edge (upper panel) and the corresponding height profile (lower panel). The $dI/dV$ spectra clearly show the presence of an increased local density of states (LDOS) near the...
a smaller voltage range and with smaller modulation amplitude positions of the observed spectral features to epitaxially grown WTe₂. The observation is further supported by our density functional theory calculations of the monolayer WTe₂/NbSe₂ heterostructure, which show only minimal modifications of the WTe₂ electronic structure compared to a freestanding WTe₂ monolayer. Measurements of the monolayer WTe₂ dI/dV spectrum over a smaller voltage range and with smaller modulation amplitude (Fig. 2c) reveal a new feature that resembles a superconducting gap characterized by a dip in the dI/dV signal at the Fermi energy, with peaks on either side of the gap. When decreasing the measurement temperature from 4.7 K to 2.8 K, the gap deepens and the peaks sharpen, whereas when increasing the temperature the gap vanishes at ~6 K. The evolution of the gap under application of a surface-normal magnetic field at 4.7 K (Fig. 2d) shows that with increasing magnetic field, the gap becomes less deep until it has nearly vanished at 1 T. We find that a fit of the Bardeen–Cooper–Schrieffer (BCS) model describes both the monolayer WTe₂ and the NbSe₂ data well (Fig. 3a). For NbSe₂, the fit results in a superconducting gap of 0.72 ± 0.02 meV. In addition to following the trend of a superconducting gap with applied magnetic field, the vanishing of the gap near 1 T is similar to the Ginzburg–Landau estimate for the upper critical field of bulk NbSe₂ (ref. 23). We conclude that the gap feature observed on the monolayer WTe₂ is indeed a superconducting gap.

To confirm the proximity-induced nature of the observed superconducting gap on the WTe₂, we explore its evolution as a function of WTe₂ thickness. The exfoliation procedure naturally produces terraces of different thickness in our samples, enabling thickness-dependent gap measurements within a single sample. Figure 3b shows the superconducting gap measured on terraces with different numbers of WTe₂ layers N, revealing that the gap decreases with increasing N, as expected for decaying superconducting correlations near the boundary of a superconducting–metal interface. To quantify this behaviour, we fitted the BCS model to each of the spectra in Fig. 3b and plot the extracted gap sizes as filled circles in Fig. 3c. In the thick limit (N ≥ 3), we find that the observed behaviour shows...
excellent agreement with transport measurements of proximity-induced superconductivity in bulk WTe$_2$ flakes$^{24,25}$, extending the previous studies to the ultra-thin limit (Supplementary Section 5). For $N < 3$ we observe a more rapid decrease of the extracted gap as a function of $N$ that may be explained by the strong variation of the electronic structure of the WTe$_2$ in this thickness range, resulting
For bilayer WTe$_2$ on NbSe$_2$, using a similar procedure, we find an approach that of NbSe$_2$ as the WTe$_2$ layer thickness goes to zero.\(^{24}\)

The size of the induced gap is \(\Delta_{(\text{edge})} = 0.75 \pm 0.08\) meV.

The observation of a superconducting gap in the edge state of monolayer 1T’-WTe$_2$ provides strong evidence that we have created a 1D topological superconductor in a van der Waals heterostructure. The topological nature of a superconducting quantum spin Hall edge state could be explicitly demonstrated in an STM measurement by creating a boundary with a portion of the same quantum spin Hall edge state in which a topologically trivial gap has been opened.\(^{4}\) This would localize Majorana zero modes at the boundary, which can be identified as a zero-bias conductance peak within the superconducting gap.\(^{31}\) Creating such a boundary is straightforward in the van der Waals material platform, for example by integrating a van der Waals magnetic insulator into the heterostructure shown in Fig. 1a to open a local Zeeman gap.

The groundwork for such an experiment with a clear path toward the realization of Majorana quasi-particles. In addition, the method of sample preparation outlined in this work may be easily adapted to numerous experiments involving surface-probe studies or air-sensitive materials.

**Online content**

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Methods

WTe₂ and NbSe₂ were exfoliated onto SiO₂ in a nitrogen-filled glovebox. A WTe₂ flake with regions of different thickness was transferred onto a (20 ± 1) nm-thick NbSe₂ flake using the technique depicted in Fig. 1a. At this thickness, the electronic properties of the NbSe₂ are bulk-like and the critical temperature below which the NbSe₂ becomes superconducting is $T_c \approx 7$ K (ref. 28). For optical images of the sample and further details about the sample fabrication, see Supplementary Section 1. The STM tip was approached to the WTe₂/NbSe₂ heterostructure using a capacitive technique adapted from ref. 29. The commercial CreaTec STM helium bath temperature was 4.2 K with the ability to intermittently reach ~1 K by pumping on the cryostat. The resulting STM temperatures were 4.7 K and 2.8 K, respectively, due to vibration isolation and optical access. The STM was equipped with an electrochemically etched tungsten tip, which was indented into gold before and between measurements. The lock-in frequency was set to $f = 925$ Hz in all $dI/dV$ measurements. All superconducting gap measurements were performed at $V_{\text{peak}} = 5$ mV with $V_{\text{mod}} = 100$ μV peak-to-peak and $I = 100$ pA, except in Fig. 2c, where $V_{\text{peak}} = 10$ mV. The spectra in Fig. 2a,b were acquired using $V_{\text{mod}} = 5$ mV. In Fig. 4a $V_{\text{peak}} = 300$ mV, $I = 100$ pA and $V_{\text{mod}} = 5$ mV and in Fig. 4b $V_{\text{peak}} = 300$ mV, $I = 110$ pA and $V_{\text{mod}} = 10$ mV. For quantitative comparison, the spectra in Fig. 4a,b were normalized to $I$ and $V_{\text{mod}}$.

Data availability

The data represented Figs. 1, 2, 3 and 4 are available as Source Data with the online version of the paper. All other data that support the plots within this paper and other findings of this study are available from the corresponding author upon reasonable request.

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Author contributions

F.L., D.W., R.M.F. and B.M.H. designed the experiment. F.L. and D.W. acquired the experimental data and F.L., D.W. and R.M.F. analysed it. F.L., D.W. and S.C.d.I.B. fabricated the samples. F.L., D.W., S.C.d.I.B., R.M.F. and B.M.H. wrote the manuscript, and all authors commented on it. J.Y. grew the WTe₂ crystals. D.G.M. provided other van der Waals crystals used in this study. M.W. performed density functional theory calculations. R.M.F. and B.M.H. supervised the project.

Competing interests

The authors declare no competing interests.

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