Dominant \textit{s}-wave superconducting gap in PdTe$_2$ observed by tunneling spectroscopy on side junctions

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We have fabricated superconductor-normal metal side junctions with different barrier transparencies out of PdTe$_2$ crystalline flakes and measured the differential conductance spectra. Modeling our measurements using a modified Blonder, Tinkham, and Klapwijk (BTK) formalism confirms that the superconductivity is mostly comprised of the conventional \textit{s}-wave symmetry. We have found that for junctions with very low barrier transparencies, the junctions can enter a thermal regime, where the critical current becomes important. Adding this to the BTK model allows us to accurately fit the experimental data, from which we conclude that the superconductivity in the \textit{a-b} plane of PdTe$_2$ is dominated by conventional \textit{s}-wave pairing.

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I. INTRODUCTION

The search for the elusive Majorana particle has brought physicists to the area of topological superconductivity. The mixture of Dirac physics and superconductivity (SC) is seen as a promising way of creating Majorana quasiparticles [1], which in turn opens up the possibility of quantum computing through a process called braiding [2]. Experimental research has focused on the interface effects of superconductors coupled to either semiconductors with strong spin-orbit coupling [3,4] or topological matter [5–8]. Topological superconductors, for example Cu$_x$Bi$_2$Se$_3$, are also studied in the context of Majorana physics [9,10]. The transition-metal dichalcogenide PdTe$_2$ belongs to the $P3\bar{3}m1$ space group and is known to be a superconductor [11–13]. Recent experiments have shown that this material is also topological as it possesses a type-II Dirac cone [14–16], highlighting it as an extraordinary material, that could host unconventional superconductivity intrinsically [17]. Notably, Teknowijoyo \textit{et al.} have narrowed the possible order parameter (OP) symmetries down to three candidates: $A_{1g}$ (conventional \textit{s}-wave) pairing, $A_{1u}$ (helical \textit{p}-wave) pairing, or $E_{g(1,0)}$ (nematic \textit{p} + \textit{f}-wave) pairing, by showing that the order parameter of PdTe$_2$ is nodeless [18]. The latter two pairings are nontrivial. Experiments investigating the nature of the superconductivity in PdTe$_2$ have so far found no indication of unconventional superconductivity [12].

In this paper we present tunneling spectroscopy measurements performed on PdTe$_2$–normal metal side junctions, to shed light on the in-plane properties of the superconducting order parameter. All patterning for these steps was done using standard electron-beam lithography. The devices differ in their interfaces between the PdTe$_2$ and the normal metal. The first type of device was made without a specific barrier and is a 500-nm-wide SN interface between PdTe$_2$ and gold, with a normal metal layer of palladium was sputter deposited on the aluminum oxide without breaking the vacuum. The second type of device was made by transferring the argon milled flakes to a sputter machine where they were cleaned of contaminations by low rf power plasma etching. On the cleaned surface, 1 nm of Al was sputter deposited, followed by oxidization in 10 mbar of oxygen for 1 h to form an Al$_2$O$_3$ oxide barrier. To finalize the devices, a normal metal layer of palladium was sputter deposited on the aluminum oxide without breaking the vacuum. The $R_N$ was about 200 $\Omega$ at 15 mK. The third type of devices only one was fabricated. This device was transferred to an atomic layer deposition apparatus after argon milling, where a 1.2-nm-thick Al$_2$O$_3$ layer was grown.
at 100 °C, followed by ex situ deposition of 40 nm of gold by sputter deposition. These SIN junctions have an $R_N$ of about 2 kΩ at 15 mK. Although many junctions were made, one SIN junction had this resistance value at base temperature, whereas the other showed $R > 1$ Ω. Several of our similarly fabricated SIS junctions did show an $R_N$ of 2 kΩ at 15 mK, but are not included in this work on SIN junctions. For each of the three S(1)N types, measurements on one representative device are presented in this work.

III. RESULTS AND ANALYSIS

We drive a dc bias current with a small ac excitation through the junctions while measuring both the dc and ac response across the junction to probe the differential resistance. The measured differential resistance is numerically inverted to differential conductance and plotted against the measured dc bias voltage. The results of these measurements at the lowest temperature reached ($T < 100$ mK) are shown as gray circles in Fig. 1. Comparing the three graphs we see a clear evolution of the main feature around zero bias. In Fig. 1(a) we see a dented plateau around zero bias, accompanied by sharp dips in conductance at ±0.5 mV. Figure 1(b) shows a quite different shape. The dented plateau around zero has been replaced by an Andreev-like spectrum with coherence peaks surrounding a clear dip. The final device, whose differential conductance is shown in Fig. 1(c), has the highest normal state resistance. Around zero bias a small zero-bias conductance peak (ZBCP) is visible.

Because our PdTe$_2$ flakes are less than 100 nm thick, which is less than the reported superconducting coherence length [11,18], we have modeled the conductance spectra numerically using a two-dimensional (2D) BTK formalism for different order parameters. In this model, the bands are assumed to be parabolic since the Fermi energy is much larger than the energy where the type-II Dirac points reside [16]. The chemical potential mismatch, $\mu_s/\mu_n$, is set to 1 for simplicity, so that $Z = Hm_s/h^2k_{sc}$, with $H$ the height of the $\delta$-shaped barrier, is the only barrier parameter. Teknowijoyo et al. have experimentally determined the OP in PdTe$_2$ to be nodeless, which, together with crystal symmetry constraints, leaves us with three different pair potentials: $A_{1g}$ (conventional $s$-wave), $A_{1u}$ (helical $p$-wave), and $E_{u(1,0)}$ (nematic $p + f$-wave). The latter two correspond to the $d$ vectors $d_{A_{1g}} = k_x\hat{x} + k_y\hat{y} + k_z\hat{z}$ and $d_{E_{u(1,0)}} = k_x(k_z^2 - 3k_y^2)\hat{x} + k_y\hat{y} + k_z\hat{z}$. Before moving on to fitting our measured conductance spectra, we show the general features of the three OPs in a 2D BTK model, where $k_z = 0$. Figures 2(a)–2(c) show the angle dependence of the superconducting gap magnitude. It is obvious from these plots that all three are nodeless. Note that OPs of the $s$ wave, (a), and $A_{1u}$ pairing, (b), differ in their angle dependence of the phase, rather than gap magnitude. Figures 2(d)–2(f) show the normalized conductance as a function of the angle with respect to the interface normal. Brighter colors indicate a higher conductance in these graphs. Both the $A_{1u}$ and the $E_{u(1,0)}$ pairing exhibit helical edge states within the superconducting gap. The panels labeled (g)–(i) show the calculated conductance spectra for dimensionless barrier strength $Z = 0, 0.5, 1$, and 4. The legend is included in panel (i). These $dI/dV$ spectra are the result of angle averaging over a semicircle directed at the interface. It should be noted that no signs of unconventional superconductivity have been found in differential conductance measurements along the $c$ axis, which rules out three-dimensional isotropic $A_{1u}$ pairing but leaves room for an anisotropic variant [12,14]. The other nodeless pairing symmetry, $E_{u(1,0)}$, consists of components that are linear in $k$ and cubic in $k$, i.e., $p$-wave + $f$-wave symmetry. This can behave like a fully gapped system only when the $k^3$ component is sufficiently strong compared to the linear term. Although the $E_{u(1,0)}$ nematic $p + f$-wave state is unlikely to occur in nature, recent reports on the topological superconductor Cu$_2$Bi$_2$Se$_3$ have found indications of $Eu$ pairing symmetry [25–27].

Comparing our model to the differential conductance curves displayed in Fig. 1, it appears that only conventional $s$-wave pairing cannot adequately explain all our findings. Although the data obtained on the two high-resistance devices...
have helical edge states at zero energy. Note that due to the anisotropy of the
procedure is shown as a red line in Figs. 1(b) and 1(c). Every
conventional
on the other hand, can be fitted well using only the con-
differential conductance of the two most resistive junctions,
the data of Fig. 1(a), i.e., the most transparent junction. The
lower-resistance device are absent in Fig. 2(g), which shows
the resulting differential conductance of the
s-wave
model. The helical
p-wave
symmetry,
does not refer to the typical bulk
current, a voltage suddenly appears across the junction, which
can stabilize unconventional pairing mechanisms \[10,17\].

However, using a combination of conventional s-wave and
helical p-wave pairing, we were unable to accurately model
the data of Fig. 1(a), i.e., the most transparent junction. The
differential conductance of the two most resistive junctions,
on the other hand, can be fitted well using only the
conventional s-wave pairing model. The result of this fitting
procedure is shown as a red line in Figs. 1(b) and 1(c). Every
part, except for the ZBCP in Fig. 1(c) is described by the
BTK model, using a dimensionless barrier strength \(Z \approx 0.7\).
We will leave the ZBCP for now and turn our attention to the
dominant \(s\)-wave superconducting gap in PdTe \(2\) as the
unique spin (or pseudo-spin) structure of a Dirac semimetal
long as it is nodeless \[18\], is not unimaginable in PdTe\(2\) as the

To explain the origin of the sharp dips and dented plateau
of Fig. 1(a) we extend our BTK model by taking into account
the influence of the interfacial critical current on the obtained
d\(I\)/d\(V\) spectra \[20–24,28\]. See Supplemental Material \[29\]
for additional information on the model. The BTK model
assumes ballistic transport through the junction at all bias
voltages, but in the case of very low resistance junctions, the
junction may leave the ballistic regime and enter the thermal
regime: while increasing the bias current through these
transparent junctions we reach the critical current
\(I_c\), an effect
that comes on top of the BTK model. This critical current
does not refer to the typical bulk \(I_c\) of a superconductor, but
rather to a reduced critical current in the disordered surface
of the PdTe\(2\) close to the interface. Upon reaching this critical
current, a voltage suddenly appears across the junction, which
is represented as a step in the IV characteristic. Taking the
derivative of this will yield sharp dips in d\(I\)/d\(V\) at the critical
current. The red line in Fig. 1(a) shows the striking agreement
of an s-wave BTK model with our data, when the effect of
\(I_c\) is taken into account. The BTK parameters, as well as \(I_c\),
are reported inside the graph. \(F\) describes the mixing of the

FIG. 2. The BTK model for conventional \(s\)-wave symmetry, \(A_{1u}\), and \(E_{u(1,0)}\) pairing. (a)–(c) show the angle dependence of the gap, \(\Delta\),
indicating the shape of the OP and the fact that it is nodeless. (d)–(f) show the angle-dependent conductance at different energies calculated for
barrier strength \(Z = 4\). The colorscale reflects the conductance, where brighter colors indicate higher conductance. Both \(A_{1u}\) (e) and \(E_{u(1,0)}\) (f)
have helical edge states at zero energy. Note that due to the anisotropy of the \(E_{u(1,0)}\) pair potential, some of the states with large \(k\) components
on the normal metal side have no superconducting equivalent at the same energy and result in zero conductivity. (g)–(i) are the conductance
spectra obtained for different dimensionless barrier strengths, \(Z\), in the BTK model. They are the result of averaging the conductance over
angles between \(-90^\circ\) and \(+90^\circ\). The legend in (i) shows which line represents which \(Z\) and is valid for (g) and (h) as well.
FIG. 3. Additional measurements and analysis on the highest resistance sample. (a) $dI/dV$ of the 2.16 kΩ sample for different temperatures measured over a large range of bias voltage. For clarity, all the curves except for the 15 mK curve have been given a constant offset. (b) $s$-wave BTK fits (colored lines) to the measured $dI/dV$ of the 2.16 kΩ junction (gray circles) at different temperatures. Again, all the curves except for the 15 mK curve have been given a constant offset. The temperature and fitted gap $\Delta$ are indicated next to the line. $Z$ and $\Gamma$ are shared across the curves and are indicated in the top-right corner of the graph. (c) The superconducting gap from the BTK fits as a function of temperature (black circles) and the position of the shallow dip versus temperature (red circles). Dashed lines show the standard temperature dependence from BCS theory for a $T_c$ of 1.7 K. (d) The height of the ZBCP as a function of temperature.

$I_c$ model and the BTK model through a linear combination, where $F = 0$ means purely BTK model and $F = 1$ is purely the $I_c$ model. We stress that this fitting is performed using only conventional $s$-wave pairing, like in Fig. 1(c). The device with the largest barrier is apparently in the ballistic regime for all applied currents, whereas this does not hold for the most transparent device. The $dI/dV$ features, occasionally ascribed to unconventional superconductivity, arise in our case from high transparency of the junction in combination with a disordered interface. This high transparency can be due to the design of the device, or an accidental feature, such as a pinhole or otherwise broken barrier. For an example of how such a $dI/dV$ spectrum can easily be misinterpreted as originating from $p$-wave superconductivity see the Supplemental Material [29].

So far we have found that the main features of all three measured devices can be understood with the same OP symmetry, even though their differential conductance spectra differ greatly. The high-resistance device is our best candidate for a more extensive conductance spectroscopy study, as it exhibits ballistic transport for up to 8 mV. We have measured the $dI/dV$ spectrum of this device at different temperatures and for a much larger range of bias currents. The experimental data is presented in Fig. 3(a). Figure 3(b) serves as a zoomed-in version of this graph around zero bias and shows, as solid lines, the curves obtained from a conventional $s$-wave BTK model. The theoretically obtained curves describe the data very well. A shallow dip feature presents itself in Fig. 3(a) at bias voltages greater than 5 mV, far beyond the superconducting gap (~300 $\mu$V). The dip differs from the dips earlier attributed to the critical current. Such dips are quite sharp, since they relate to an instant increase in voltage, whereas this feature is shallow and stretched wide in voltage. Furthermore, we have plotted the position of this dip as a function of temperature in red circles in Fig. 3(c). They are accompanied by the superconducting gap $\Delta$ as extracted from the BTK fit on the low-bias part of this dataset. Both temperature dependences can be described using standard BCS theory. The two dashed lines show this standard BCS behavior, scaled to the voltage value at the lowest temperature.

Over the past decades there have been numerous experiments in which dips such as presented in Fig. 3(a) have been observed [30–32]. A possible origin of this dip is that weak spots in the barrier are responsible for the crossover into the thermal regime at larger currents, similar to our $I_c$ model [31,32].

The final feature we discuss is the aforementioned ZBCP. This peak can clearly be distinguished in the low-bias region of the low-transparency device at sufficiently low temperatures. We have subtracted the BTK fits shown in Fig. 3(b) from the respective data and tracked the height of this peak as a function of temperature. The extracted peak heights are shown in Fig. 3(d). We see that the temperature dependence of the ZBCP is linear and the temperature at which the peak appears is much lower than the reported critical temperature of PdTe$_2$. At these temperatures the thermal energy, $k_BT$, is smaller than the width of the ZBCP, which hints that we are probing a different characteristic energy scale here. Recent studies of the superconductivity of PdTe$_2$ have confirmed the existence of multiple superconducting channels, related to parallel bulk and surface superconductivity [11]. Because only one device of the third type was fabricated, it is unclear whether the ZBCP arises from intrinsic superconducting properties, or from interface effects inside this specific device.

IV. CONCLUSION

In short, we have fabricated three PdTe$_2$/normal metal side junctions with different transparencies. The shape of the conductance spectra heavily depends on the normal state resistance of the junction and can make conventional superconductivity look unconventional. One should exert caution in analyzing the data of low-resistance SN junctions and confirm that the junction is solely in the ballistic limit, or include the effect of the critical current on the $dI/dV$ spectrum in one’s model. Taking these critical current effects into account in the data analysis, the conductance spectroscopy measurements on our devices indicate that the order parameter in PdTe$_2$ is dominated by conventional $s$-wave pairing.

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