Realization of a double-slit SQUID geometry by Fermi arc surface states in a WTe$_2$ Weyl semimetal.

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We experimentally study electron transport between two superconducting indium leads, coupled to the WTe$_2$ crystal surface. WTe$_2$ is characterized by presence of Fermi arc surface states, as a predicted type-II Weyl semimetal candidate. We demonstrate Josephson current in unprecedentedly long 5 $\mu$m In-WTe$_2$-In junctions, which is confirmed by $I-V$ curves evolution with temperature and magnetic field. The Josephson current is mostly carried by the topological surface states, which we demonstrate in a double-slit SQUID geometry, realized by coupling the opposite WTe$_2$ crystal surfaces.

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I. INTRODUCTION

Recent renewal of interest to semimetals is mostly connected with topological effects. Weyl semimetals are conductors whose low-energy bulk excitations are Weyl fermions. Like other topological materials, Weyl semimetals are characterized by topologically protected metallic surface states, which are known as Fermi arc surface states. This concept of the Fermi arc states has now been extended to type II materials, like MoTe$_2$ and WTe$_2$, which contain electron and hole pockets. The non-trivial properties of these materials have been demonstrated in magnetotransport experiments.

Topological materials exhibit non-trivial physics in proximity with a superconductor. For the topological insulators, it is expected to allow topological superconductivity regime, which stimulates a search for Majorana fermions. In the case of Weyl semimetals, the proximity is predicted to produce specular Andreev reflection, or even to superconducting correlations within a semimetal. Moreover, topological transport is responsible for Josephson current in 1-2 $\mu$m long superconductor-normal-superconductor (SNS) junctions in graphene.

The edge current contribution can be retrieved even for systems with conducting bulk by analyzing Josephson current suppression in low magnetic fields. The maximum supercurrent is periodically modulated, with period which is defined by the magnetic flux quantum $\Phi_0 = \pi \hbar c/e$. 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, which is a fingerprint of a superconducting quantum interference device (SQUID). It is therefore reasonable to study Josephson current suppression in a long SNS junction on a three-dimensional Weyl semimetal surface.

Here, we experimentally study electron transport between two superconducting indium leads, coupled to the WTe$_2$ crystal surface. WTe$_2$ is characterized by presence of Fermi arc surface states, as a predicted type-II Weyl semimetal candidate. We demonstrate Josephson current in unprecedentedly long 5 $\mu$m In-WTe$_2$-In junctions, which is confirmed by $I-V$ curves evolution with temperature and magnetic field. The Josephson current is mostly carried by the topological surface states, which we demonstrate in a double-slit SQUID geometry, realized by coupling the opposite WTe$_2$ crystal surfaces.

II. SAMPLES AND TECHNIQUE

WTe$_2$ compound was synthesized from elements by reaction of metal with tellurium vapor in the sealed silica ampule. The WTe$_2$ crystals were grown by the two-stage iodine transport, that previously was successfully applied for growth of other metal chalcogenides like NbS$_2$ and CrNb$_3$S$_6$. The WTe$_2$ composition is verified by energy-dispersive X-ray spectroscopy. The X-ray diffraction (Oxford diffraction Gemini-A, MoK$\alpha$) confirms $Pmn2_1$ orthorhombic single crystal WTe$_2$ with lattice parameters $a = 3.48750(10)$ Å, $b = 6.2672(2)$ Å, and $c = 14.0629(6)$ Å. We check by standard magnetoresistance measurements that our WTe$_2$ crystals demonstrate large, non-saturating positive magnetoresistance up to 14 T field, as it has been shown for WTe$_2$ Weyl semimetal.

A sample sketch is presented in Fig. 1. Superconducting leads are formed by lift-off technique after thermal evaporation of 100 nm indium on the insulating SiO$_2$ substrate. A WTe$_2$ single crystal (≈ 0.5mm $\times$ 100$\mu$m $\times$ 0.5$\mu$m dimensions) is weakly pressed to the indium leads pattern, so that planar In-WTe$_2$ junctions (10 $\times$ (≈ 5)$\mu$m$^2$) are formed at the bottom surface of the crystal WTe$_2$ in Fig. 1.

Charge transport is investigated between two superconducting indium leads in a four-point technique. An example of electrical connections is presented in Fig. 1: 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. In this connection scheme, all the wire resistances are excluded, which is necessary for low-impedance In-WTe$_2$-In junctions (below 0.5 Ohm normal resistance in the present experiment). The measurements are performed in standard He$^4$ cryostat in the temperature range 1.4 K – 4.2 K. The indium leads are superconducting below the critical temperature $T_c$ $\approx$ 3.4 K.

III. EXPERIMENTAL RESULTS

To obtain $I-V$ characteristics, we sweep the dc current $I$ and measure the voltage drop $V$. Fig. 2 presents $I-V$ examples in two different experimental configurations.

In zero magnetic field, at low temperature $1.4 \text{ K} < T_c$, transport between two 5 $\mu$m spaced contacts S1 and S2 is of clear Josephson-like behavior, as shown by the blue curve in Fig. 2 (i) by the four-point connection scheme we directly demonstrate zero resistance region at low currents; (ii) the non-zero resistance appears as sharp jumps at current values $\pm I_c$ $\approx$ 4 mA. The jump positions are subjected to small hysteresis with the sweep direction, so they are slightly different for two $I-V$ branches in Fig. 2. Because of similar preparation technique, different samples demonstrate even quantitatively similar behavior: the obtained $I_c$ values differ within 10% of magnitude for different samples and in different coolings. In contrast, the resistance is always finite between 80 $\mu$m separated S1 and S3 indium leads, see the red curve in Fig. 2.

Even for the closely-spaced contacts S1 and S2, $I-V$ curve can be switched to standard Ohmic behavior, if the indium superconductivity is suppressed by temperature or high current (above $\approx$ 30 mA for the present dimensions), as depicted in the left inset to Fig. 2. The zero-resistance state can also be suppressed by magnetic field, as it is demonstrated in the right inset to Fig. 2.

Thus, we demonstrate in Fig. 2 that two superconducting contacts induce Josephson current in an unprecedentedly long 5 $\mu$m $>> \xi_{Tn}$ In-WTe$_2$-In junction, where $\xi_{Tn}$ $\approx$ 300 nm is the indium correlation length.

As usual for SNS junctions, an important information can be obtained from the maximum supercurrent $I_c$ suppression by temperature and magnetic field. To analyze $I_c(B,T)$ behavior, we use $dV/dI$($I$) characteristics like ones presented in the right inset to Fig. 2. The dc current is additionally modulated by a low ac component (100 nA, 10 kHz), an ac part of $V$ ($\sim dV/dI$) is detected by a lock-in amplifier. We have checked, that the lock-in signal is independent of the modulation frequency in the 6 kHz – 30 kHz range, which is defined by applied ac filters. To obtain $I_c$ values with high accuracy for given ($B,T$) values, we sweep current $I$ ten times from zero (superconducting state) to above $I_c$ (resistive state), and then determine $I_c$ as the average value of $dV/dI$ jump.
The observed oscillations within 5% of $I_c(B=0)$ 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 orientations, 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.

The results are presented in Fig. 3(b), $I_c(B)$ 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 orientations, 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.

The experimental $I_c(T)$ decay has been reported in long 1.5-2 μm>> $\xi_\text{In}$ SNS junctions on graphene, and has been connected with topological transport. WTe$_2$ is regarded as type-II Weyl semimetal, which contains topological Fermi arc surface states. These surface states are usually decoupled from the bulk. On the other hand, Weyl surface states inherit the chiral property of the Chern insulator edge states. Because of topological protection, they can efficiently transfer the Josephson current. This might be a reason to have slow $I_c(T)$ dependence in our nominally long >> $\xi_\text{In}$ ≈ 300 nm devices.

We should connect $I_c(B)$ behavior with the distribution of the Josephson current within the WTe$_2$ crystal, see Fig. 4. The sample thickness is comparable with indium coherence length ∼$\xi_\text{In}$ ≈ 300 nm, so the regions of proximity-induced superconductivity couples two opposite sample surfaces near the In leads (blue regions in Fig. 4). 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 is regarded.

The experimental $I_c(B)$ suppression pattern well corresponds to the double-slit SQUID 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, see Fig. 4. The latter can be estimated from $\Delta B = 2$ mT as $S \approx 10^{-8}$cm$^2$, which gives 0.3μm sample thickness for our 5 μm long junctions. This estimation is in good correspondence with the known WTe$_2$ crystal thickness.

If the magnetic field is perpendicular to the WTe$_2$ crys-
tal 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. Thus, we observe strong $I_c(B)$ suppression in Fig. 2(b) with oscillations in low fields, which reflects the effective junction area $S$. The experimentally observed period $\Delta B = 0.1 \text{ mT}$ in the inset to Fig. 2(b) corresponds to $S \approx 2 \times 10^{-7} \text{cm}^2$, i.e. to the $\approx 5 \text{ m}\times 5 \text{ m}$ SNS junctions, which well correspond to the sample dimensions.

V. CONCLUSION

As a conclusion, we experimentally study electron transport between two superconducting indium leads, coupled to the WTe$_2$ crystal surface. WTe$_2$ is characterized by presence of Fermi arc surface states, as a predicted type-II Weyl semimetal candidate. We demonstrate Josephson current in unprecedentedly long 5 $\mu$m In-WTe$_2$-In junctions, which is confirmed by $I-V$ curves evolution with temperature and magnetic field. The Josephson current is mostly carried by the topological surface states, which we demonstrate in a double-slit SQUID geometry, realized by coupling the opposite WTe$_2$ crystal surfaces.

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