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Realization of a double-slit SQUID geometry by Fermi arc surface states in a WTe_2 Weyl semimetal

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Like other topological materials, Weyl semimetals are characterized by topologically protected metallic surface states, which are Fermi arcs in k-space [1].

The edge current contribution can be retrieved even for systems with conducting bulk by analyzing Josephson current behavior in low magnetic fields [2, 3]. It is well known, that the homogeneous supercurrent density in the conductor corresponds to a single-slit Fraunhofer pattern. As the edge currents emerge in a two-dimensional topological system, the sinusoidal oscillation pattern appears [2, 3], which is a fingerprint of a superconducting quantum interference device (SQUID). Thus, it is reasonable to study supercurrent behavior in Josephson junction, fabricated on a three-dimensional Weyl semimetal surface (see Fig. 1).

In zero magnetic field, at low temperature $1.4\,\mathrm{K} < T_c$, transport between two $5\,\mu$m spaced contacts S1 and S2 is of clear Josephson-like behavior in an unprecedentedly long $L = 5\,\mu$m In-WTe_2-In junction. This L value exceeds the mean free path in WTe_2 $l_e \approx 1\,\mu$m, so it should be compared with the coherence length of the diffusive superconductor-normal-superconductor (SNS) junction $\xi = (l_e \times \hbar v_F^N/\pi\Delta_{in})^{1/2} \approx 200\,\mathrm{nm}$, where Fermi velocity is $v_F^N \approx 1.5 \cdot 10^7 \frac{\mathrm{cm}}{\mathrm{s}}$ from angle-resolved photoemission spectroscopy (ARPES) data, and $\Delta_{In} = 0.5\,\mathrm{meV}$ is the indium superconducting gap. From this estimation, our In-WTe_2-In junction is a long $\xi \ll L$ diffusive $L > l_e$ one.

As usual for SNS junctions, important information can be obtained from the maximum supercurrent I_c behavior with temperature or magnetic field. $I_c(T)$ monotonously falls to zero at 3.5 K, which well corresponds to the indium critical temperature (see Fig. 2a).

To our surprise, $I_c(B)$ pattern crucially depends on the magnetic field orientation to the In-WTe_2-In junction plane (see Fig. 2b). If the magnetic field is perpendicular to the plane, strong suppression of $I_c(B)$ is observed, which is usual for standard Josephson junctions due to dephasing effects. In contrast, $I_c(B)$ is diminishing very slowly (within 10 % until the indium critical field) for the parallel magnetic field. For both orientations, we observe equidistant $I_c(B)$ oscillations within 5 % of I_c magnitude, see also inset to Fig. 2b. The oscillations are characterized by high $\Delta B = 2\,\mathrm{mT}$ period for the parallel field and by low $\Delta B = 0.1\,\mathrm{mT}$ for the perpendicular one. It can be easily seen, that the observed $I_c(B)$ behavior in parallel magnetic fields resem-

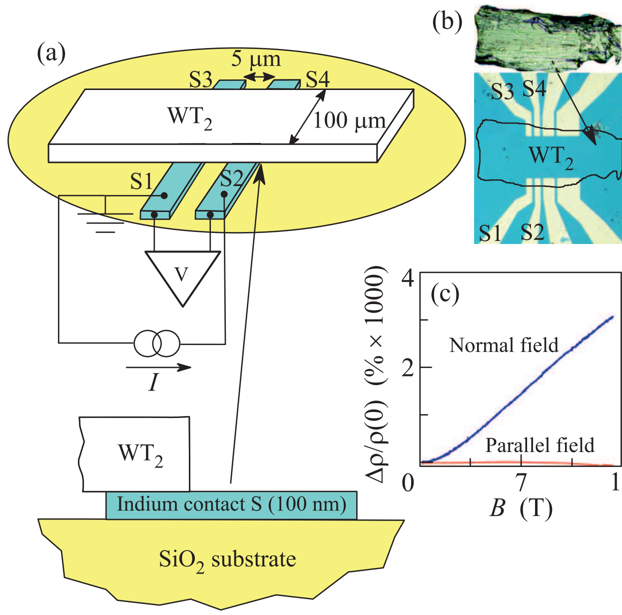

Fig. 1. (Color online) (a) – Sketch of the sample with indium contacts to the bottom surface of a WTe_2 crystal (not to scale). $10\,\mu$m wide indium superconducting leads (S1–S4) are formed on the insulating SiO_2 substrate. $5\,\mu$m long In-WTe_2-In junctions are fabricated by weak pressing a WTe_2 crystal ($\approx 0.5\,\mathrm{mm} \times 100\,\mu\mathrm{m} \times 0.5\,\mu\mathrm{m}$) to the indium leads pattern. Charge transport is investigated between two superconducting electrodes in a four-point technique: the S1 electrode is grounded; a current I is fed through the S2; a voltage drop V is measured between these S1 and S2 electrodes by independent wires because of low normal In-WTe_2-In resistance. (b) – Top-view images of the indium leads and WTe_2 crystal. (c) – Large positive magnetoresistance $\rho(B) - \rho(B = 0)/\rho(B = 0)$ for our WTe_2 samples in normal magnetic field (the blue curve) at 1.4 K, which goes to zero in parallel one (the red curve), as it has been shown for WTe_2 Weyl semimetal

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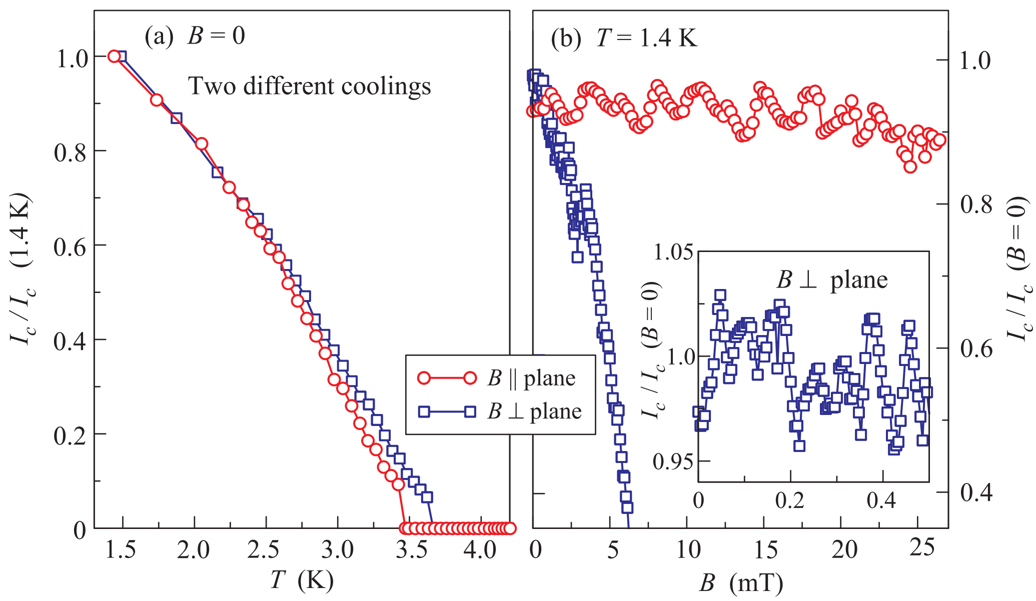

Fig. 2. (Color online) Suppression of the maximum supercurrent I_c by temperature (a) or magnetic field (b). (a) – $I_c(T)$ monotonously falls to zero at 3.5 K, which well corresponds to the indium critical temperature (different symbols refer to different sample coolings). The curves are obtained in zero magnetic field. (b) – $I_c(B)$ suppression pattern crucially depends on the magnetic field orientation to the In-WTe_2-In junction plane: it is extremely strong for the perpendicular field, while it is very slow (within 10 % until the critical field) for the parallel orientation. For both rientations, there are oscillations in $I_c(B)$, the period is much higher for the parallel magnetic field (2 mT and 0.1 mT, respectively). The curves are obtained at minimal 1.4 K temperature. All the experimental points are well reproducible, variation of I_c in different sweeps is below the symbol size

bles double-slit SQUID behavior [2, 3], so the surface transport is important in WTe_2.

We should connect $I_c(B)$ behavior in parallel magnetic field with non-trivial distribution of the Josephson current within the WTe_2 crystal. The sample thickness is comparable with the coherence length $\xi \approx 0.2\,\mu$m, so the regions of proximity-induced superconductivity couples two opposite sample surfaces near the In leads. The Josephson current is transferred by topological surface states, so there are two parallel weak links between the superconducting leads. In other words, a non-symmetric double-slit SQUID geometry [2, 3] is realized.

The experimental $I_c(B)$ pattern well corresponds to the double-slit SQUID [2, 3] with two non-equivalent weak links. Parallel magnetic field induces a phase shift between the opposite WTe_2 surfaces, so it controls the magnetic flux through the effective SQUID area. The latter can be estimated ($S\Delta B \sim \Phi_0 = \pi\hbar c/e$) from $\Delta B = 2$ mT as $S \approx 10^{-8}\,\text{cm}^2$, which gives $0.3\,\mu$m sample thickness for our $5\,\mu$m long junctions. This estimation is in good correspondence with the known WTe_2 crystal thickness and ξ values.

If the magnetic field is perpendicular to the WTe_2 crystal plane, there is no phase shift between the the opposite sample surfaces. Instead, $I_c(B)$ reflects homogeneous supercurrent distribution within the surface state in two equivalent SNS junctions.

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1. As a recent review see: N. P. Armitage, E. J. Mele, and Ashvin Vishwanath, Rev. Mod. Phys. **90**, 15001 (2018).
2. S. Hart, H. Ren, T. Wagner, P. Leubner, M. Mhlbauer, C. Brne, H. Buhmann, L. W. Molenkamp, and A. Yacoby, Nature Phys. **10**, 638 (2014).
3. V. S. Pribiag, A. J. A. Beukman, F. Qu, M. C. Cassidy, C. Charpentier, W. Wegscheider, and L. P. Kouwenhoven, Nature Nanotech **10**, 593 (2015).