Surface superconductivity in a three-dimensional Cd$_3$As$_2$ semimetal at the interface with gold contact

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We experimentally investigate charge transport through a single planar junction between Cd$_3$As$_2$ Dirac semimetal and a normal Au lead. For non-superconducting bulk Cd$_3$As$_2$ samples, we observe non-Ohmic $dV/dI(V)$ curves, which strongly resemble standard Andreev reflection with well-defined superconducting gap. Andreev-like behavior is demonstrated for Cd$_3$As$_2$ samples with different surface and contact preparation techniques. We connect this behavior with surface superconductivity due to the flat-band formation in Cd$_3$As$_2$, which has been predicted theoretically. The conclusion on superconductivity is also supported by the gap suppression by magnetic fields or temperature.

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I. INTRODUCTION

Cd$_3$As$_2$ is predicted to be a three-dimensional Dirac semimetal, so it has symmetry-protected conic dispersion in the bulk spectrum, which has been experimentally confirmed by angle-resolved photoemission spectroscopy (ARPES) and scanning tunneling microscopy measurements. Due to the Dirac spectrum, Cd$_3$As$_2$ demonstrates interesting physical properties, e.g. unusual magnetoresistance phenomena, associated with chiral anomaly, and ultrahigh carrier mobility. Some features of exotic surface transport have been demonstrated by observation of quantum oscillations.

By breaking certain symmetries, Cd$_3$As$_2$ can be driven to different topological phases, such as topological insulator, Weyl semimetal, or even topological superconductor. The latter is notably attractive due to the surface states hosting Majorana fermions.

There are two ways to induce superconductivity in bulk Cd$_3$As$_2$: by carrier doping, which is only a theoretical prediction so far, or by external pressure. In the latter case bulk superconductivity appears around 3.5 GPa. In addition, point contact spectroscopy experiments reveal signatures of superconductivity in a tip contact region (so-called tip induced superconductivity), while no effect is observed in the case of a soft contact. The origin of the effect is still debatable, e.g., it is not clear, whether pressure of a tip is enough to induce superconductivity in Cd$_3$As$_2$.

On the other hand, flat-band formation stimulates surface superconductivity. In the presence of attractive interaction due to electron-phonon coupling, the high density of states associated with these flat bands dramatically increases the superconducting transition temperature. This property is generic and does not depend much on the details of the system. In particular, superconductivity has been observed in twisted bilayer graphene.

Flat bands may emerge due to interaction or topological effects. Historically flat bands were first discussed in the context of Landau levels. Now, they are considered as a class of fermionic systems with a dispersionless spectrum that has exactly zero energy, i.e. with diverging density of states. Interaction effects could be expected for high-mobility carriers in Cd$_3$As$_2$. The simplest example of topological flat-band formation is known for nodal-line semimetals. On the boundary of each topological insulator inside the nodal loop there should be the zero energy state. But this occurs for all the insulators inside the loop, so all these zero energy states on the surface form the 2D flat band. The topological flat-band formation is not also impossible for Cd$_3$As$_2$ material, since it is known to experience transition to different topological phases. It is important that if surface superconductivity appears in Cd$_3$As$_2$ Dirac semimetal due to fundamental effects, it should be independent on the contact preparation technique.

Here, we experimentally investigate charge transport through a single planar junction between Cd$_3$As$_2$ Dirac semimetal and a normal Au lead. For non-superconducting bulk Cd$_3$As$_2$ samples we observe non-Ohmic $dV/dI(V)$ curves, which strongly resemble standard Andreev reflection with well-defined superconducting gap. Andreev-like behavior is demonstrated for Cd$_3$As$_2$ samples with different surface and contact preparation techniques. We connect this behavior with surface superconductivity due to the flat-band formation in Cd$_3$As$_2$, which has been predicted theoretically. The conclusion on superconductivity is also supported by the gap suppression by magnetic field or temperature.

II. SAMPLES AND TECHNIQUE

Cd$_3$As$_2$ crystals were grown by crystallization of molten drops in the convective counterflow of argon held at 5 MPa pressure. For the source of drops the stalgmometer similar to one described was applied. The
crystals sometimes had signs of partial habit of α-Cd₃As₂ tetragonal structure. About one fifth of the drops were single crystals, like ones depicted in Fig. 1 (a). The EDX measurements and X-ray powder diffractograms always confirmed pure Cd₃As₂.

Fig. 1 (b) shows a top-view image of a sample. The leads pattern is formed by lift-off technique after thermal evaporation of 100 nm Au on the insulating SiO₂ substrate. The 10 µm wide Au leads are separated by 5 µm intervals, see Fig. 1 (b).

Small (less than 100 µm size) Cd₃As₂ single crystals are obtained by a mechanical cleaving method, somewhat similar to described in Ref. 39 we crush the initial 5 mm size Cd₃As₂ single crystal onto small fragments. This procedure allows to create a clean Cd₃As₂ surface without mechanical polishing or chemical treatment.

Then, the obtained small Cd₃As₂ crystal is transferred to the Au leads pattern and pressed slightly with another oxidized silicon substrate. A special metallic frame allows to keep substrates parallel and apply a weak pressure to the piece. No external pressure is needed for a Cd₃As₂ crystal to hold on a substrate with Au leads afterward.

For comparison, we also defined 100 µm × 100 µm Au contacts by standard photolithography on the cleaved along (112) and mechanically polished surface of the initial Cd₃As₂ drop. In this case, Cd₃As₂ surface degradation could be expected due to the polishing process.⁵⁰

We check by standard magnetoresistance measurements that our Cd₃As₂ samples demonstrate large magnetoresistance with Shubnikov de Haas oscillations in high magnetic fields, see Fig. 2, indicating high quality of Cd₃As₂. From the oscillations’ period in the inverse magnetic field, see the inset, and zero-field resistance value we estimate the concentration of carriers as \( n \approx 2.3 \times 10^{18} \text{ cm}^{-3} \) and low-temperature mobility as \( \mu \approx 10^6 \text{ cm}^2/\text{Vs}, \) which is in the good correspondence with known values.

We study electron transport across a single Au-Cd₃As₂ junction in a standard three-point technique, see Fig. 1 (a): one Au contact is grounded and two other contacts are used for applying current and measuring potential. Charge transport is investigated with a standard three-point technique: the studied contact (C3) is grounded and two other leads with \( \approx 5 \mu \text{m} \) overlap, forming planar junctions.

The measurements are performed in a dilution refrigerator equipped with superconducting solenoid.

III. EXPERIMENTAL RESULTS

Examples of \( dV/dI(V) \) characteristics are shown in Fig. 3 for different Au-Cd₃As₂ junctions. Since the \( dV/dI(V) \) curves of the junctions might be sensitive to the interface quality, e.g. as it is known for normal-superconductor junctions, Fig. 3 (a) and (c) demonstrate maximum device-to-device fluctuations for samples with cleaved Cd₃As₂ fragments, while Fig. 3 (d) shows \( dV/dI(V) \) curve variation for large junctions on polished Cd₃As₂ surface.

The main experimental finding is the prominent non-Ohmic behavior, which is reflected in about 10% resistance dip around zero bias. This behavior is well-reproducible for different samples, see Fig. 3 while the shape and the width of the dip may vary from sample to sample, the qualitative behavior is the same.
The bulk Cd$_3$As$_2$ material is not superconducting\textsuperscript{22}, which is confirmed by finite four-point resistance in Fig. 2. Since an Au lead is also normal, the Andreev-like behavior of experimental $dV/dI(V)$ curves should reflects surface superconductivity at Au-Cd$_3$As$_2$ interface.

IV. DISCUSSION

As a result, we observe $dV/dI(V)$ curves, which are qualitatively analogous to tip induced superconductivity\textsuperscript{22,23}, for wide planar contacts without external pressure.

Formally, standard BTK-theory\textsuperscript{24} is appropriate in the ballistic limit, when the contact diameter is less than elastic and inelastic mean free paths. In the opposite (thermal) limit, peaks in $dV/dI$ reflect superconducting transition due to the critical current in the junction.

The ballistic regime is obviously realized for the clean Cd$_3$As$_2$ surface, as we see in Fig. 3(a) and (b), since the mean free path exceeds 25 µm at given concentration and mobility. In this case, in contrast to the tip experiments, the width of the dip is defined by the superconducting gap for the best junctions, like in Fig. 3(a), as it is expected\textsuperscript{24,25} for standard Andreev reflection\textsuperscript{44,45}. This conclusion is supported by qualitative behavior of $\Delta(T)$ and $\Delta(B)$ dependencies in Fig. 4(b) and in the inset to Fig. 5. Also, the depth $\Delta R$ of the resistance dip is nearly constant at low temperatures, see Fig. 3(c), which is consistent with the BTK dependence\textsuperscript{24} for the transparent interface. We wish to emphasize here, that the...
actual gap value is smaller than the width of the dip in Figs. 1-4 because the $dV/dI(V)$ curves in Fig. 3 (a-b) still contain an unknown bulk contribution. The actual gap value should be obtained from the $\Delta(T)$ dependence.

The thermal limit is obviously realized for the polished Cd$_3$As$_2$ surface with large contacts in Fig. 2 (d), so the differential resistance is driven by current, which achieves the critical value $I_c$ at low (about 1 $\mu$V) imbalances at the interface. We wish to mention, that for narrow superconductors between two massive normal metals, electron cotunneling and crossed Andreev reflection should be taken into account. Both these effects are extremely sensitive to the transmission of the interfaces, see Fig. 12 in Ref. 24, which should be responsible for the device-to-device fluctuations in Fig. 3 (a) and (c).

The interface superconductivity has been demonstrated in a number of various systems, with different discussed microscopic mechanisms. In our experiment, superconductivity should originate from fundamental effects in topological Dirac semimetal, since it is independent of contact preparation details. The obvious candidate is the flat-band formation due to interaction or topology. For our samples with the bulk carrier density $n \approx 2.3 \times 10^{18}$ cm$^{-3}$ and the corresponding effective mass 0.044, the interaction parameter $r$ is about 1. Even if this value is enhanced for low densities near the sample surface, it seems to be too small to produce noticeable interaction effects. On the other hand, Cd$_3$As$_2$ Dirac semimetal is known to experience transition to different topological phases, so one could propose topological mechanism, similar to surface states in nodal-line semimetal. The possibility of such transitions is also supported by recent theoretical predictions for different semimetal systems. For Cd$_3$As$_2$ Dirac semimetal, flat bands are evidenced in ARPES and magneto-optics experiments.

Another possibility is the strain effects. In Dirac semimetals strain generically acts as an effective gauge field on Dirac fermions and creates pseudo-Landau orbitals without breaking time-reversal symmetry. The zero-energy Landau orbitals form a flat band in the vicinity of the Dirac point, so the high density of states of this flat band gives rise to interface superconductivity. We observe finite four-point resistance between different contacts in Fig. 2 which well correspond to the fact, that strain-induced flat-band formation is only occurs at Au-Cd$_3$As$_2$ interface due to materials misfit.

V. CONCLUSION

As a conclusion, we experimentally investigate charge transport through a single planar junction between Cd$_3$As$_2$ Dirac semimetal and a normal Au lead. For non-superconducting bulk Cd$_3$As$_2$ samples, we observe
non-Ohmic $dV/dI(V)$ curves, which strongly resemble standard Andreev reflection with well-defined superconducting gap. Andreev-like behavior is demonstrated for CdAs$_2$ samples with different surface and contact preparation techniques. We connect this behavior with surface superconductivity due to the flat-band formation in CdAs$_2$, which has been predicted theoretically. The conclusion on superconductivity is also supported by the gap suppression by magnetic fields or temperature.

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