Visualizing coexisting surface states in the weak and crystalline topological insulator Bi$_2$Tel

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Dual topological materials are unique topological phases that host coexisting surface states of different topological nature on the same or on different material facets. Here, we show that Bi$_2$Tel is a dual topological insulator. It exhibits band inversions at two time reversal symmetry points of the bulk band, which classify it as a weak topological insulator with metallic states on its ‘side’ surfaces. The mirror symmetry of the crystal structure concurrently classifies it as a topological crystalline insulator. We investigated Bi$_2$Tel spectroscopically to show the existence of both two-dimensional Dirac surface states, which are susceptible to mirror symmetry breaking, and one-dimensional channels that reside along the step edges. Their mutual coexistence on the step edge, where both facets join, is facilitated by momentum and energy segregation. Our observation of a dual topological insulator should stimulate investigations of other dual topological classes with distinct surface manifestations coexisting at their boundaries.

Band and insulators are classified into different classes according to the topology of their band structures. In the presence of time reversal symmetry, insulators are divided into trivial insulators and topological ones, with the latter hosting symmetry-protected metallic states on their surfaces. Lattice symmetries further refine the classification and introduce subclasses into the trivial class, for which only some of the surfaces carry topologically protected metallic states. Examples include the weak topological insulator (WTI)1, for which the protecting symmetries are time reversal symmetry and a particular discrete translational invariance, and topological crystalline insulators (TCI)2–7, for which the protecting symmetries are crystalline symmetries, such as mirror and rotation. Remarkably, the same material can host surface states of a different nature on different material facets that originate from the same bulk band inversions. Here, we provide experimental realization of such a dual topological insulator that exhibits different surface states on different facets.

Dual topological classification can be realized by different forms. One form may refer to dual protection of surface states by multiple bulk symmetries. This is the case in the canonical strong topological insulators Bi$_2$Se$_3$ and Bi$_2$Te$_3$ (ref. 8), and in other compounds9,10. On top of time reversal symmetry, these compounds host three mirror planes related by C$_3$ symmetry, which simultaneously classify them as TCIs. Consequently, in the presence of a magnetic field in a direction that preserves the mirror symmetry the Dirac surface states would not become gapped out but merely shift from the time reversal invariant momentum at Γ. A different type of dual topological classification arises when distinct topological indices can be assigned at different momenta in the Brillouin zone. For instance, Dirac and Fermi arc states were predicted to coexist in both LaPtBi11 and in Cu$_3$S$_2$ due to their dual bulk classification as Weyl semimetals and strong topological insulators. A different realization of such coexistence was shown to be stable at the interface between a Weyl semimetal and a strong topological insulator12. A third kind of dual topological classification, which is the focus of this study, occurs when multiple topological indices can be assigned to the bulk band structure; however, these give rise to different topological surface states on different surfaces of a given material. This was predicted to occur in Bi$_2$Te$_3$13–15, which we study here, and in Bi$_2$Te$_5$, in which only the existence of the TCI surface states was directly measured16. In both compounds, an even number of bulk band inversions can be simultaneously assigned with weak topological indices and mirror Chern numbers. Consequently, time reversal symmetry-protected Dirac states are expected to form on one set of surfaces, and mirror symmetry-protected Dirac states will form on a distinct set of surfaces.

The layered compound Bi$_2$Te$_3$14,15,17–19 (Fig. 1a) is composed of stacked layers in which a Bi bilayer is incorporated between two layers of the trivial semiconductor BiTeI. A Bi bilayer (Fig. 1b) was shown to be a two-dimensional topological insulator (2D TI)20,21, hence a unit-cell layer of TeBiI–Bi$_2$–IBiTe is expected to be a robust 2D TI21. In general, when layers of 2D TIs are stacked and weakly coupled, they form a WTI22. Recent studies have predicted that a mirror-protected TCI can also be described using a coupled-layer construction23. Indeed, theoretically, three-dimensional (3D) Bi$_2$Te$_3$ was predicted to have a dual topological classification inclusive of both a WTI and a TCI24. More recently, it was predicted that, when some of its symmetries are broken, Bi$_2$Te$_3$ is classified as a higher order topological insulator that exhibits topological hinge modes25,26. The dual WTI–TCI classification can be derived from the two band inversions located at the Γ and Z time reversal symmetric points of the 3D bulk Brillouin zone (Fig. 1c)24,25. Projecting these inverted bulk bands onto the (010) ‘side’ surfaces, two surface Dirac cones form—at the Γ point and at the Z point of the (010) surface Brillouin zone25. On the (001) ‘top’ and ‘bottom’ surfaces, the two
inverted bulk bands are projected to the same point. The two surface Dirac bands should therefore hybridize and fully gap out (Fig. 1d), leading to the characteristic WTI surface phenomenology comprising of metallic side surfaces and insulating top and bottom surfaces. However, the existence of three \( \Gamma-Z-M \) mirror planes in \( \text{Bi}_2\text{TeI} \) (Fig. 1a) protects the band crossing points along their mirror projection lines (\( \Gamma-M \)) on the (001) surface. As a consequence, three pairs of Dirac surface states are expected on the (001) surface band structure (Fig. 1c). This classifies \( \text{Bi}_2\text{TeI} \) as a TCI, together with its classification as a WTI. We study the intricate coexistence of the WTI and TCI surface states (Fig. 1f). In particular, we focus on (001) facet edges where the two types of states interact, and examine their interplay as well as their individual and mutual response to disorder. By mapping the local density of states (LDOS) on terraces and step edges on the (001) surface, we directly visualize one-dimensional (1D) metallic channels coexisting alongside 2D topological surface states. The TCI surface states appear on all surface terminations and are susceptible to the mirror symmetry breaking imposed by the step edges. The 1D channels appear only on step edges that contain a Bi bilayer, and are absent at step edges that do not contain that layer. The two types of surface states can coexist due to the large momentum transfer involved in their hybridization.

**TCI surface states under mirror symmetry-breaking perturbation**

Single crystals of \( \text{Bi}_2\text{TeI} \) (see Methods and Supplementary Section 1) were cleaved in ultra-high vacuum conditions and measured in a scanning tunnelling microscope (Unisoku) at 4.2 K. Figure 2a shows a typical topographic image of such a cleaved surface, exhibiting a series of several adjacent terraces that end at rough crystallographic step edges (right inset). To observe the TCI surface states directly, we measured the LDOS on the surface of the different terraces. A typical \( \frac{dI}{dV}(V) \) spectrum measured on a Bi-terminated surface (at the location marked by a blue arrow in Fig. 2a) is given by the solid line in Fig. 2b. The surface spectrum shows metallic behaviour with reproducible peak-like features at several characteristic energies. We compare the measured spectrum to ab initio calculations of the bulk and surface density of states (see Supplementary Section 2 for detailed ab initio calculations). Good agreement of the measured peak-like features with those found in the calculated bulk density of states (greyed area in Fig. 2b) reveals that these correspond to bulk bands. However, in contrast to the calculated semiconducting bulk spectrum with a bulk gap of about 160 meV, the spectrum we measure on the surface is fully metallic. This apparent discrepancy is resolved by calculating the surface density of states projected on the Bi-terminated (001) surface (dotted line in Fig. 2b), which shows excellent agreement with the measured curve throughout the spectrum. The in-gap surface LDOS is therefore contributed entirely by surface states. In the calculation, these correspond to the TCI Dirac surface states with the Dirac node at the vicinity of the Fermi energy regardless of surface termination (for more details see Supplementary Fig. 4).

To directly visualize the dispersion of metallic in-gap surface states and to verify their identification with the TCI Dirac states, we measure the quasiparticle interference (QPI) patterns that they embed in the LDOS upon scattering off the step edges. The Fourier transform of such a modulated \( \frac{dI}{dV}(V) \) map (see also Supplementary Fig. 9), measured on the (001) Te-terminated surface near a step edge, is shown in Fig. 2c. Indeed, dispersing QPI patterns span the whole energy range down to about 100 meV below the Fermi level, thus crossing the 100 to \(-100\) meV energy range, which corresponds to the bulk gap.

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**Fig. 1 | Dual topological classification in \( \text{Bi}_2\text{TeI} \).** a. The side view of the \( \text{Bi}_2\text{TeI} \) layer structure shows layers of the 2D TI Bi bilayer sandwiched between layers of the non-topological semiconductor BiTeI. The top view captures the three mirror symmetry axes (\( m \)) of the trigonal structure of the layers. b. A single Bi bilayer is a 2D TI with helical metallic channels running on its edges. Red and blue colours represent the opposite helicities of the upper and lower parts of the Dirac cones. c. Two inverted gaps located at the \( \Gamma \) and \( Z \) high symmetry points of the 3D bulk Brillouin zone. Their projection on the side (010) surface yields two Dirac cones at \( \Gamma \) and \( Z \) that form a WTI. Their projection on the top (001) surface yields two overlapping Dirac cones that are slightly shifted in energy, forming a degenerate nodal line. d. Without mirror symmetry the Dirac cones hybridize and the nodal line may gap out. e. With mirror symmetry the nodal line is protected on the \( \Gamma - M \) mirror projection lines, leading to six Dirac cones on the top surface. f. The combined surface spectrum of the (001) surface with the 1D channel along crystallographic step edges consists of six 2D Dirac cones along the \( \Gamma - M \) directions and a helical 1D state at the \( \Gamma \) point.
To associate these QPI patterns with the corresponding scattering processes, we calculate the surface-projected band structure of the Te termination, shown in Fig. 2d along the $\Gamma - K$ direction. All the surface states on this termination correspond to one of three interconnected Dirac bands, protected by the mirror symmetry; two of them are located at energies above and below the bulk gap (blue circles), while the third Dirac cone appears near the Fermi energy, within the bulk gap (red circle), without overlapping any other surface or bulk states. Qualitatively, the magnitude of the scattering wavevectors we find in QPI is too small (less than 5 nm$^{-1}$) to connect time reversal-related Dirac bands on opposite sides of the Brillouin zone (about 10 nm$^{-1}$ apart). Accordingly, we associate the QPI with oblique scattering along $\Gamma - K$ between adjacent Dirac bands located about the $\Gamma - M$ directions. Lack of direct backscattering is commonly associated with the helical spin texture of the topological Dirac dispersion.

By quantitative comparison of the momentum transfer associated with all possible scattering processes with the measured ones, we find that the measured QPI patterns are contributed mainly by two scattering processes at two different energy regimes. At higher energies, down to about 150 meV, QPI originates from the hole side of the upper Dirac band. In particular, it is contributed by the scattering process, marked in Fig. 2e by a red arrow, between two high-density points on the linearly dispersing pockets located along the $\Gamma - M$ direction.
The energy evolution of this process is captured by the linearly dispersing red dotted line in Fig. 2c, which directly coincides with the dispersing QPI mode. At lower energies, below about 150 meV, this pocket closes as it merges with the electron side of the Dirac band whose node is about the Fermi energy. Concurrently, the measured QPI pattern becomes fairly non-dispersing. We identify this QPI with the scattering process, marked in Fig. 2f by a pink arrow, between two high-density points located around two different Γ–M directions. Since these two points disperse linearly in the same way, they give rise to interband momentum transfer that does not disperse much in energy, in agreement with the measured QPI value (pink dots in Fig. 2c). While no other surface or bulk states exist at this energy range, this directly identifies the measured in-gap states with the topological TCI states, located near the Fermi energy, on the (001) Te-terminated surface.

We further examined the topological protection of the TCI in-gap states by applying a symmetry-breaking perturbation that selectively affects only the topological surface states. For the (001) surface states in Bi₂TeI, such a symmetry-breaking perturbation is provided by the step edges that naturally appear on a cleaved (001) surface and break the mirror symmetry of the lattice. We therefore measured the dV/dI(V) spectrum (Fig. 2g) along a line cut (grey line in Fig. 2a) taken across all seven terraces. We find that ‘on’ the terraces, far from the edges, the spectrum is predominantly metallic, irrespective of the specific cleaved termination. Such unselective metallic behaviour is uncommon for non-topological Shockley or dangling-bond surface states whose existence is surface dependent.

Remarkably, in the face of this robustness, we find a consistent suppression in the LDOS of the in-gap surface states in the vicinity of all six crystallographic step edges (coloured in pale blue). Representative density of states spectra taken near and far from a step edge (at the blue and black arrows in Fig. 2g, respectively) are directly compared in Fig. 2h. This clearly demonstrates the suppressed in-gap LDOS over about 50 meV above and below the Fermi energy, in the vicinity of the step edge. In contrast to trivial states, the TCI surface states are highly susceptible to mirror symmetry breaking. Accordingly, the observed LDOS suppression further identifies the observed in-gap metallic surface states with the (001) mirror symmetry-protected TCI surface states.

We find that the in-gap LDOS decreases at the vicinity of the step edges but does not vanish. This is the expected behaviour of the mirror-protected topological surface states considering their three protecting mirror planes. A straight crystallographic step edge that appears on the (001) surface breaks at least two out of the three mirror symmetry planes of the crystal. As a result, of the six Dirac cones that reside on the surface, the ones that were protected by those mirror planes will gap out. This is shown schematically in the inset in Fig. 2h. Moreover, the contours of the step edges that we observe on the surface of Bi₂TeI, shown in Fig. 2a and in the right inset, are not atomically straight. The LDOS of the TCI states is therefore expected to decrease at the vicinity of all step edges, but the extent of this suppression is expected to change with the local morphology of the step edge. The remaining in-gap LDOS is, accordingly, contributed by the ungapped TCI states, or is due to impurity states. An important observation is that for all step edges shown in Fig. 2a, the LDOS is notably suppressed only on the upper side of the terrace (demonstrated in the inset). We attribute this asymmetry to the asymmetric boundary condition that a step edge imposes on the surface states in the upper and lower terraces. For the wavefunction on the lower terrace, the layer in which it resides continues through the step edge, while for the wavefunction in the upper terrace the layer terminates abruptly at the step edge. As a result, the gap induced by the mirror symmetry breaking is expected to be stronger on the upper side of the step edge.

1D edge channels of a WTI
We now turn to investigate the properties of the WTI states. Unlike the TCI states, which showed insensitivity to the ‘top’ terrace termination, the composition of the ‘side’ surface, which during cleavage becomes fragmented into well-separated step edges, is detrimental to the formation of topological boundary states. Since the Bi bilayer is the essential building block of the WTI surface states, a step edge of a terrace terminating with a single Bi bilayer in its layer composition is expected to host a 1D conducting helical channel that is...
protected by time reversal symmetry\textsuperscript{29-31}. Similar 1D channels were measured previously on the surface of WTI Bi\textsubscript{1}Rh\textsubscript{3}I\textsubscript{6} (refs. \textsuperscript{12,33}). While in generic WTI these channels appear on the background of a gapped surface, in Bi\textsubscript{2}Te\textsubscript{3} they would coexist with the TCI surface states, providing a unique opportunity to investigate their interaction.

In Fig. 3 we show a visualization of 1D conducting channels measured on step edges on the surface of two different samples of Bi\textsubscript{2}Te\textsubscript{3}. The crystallographic step between terraces 2 and 3 (presented in Fig. 2a) has a unit-cell height of 1.7 nm. In contrast to smaller steps that may lack Bi bilayers, or to higher steps that may host two coupled Bi bilayers, a step of unit-cell height must contain only a single Bi bilayer. As a result, a 1D topological channel is expected at its boundary. The locally averaged dI/dV(V) curves measured right at this step edge, along with the ones measured on top of the two adjacent terraces, are shown in Fig. 3a (solid and dashed lines, respectively). The two different terraces exhibit almost overlapping dI/dV(V) curves with a finite in-gap LDOS contributed by the TCI surface states. The dI/dV(V) measured on the step edge is clearly distinguished. It exhibits an additional notable increase in the in-gap LDOS that peaks 100 meV (red arrow) below the onset of the conduction band (black arrow), and extends across the bulk gap. We note that this peak energy is well below the typical energy window over which the TCI surface states are suppressed at the step edges, allowing simultaneous observation and identification of the appearance of the WTI 1D channels and suppression of the TCI states. Our ab initio calculations (Supplementary Fig. 5) show a similar peak-like structure of a 1D topological channel residing at a step edge crystal termination. Spectroscopic maps measured at different locations across step edge 2–3 (Fig. 3b) clearly visualize a 0.5-nm-wide 1D channel running along the step edge. Similar spectroscopy of a 1D edge channel was measured at step edges 5–6 (Fig. 3c), as well as on a unit-cell-high step edge measured on a different sample (Fig. 3d). In the other sample, however, the Fermi energy resides at the top of the valence band rather than at the bottom of the conduction band. Yet, in both samples, the characteristic peak-like feature appears 100 meV below the onset of the conduction band.

1D channels at step edges can also result from non-topological origins, such as dangling bonds at the terrace boundaries. While the existence of these channels is independent of the Bi bilayer content of the terrace, the formation of the topological channels must be correlated with the existence of a Bi bilayer in the terrace layer structure. Terraces containing a single or an odd number of Bi bilayers must host topological channels, while step edges with no Bi bilayers are not expected to host topological channels. In the case of an even number of Bi bilayers, the edge states may gap out in pairs\textsuperscript{4}. We examined the relationship between the formation of 1D channels and the Bi bilayer content of the measured step edges. To determine the Bi bilayer content we resolved the layer termination of the whole staircase structure. As shown in Fig. 3e, by correlating the staircase height profile with the layer structure of Bi\textsubscript{2}Te\textsubscript{3}, we find that there is only one configuration for which all terrace cleave planes fall between van der Waals-coupled layers. All other configurations (see Supplementary Fig. 6) involve breaking some covalently bonded layers, which makes them improbable. We further verified this favourable configuration by cross-correlation analysis of the atomically resolved topographic images measured on the various terraces (see Supplementary Fig. 7), as well as by the spectral characteristics of the terraces. Cross-checking the information from these independent analysis methods allowed us to uniquely determine the layer ordering of the whole staircase (Fig. 3e). We find that terraces 2, 3 and 6 are terminated by Bi bilayers, while terraces 4 and 5 are terminated by Te and I, respectively. Comparing this identification with the measured dI/dV(V) shows excellent agreement. Step edges 2–3 and 5–6, whose upper terraces are terminated by a Bi bilayer, indeed host topological channels (Fig. 3a–c). However, step edges 3–4 and 4–5, with no Bi bilayer content, do not show any increase in the in-gap LDOS with respect to the spectra measured on their adjacent terraces, nor the characteristic peak that we consistently identify with the topological edge channel at the step edge and the presence or absence of a Bi bilayer must be correlated with the existence of a Bi bilayer in the terrace layer structure. As shown in Fig. 3e, by correlating the staircase height profile with the layer structure of Bi\textsubscript{2}Te\textsubscript{3}, we find that there is only one configuration for which all terrace cleave planes fall between van der Waals-coupled layers. All other configurations (see Supplementary Fig. 6) involve breaking some covalently bonded layers, which makes them improbable. We further verified this favourable configuration by cross-correlation analysis of the atomically resolved topographic images measured on the various terraces (see Supplementary Fig. 7), as well as by the spectral characteristics of the terraces. Cross-checking the information from these independent analysis methods allowed us to uniquely determine the layer ordering of the whole staircase (Fig. 3e). We find that terraces 2, 3 and 6 are terminated by Bi bilayers, while terraces 4 and 5 are terminated by Te and I, respectively. Comparing this identification with the measured dI/dV(V) shows excellent agreement. Step edges 2–3 and 5–6, whose upper terraces are terminated by a Bi bilayer, indeed host topological channels (Fig. 3a–c). However, step edges 3–4 and 4–5, with no Bi bilayer content, do not show any increase in the in-gap LDOS with respect to the spectra measured on their adjacent terraces, nor the characteristic peak that we consistently identify with the topological 1D channel (Fig. 3f,g, respectively). We thus confirm complete correlation between the presence or absence of the 1D metallic edge channel at the step edge and the presence or absence of a Bi bilayer in the step edge layer composition. This suggests the topological nature of the observed 1D channels. It also rules out identification of the 1D channels with TCI 1D edge modes, which were recently suggested to exist in SnTe\textsuperscript{40}, since these should be termination independent.

**Interaction between the TCI and WTI surface states coexisting on hinges**

A striking observation in Fig. 3b is that the 1D edge channels coexist with the adjacent 2D TCI surface states, rather than hybridizing with them. We attribute this decoupling to the large momentum transfer required for their hybridization\textsuperscript{15,26}. This is
demonstrated in Fig. 1f by the combined band structure of the 2D TCI states and the 1D edge channel. The mirror-protected Dirac cones are located on the $\Gamma - M$ directions away from the $\Gamma$ point\textsuperscript{14,15}. In contrast, the 1D state, which is contributed by the Bi bilayer\textsuperscript{14,18} and is protected by time reversal symmetry, is bound to the time reversal asymmetric $\Gamma$ point (Fig. 1b). Hence, the hybridization of the two is suppressed by the large momentum separation and they are topologically protected from gapping in a manner similar to that exhibited by the bulk Weyl states of a Weyl semimetal\textsuperscript{17,28}. Nevertheless, the level of protection is somewhat diminished, as it depends on the ability of scatterers to provide the finite momentum transfer. Accordingly, the ability to resolve these 1D channels, as well as their spatial distribution along the step edge, is strongly affected by the high level of disorder observed at the step edges (insets in Fig. 2a).

We find that at some disordered regions the channels appear quite fragmented, as opposed to the continuous channel imaged on the straight segments of the step edge in Fig. 3b. We map the spatial distribution of the wavefunction of the edge channel on the disordered terrace next to the rough step edge, whose topography is shown in Fig. 4a. The complex topographic landscapes imaged in Figs. 2a and 4a (and Supplementary Figs. 6 and 7) result from the combination of resolved crystal structure, disorder and the spatially modulated LDOS response to such disorder. Indeed, the $dI/dV(V)$ spectra in Fig. 4b, taken at different positions across the terrace, show a varying intensity of the $\sim100$ meV peak that is characteristic of the edge channel. We spatially map the intensity distribution of the edge channel wavefunction across the terrace in Fig. 4c. We find that while in some segments it is bound to the step edge, in others it becomes fragmented. This behaviour stands in sharp contrast to the robustness demonstrated for the edge modes both in the WTI Bi\textsubscript{3}Rh\textsubscript{2}I\textsubscript{5} (ref. 13) and in Bi bilayers\textsuperscript{29,30}. The imaged wavefunction distribution bears a resemblance to previously imaged localized states\textsuperscript{29,30}, although these differ in dimensionality and in their topological nature. Chemical disorder is thought to lead to fluctuations in the spatial distribution of the wavefunction of the 1D channels. While these channels are expected to be immune to spatial disorder, to avoid it they might penetrate deeper into the bulk, or sideways, away from the step edge and into the terrace surface. When mapped locally, this would appear as local disappearance or spatial fragmentation. Still, this fragmented structure seems to be unique to the hinges in Bi\textsubscript{3}Te\textsubscript{3}, where the two distinct surface states of the WTI and TCI coexist.

We verified the existence and visualized the coexistence of TCI and WTI surface states in Bi\textsubscript{3}Te\textsubscript{3}. The TCI Dirac surface states appear on all terraces, regardless of composition and termination, and are found to be susceptible to mirror symmetry breaking by the step edges. The WTI edge modes, on the other hand, appear selectively only on those step edges at which a Bi bilayer terminates. Their coexistence is enabled by these surface states being separated in real space, momentum space and energy. In real space, the separation is a consequence of the different facets on which the TCI and WTI surface states reside, which still allows their interaction on facet edges. In momentum space, it originates from the confinement of the 2D TI Dirac node to time reversal invariant momentum, while no such confinement occurs for the TCI. On the energy axis, the separation is a result of the details of the energy dispersion. Our measurements highlight the unique interplay of these protection mechanisms. We observe the states on terraces and step edges where their spatial separation is minimal. Remarkably, they remain decoupled due to their separation in momentum space and in energy. From a practical point of view, our findings raise the possibility of engineered samples with designed terraces, step edges and symmetry-breaking perturbations. Such devices will have defined regions whose properties are determined by the specific combination of topological surface states that they host.

### Online content
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Methods

Bi₂TeI single crystals were grown via a self-flux method using BiI₃, Te and Bi as starting materials. A mixture with composition Bi₂TeI was placed in an alumina crucible sealed in an evacuated quartz tube. The mixture was heated at 300 °C for 10 h and 550 °C for 20 h, and then slowly cooled to room temperature at a rate of 2 °C h⁻¹. The obtained crystals were silver-grey with a typical dimension of 2 × 2 × 0.2 mm³. The Bi₂TeI single crystals were cleaved in the scanning tunnelling microscope load lock at ultra-high vacuum conditions, at room temperature, using the scotch tape technique. Cleaving the sample in alignment with its layer orientation exposes a fresh surface along the (001) direction with multiple terraces and islands of different heights. Although the easy cleavage plane is along the two van der Waals-coupled tellurium terminations, we find that it also occurs along other van der Waals-coupled layers. All dI/dV(V) measurements were taken at 4.2 K using standard locking techniques. Typical parameters are a lock-in frequency of 733 Hz, a.c. amplitude of 3 mV, parking bias of −300 meV and current set point of 300 pA.

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.

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Author contributions

A.K.N., A.S. and A.N. acquired the data and performed the analysis. Y.Q., A.I., A.Z. and L.P. grew and characterized the samples. H.F., Y.S. and B.Y. calculated the ab initio model. C.F., H.B. and N.A. conceived the experiment and wrote the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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