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Reentrant proximity-induced superconductivity for GeTe semimetal

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While Weyl semimetals (WSM) with broken time-reversal symmetry are magnetically ordered materials [1], WSMs with broken inversion symmetry have to obtain bulk ferroelectric polarization [1]. Due to the gapless bulk spectrum, a non-centrosymmetric Weyl semimetal is the natural representation of the novel concept of intrinsic polar metal. Among these materials, GeTe is of special interest due to the reported giant Rashba band splitting. Direct correlation between ferroelectricity and spin textures was demonstrated in this material [2]. Ferroelectric Rashba semiconductor GeTe is predicted to be topological semimetal in low-temperature (below 700 K) ferroelectric α-phase [3].

In superconductor structures, field-induced reentrant effects are usually associated here with the influence of the external magnetic field on the spin subsystem. Thus, it it reasonable to study also proximity-induced superconductivity in α-GeTe.

In our experiment, GeTe single crystal flakes are obtained by mechanical exfoliation from the initial ingot. The chosen flake is placed immediately on the standard Si/SiO_2 substrate with pre-defined $2\,\mu$m wide In contact leads. The measurements below are performed within the 30 mK – 1.2 K temperature range in a dilution refrigerator equipped with a superconducting solenoid.

$dV/dI(V)$ differential resistance curves show well-developed Andreev behavior for single In-GeTe junctions. Since Andreev reflection allows subgap transport of Cooper pairs, it appears experimentally as the resistance drop for voltages within the superconducting gap. In our experiment, this bias interval is about $\pm\,0.25$ mV, which is approximately twice smaller than the known 0.5 mV bulk indium gap. The gap suppression can be expected for the indium film on a top of a GeTe crystal with giant Rashba splitting, which is characterized by strong spin polarization of the surface [2].

As usual, Andreev reflection can be suppressed by expernal magnetic field. The detailed picture of the gap suppression is quite complicated, see the colormaps in Fig. 1a and b for two magnetic field orientations. While the zero-bias anomaly is suppressed monotonically (black color, about $1\,\Omega$ level), the gap (the blue regions) is sharply increased above some magnetic field value, which is about 0.05 T for normal field and 0.15 T for the in-plane one, see the $\approx$10 Ω level in Fig. 1a and b. Thus, the suppression pattern is of butterfly shape, demonstrating non-monotonic behavior of the proximized superconductivity on the surface of GeTe single crystal.

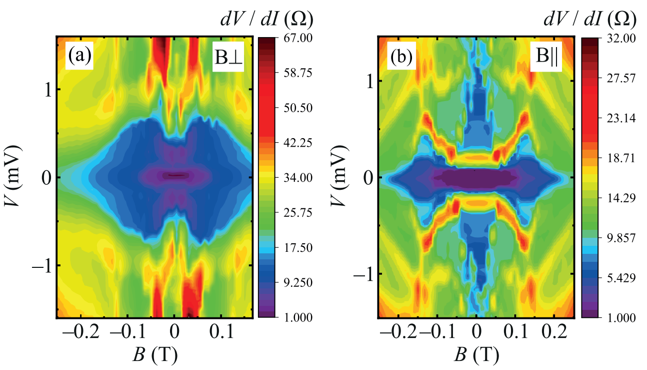

Fig. 1. (Color online) The detailed colormaps of the gap suppression for two, in-plane (a) and normal (b), magnetic field orientations, respectively. The suppression pattern is of butterfly shape, demonstrating non-monotonic behavior of the proximized superconductivity on the surface of GeTe single crystal. The superconducting gap is partially suppressed in zero magnetic field, while it is increased nearly to the bulk value for some finite field (0.05 T for normal field and 0.15 T for the in-plane one) before its full suppression. The data are obtained at 30 mK temperature

Experimental curves also demonstrate reentrant behavior of the Josephson current in magnetic field for double In-GeTe-In junctions: when sweeping from the superconducting (zero-resistance) state, it is suppressed at some magnetic field value, while reappears at higher fields. The reentrant effect is also shown by the colormap. The zero-resistance state forms two distinct areas, which are separated by the finite resistance region,

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in good correspondence to the scan at zero bias. Qualitatively similar reentrant behavior of the Josephson current can be observed for different samples.

As a result, we have detected nonmonotonic effects of the applied external magnetic field in In-GeTe proximity devices, including reentrant superconductivity in In-GeTe-In Josephson junctions. In the latter case, supercurrent reappears at some finite magnetic field. For the Andreev reflection, the superconducting gap is partially suppressed in zero magnetic field, while it is increased nearly to the bulk value for some finite field before its full suppression in Fig. 1.

Since indium is a conventional s-wave superconductor, the observed effects should be mostly associated with specific properties of the proximized noncentrosymmeric (ferroelectric) topological semimetal α-GeTe [3].

There are several characteristic features of α-GeTe, which seems to be important in In-GeTe proximity devices. First of all, topological surface states with nontrivial spin textures [2] can play an important role. In addition, there are nontrivial spin textures with nonzero spin winding numbers in the bulk of α-GeTe, which are associated with the type-II Weyl fermions around the triple points of the electronic band structure. Also, the pronounced spin-orbit splitting can influence on the proximity-induced odd-frequency triplet component of the superconductor order parameter and on the charge transport as a whole.

Thus, it seems to be quite natural to model In-GeTe heterostructures as SFN junctions with some definite magnetization and strong spin-orbit coupling. Inhomogeneous spin directions, that are possibly incorporated in the textures, could complicate the model, reduce its anisotropic properties and contribute to the field-induced nonmonotonic behavior [4–6]. The external magnetic field could modify the spin configuration, which firstly increases the superconducting gap to nearly the bulk 0.5 meV value, and suppresses it to zero in higher fields, see Fig. 1. For the Josephson effect, supercurrent flows along the GeTe surface between the In leads in the planar experimental geometry. Together with the gap value, the initial spin polarization of surface states partially suppresses the critical current, which is recovered due to the modified spin-split surface states in finite field before the full Josephson effect suppression. Thus, we attribute the order parameter depletion (or healing) to the consequence of the inverse proximity effect in superconductor-ferromagnet structures.

However, more detailed theoretical studies are required for an unambiguous interpretation of the experimental results. For example, nonmonotonic field dependence of the critical temperature occurs after the transition into the Fulde–Ferrell–Larkin–Ovchinnikov (FFLO) state in hybrid layered SFN heterostructures. Although the FFLO scenario can generally result in the reentrant behavior and looks potentially promising, the role of the strong spin-orbit coupling has not been analyzed in these effects yet, which is crucial for GeTe topological semimetal.

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