Observation of zero-bias conductance peak in topologically-trivial hybrid superconducting interfaces

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Abstract
Proximity effects between s-wave superconducting thin films and high spin–orbit topological materials are widely studied using the differential conductance spectroscopy technique, mainly to investigate the topological property of the induced superconductivity. However, very little is probed about the influence of above proximity effect on the depairing properties of the proximitized superconducting film. Here, we provide a phenomenological simulation tool to characterize the different pair-breaking mechanisms that exist at such interfaces and show how they affect the differential tunneling conductance response in applied magnetic fields. Importantly, we probe the quasiparticle-tunneling conductance at the hybrid interface and observe conductance peak pinning at zero bias in a larger field range with eventual signs of weak peak splitting. Further, the effect of varying the spin–orbit scattering and the Landé g-factor in tuning the conductance peaks show interesting trends, such as observation of zero bias conductance peak even in a topologically-trivial superconducting state.

1. Introduction

The study of proximity induced superconductivity (PIS) at the interface between an s-wave superconductor (SC) and a topological material (TM), such as 3-Dimensional (3D) topological insulators (TI) [1], 2D TI layers [2] or 1D high spin–orbit (SO) semiconducting nanowires [3] is laying a new scientific foundation bed for the exploration of conceptually rich condensed matter phenomena, especially in the quest for topological superconductivity. Here, the PIS is known to lead to three important consequences. Firstly, it induces superconducting correlations in the adjacent layer, with the pair potential dropping across the interface [4]. As shown in figure 1(a), this induced condensate pair potential, $\Delta$, then decay with a characteristic length determined by the strength of decoherence or depairing properties of the induced layer. Experimentally, similar observations at hybrid interfaces involving TMs are confirmed using angle resolved photoemission spectroscopy (ARPES) and point contact spectroscopy [5, 6]. Secondly, in some cases, the microscopic nature of the induced condensate pairs is found to differ from the singlet s-wave pairing observed in the bulk of SC films [7]. Lastly, and the least studied effect, PIS leads to suppression of superconductivity in the SC layer, giving rise to a reduced superconducting gap ($\Delta$) near the interface compared to the bulk of SC ($\Delta_0$). This suppression may be caused by different interface or bulk depairing effects [8–10], such as (i) SO scattering, that preserves time-reversal symmetry (TRS) and contributes to depairing only in presence of applied magnetic field, (ii) orbital depairing and magnetic impurity scattering, that breaks TRS even in zero field. In the case of SC/TM interfaces, there is no systematic study to probe how the above depairing mechanisms arising due to the proximity effect influences the properties of the SC layer in presence of an external Zeeman field. Importantly, one expects a strong influence on the penetration depth, coherence length and order parameter of the SC layer that can have a dramatic effect on the transport measurements.
conductance measurements using tunneling and point contact spectroscopy of different orbital symmetries is widely used to model the quasiparticle density of states and to describe the microscopic origin of the various pair-breaking mechanisms responsible for the stronger suppression of superconductivity. We focus on a device geometry, as shown in Figure 1, with the SC layer thickness smaller than $\xi$. Tunneling conductance of the devices show a conductance peak at $\pm |\Delta|$ associated either to $\Delta$, or $\Delta_r$.

In the PIS study of above SC/TM interfaces, differential tunneling conductance spectroscopy [11–13] is widely used to characterize the superconducting property of the device, mainly to visualize topological superconductivity in the induced TM layer. A topological superconductor is a gapped SC, which possesses non-trivial topological properties in their superconducting wavefunctions [14] and is theoretically proposed to support Majorana states at zero energy (i.e. at the chemical potential $\mu$). Since a change from the topologically trivial state to a non-trivial state cannot be achieved by a simple deformation of its electronic structure, this transition is achieved by initial closure of the trivial induced gap in the TM layer with increasing magnetic field. Experimentsally, a ‘rigid’ zero bias conductance peak (ZBCP) is often reported at higher magnetic fields, associating them to the Majorana modes, that does not get affected over a large range of external stimulus such as applied magnetic field or gate voltage [11, 12]. Such a response is shown to be very different from the other alternate mechanisms of zero energy quasi-particle excitations [12]. Despite these findings, they have left open some interesting questions regarding the device’s conductance response to the above external stimulus. For example, in some studies [12], with the increase in magnetic field, ZBCP is observed before the PIS gap closure and the gap then disappear without any signs of topological gap opening. Instead, the ZBCP is found to weakly split into two peaks before the PIS is completely suppressed [11, 12]. Hence, these experimental observations are not well supported with existing theoretical reports [3], leaving room for alternate mechanisms at play. In this article, we primarily address these issues by simulating the differential tunneling conductance spectroscopy of a proposed device structure shown in Figure 1(b) in presence of the Zeeman field and demonstrate interesting features that are otherwise not observed in conventional SC-normal metal interfaces. Importantly, while probing the properties of the proximitized SC layer (device A), we show how proximity effect strongly affect the device’s differential tunneling conductance response, including the observation of ZBCP and its weak peak splitting in the topologically-trivial SC state.

2. Modeling interface depairing mechanisms

Often, Blonder-Tinkham-Klapwijk (BTK) [15] formalism that considers anisotropic pairing potential with different orbital symmetries is widely used to model the quasiparticle density of states and to fit the differential conductance measurements using tunneling and point contact spectroscopy [5, 6, 11]. Here, the BTK model uses a phenomenological Dyne’s parameter $\gamma$, to incorporate depairing effects caused by finite lifetime of the quasiparticle excitations. However, the influence of other depairing effects, as discussed above, in presence of Zeeman field is not well studied. We here develop a model, better than the BTK formalism, which can capture the microscopic origin of the various pair-breaking mechanisms responsible for the stronger suppression of superconductivity. We focus on a device geometry, as shown in Figure 1(b), in a strong tunnel barrier regime, neglecting any contributions due to Andreev bound states, Kondo or weak-anti-localization to the differential conductance. To investigate tunneling conductance of such devices, we adopt a theoretical framework in
modeling the effective SC quasiparticle density of states by using the Green’s function approach developed first by Maki [8, 9] and later generalized to model s-wave SC films with thickness lower than the penetration depth. This is done by considering separate Green’s function for spin-up and spin-down superconducting electrons in an external Zeeman field, with the inclusion of impurities (magnetic and spin–orbit) as scattering centers in the SC region [10, 17–19]. Fulde [19] provides a detailed analysis of the Green function formalism, giving us the following form of the quasiparticle density of states for the spin-down (↓) and spin-up (↑) states:

\[ \rho_{\uparrow}(E) = \frac{\rho_0}{2} \text{sign}(E) \text{Re} \left\{ \frac{u_+}{(u_+^2 - 1)^{1/2}} \right\} \]

where \( \rho_0 \) is the normal density of states, \( E \) is the energy with respect to Fermi level, and \( u_\pm \) are the complex energy functions for the spin down (+) and spin-up states (−) represented as:

\[
\begin{align*}
    u_+ & = \left( \frac{E - iE}{|E|} \right) \pm E_z + \frac{\zeta u_\perp}{\Delta(1 - u_\perp^2)^{1/2}} \\
    & \mp b_{\text{fe}} \left\{ \frac{u_+ - u_-}{\Delta(1 - u_\perp^2)^{1/2}} \right\} \pm d_{\text{fe}} \left\{ \frac{u_+ + u_-}{\Delta(1 - u_\perp^2)^{1/2}} \right\}
\end{align*}
\]

(2)

Here, \( \Delta \) is the superconducting order parameter, \( \zeta, b_{\text{fe}}, d_{\text{fe}} \) are the parameters related (inversely) to the orbital depairing, spin–orbit and spin–flip scattering lifetimes [10], respectively, and the Zeeman energy (2Ez) is given by \( g_{\text{fe}} \mu_B H \) with \( H \) as the applied magnetic field in the plane of the SC film and \( g_{\text{fe}} \) as the effective Landé g-factor. It is important to note that density of states in equation (1) reduces to the theoretical form of BCS density of states in the absence of the above four depairing effects and Zeeman field. Numerical methods to solve the above coupled complex equations is known to be non-trivial due to the singularities at \( |u_\pm| = 1 \) [20] and due to the inability to generate an analytical closed-form solution [21]. Limited attempts have been made earlier to solve the above set of coupled non-linear complex functions with only the orbital depairing and spin–orbit terms by using the Fermi liquid approaches under the dirty limit [20, 22]. We extend similar approach to linearize the full form of the above coupled complex energy functions in equation (2) to successfully determine the physical solution of \( u_\pm \) for real values of the density of states. This leads to a set of four linearized equations given by:

\[
\begin{align*}
    \left( E - iE \right) y_2 + y_1 + x_2 E_z^2 & - \frac{\zeta}{\pi} (y_2 y_1 - y_1 y_2 E_z^2) - \frac{2d_{\text{fe}}}{\pi} (y_2 y_3 + y_3 y_2 E_z^2) = 0 \\
    \left( E - iE \right) y_4 + y_2 - y_3 & + \frac{\zeta}{\pi} (y_2 y_3 - y_3 y_2) - \frac{2b_{\text{fe}}}{\pi} (y_2 y_4 + y_4 y_2) = 0 \\
    y_2^2 - y_4^2 & - 2y_2^2 E_z^2 - 2y_4^2 E_z^2 \Delta^2 + \pi^2 = 0 \\
    y_2 y_4 + y_4 y_2 & = 0 \text{EQ},
\end{align*}
\]

(3)

where \( y_i; \ i \in \{1, 4\} \), represents the four complex variable related to the complex energy functions by the following expression:

\[
\begin{align*}
    y_1 & = E_z y_3 = -\pi u_\perp(1 - u_\perp^2)^{-1/2} \\
    \Delta(y_2 & = E_z y_4) = \pi(1 - u_\perp^2)^{-1/2},
\end{align*}
\]

(4)

This procedure of arriving at solution to equation (2) results in 8 sets of complex solutions, seven of which are discarded due to triviality (e.g. 0 or negative value of density of states from equation (1)). The differential tunneling conductance for the device structure in figure 1(b) is then determined (see supplementary material is available online at stacks.iop.org/JPCO/3/045005/mmedia) at any finite temperature using the above solution of the quasi-particle density of states. Figure 2 shows such a conductance map at a temperature of 30 mK with increasing strength of the four interfacial pair breaking mechanisms in zero and applied magnetic field; each of which show a characteristic response. Here, the SC film thickness is considered to be smaller than the penetration depth, leading to Zeeman splitting of the quasi-particle states in applied magnetic field [23]. Firstly, we observe that reducing the quasiparticle lifetime (i.e. increasing \( \zeta \)), leads to emergence of states within the gap (dark blue, representing a hard gap, fading to lighter shades at zero voltage bias), which may be associated to soft gap or gapless superconductivity. Furthermore, they lead to broadening of the conductance peak. Next, the orbital depairing is observed to only broaden the conductance peaks, while the spin–scattering causes both broadening of the peaks and spins flipping that strongly suppress superconductivity with the emergence of weak gapless superconductivity. In contrast, the device conductance response to an increasing spin–orbit scattering, which preserves TRS, shows an interesting trend. Here, no effect is observed on the device conductance in zero field. However, in the presence of a magnetic field, it contributes to a weak peak broadening while maintaining a hard gap. Further, due to stronger spin–mixing, it counteracts the effect of Zeeman field on the quasiparticle
Figure 2. Simulated normalized differential conductance (dI/dV, shown as colorplots in arbitrary units) versus applied bias voltage of a typical SC/TB/NM device structure for the different pair breaking parameters, (a) and (b) for Dyne’s parameter, (c) and (d) for orbital depairing, (e) and (f) for spin-scattering, (g) and (h) for spin-orbit scattering, bso, in zero magnetic field (top plots) and an applied magnetic field of 300 mT (bottom plots). Superimposed dI/dV line plots (solid line) represent the differential conductance at the parameter values corresponding to the horizontal line cuts (dashed line). For each subfigure, values of other depairing parameters are kept at 0.01, Δ(0) = 0.3 meV, g_{eff} = 10 and T = 30 mK.

states, making it harder to achieve spin-splitting (in figure 2(h), the red feature shows a negative slope). Understanding the contributions from each depairing term hence provides a comprehensive and powerful methodology to fit experimental data to extract important microscopic information about the superconducting properties of the interface layers.

3. Results and discussions

In the context of an SC/TM hybrid interface, the effect of the SO depairing and Zeeman field on the properties of the quasiparticle excitations layers may require careful analysis. Currently, very little is experimentally probed about the properties of the SC layer due to the proximity with the TM layer. Firstly, since the superconducting condensates leak into the TM layer electronic bands, we expect depairing effects, attributed mostly to SO scattering, to suppress superconductivity. Further, in the case of 1D semiconducting nanowires as TM layers, the SC condensates may experience a larger value of g_{eff}[24, 25] offering significant Zeeman interaction energy at relatively low magnetic fields that, interestingly, are not strong enough to suppress superconductivity in the SC layer. Additionally, proximity effect and/or interface structural disorder may substantially enhance the value of penetration depth (more than 200 nm in Al films) [26, 27] causing Zeeman-splitting of the quasiparticle density of states even in thicker SC films. Further, the dependence of Δ on the magnetic field may be more complex. For simplicity, we here assume Δ to decrease by a second order transition as \(\Delta(H) = \Delta(0)(1 - (H/H_c)^2)^{1/2}\), where \(H_c\) is the critical magnetic field and \(\Delta(0)\) is the zero field SC order parameter. Maki and Tsuneto [8] had shown that in the absence of depairing contributions, below the bulk critical temperature, the transition from a superconducting to normal state (due to magnetic field) moves from a second order to first order at a particular transition temperature. However, the presence of strong depairing mechanisms can significantly reduce this transition temperature or perhaps also completely suppress them leading to only second-order transitions at extremely low temperatures [21]. Similar responses may be observed experimentally [11], but require further experimental verifications.

Since the tunneling conductance is sensitive to the local quasiparticle density of states immediately after the tunnel barrier (or within the coherence length), device A (NM1/TB/SC) in figure 1(b) is expected to sense the density of states of the SC film. Hence, we simulate the differential conductance response (see figure 3) of device A with increasing in-plane Zeeman field for two different depairing terms, \(\gamma\) and \(b_{so}\) (see figure S1 for \(\zeta\), \(d_h\)). First, we assume the SC to be in proximity with a 1D high SO semiconducting nanowire and hence, choose a \(g_{eff}\) of 10. Figures 3(a) and (c) shows that with increasing Zeeman field, the device’s zero bias conductance gradually shift from a hard gap to a soft gap and finally to a peak prevailing over a finite field range (\(~100\,mT, 0.7\,T\) to \(0.8\,T\) in figures 3(a), \(~0.8\,T\) to \(~0.9\,T\) in figure 3(c)) until the ZBCP eventually splits. Further, the energy position of higher energy conductance peak is observed to increase initially and later fall down with applied magnetic field
until the critical field. We further observe, as shown in figure 3(b), that increasing γ leads to disappearance of ‘hard gap’ (even in zero field) and, due to the difficulty in resolving the ZBCP splitting, makes the ZBCP exist over a larger field range (−200 mT, 0.7 T to 0.9 T). An increase in SO scattering also enhances the field range (−200 mT, −0.9 T to 1.0 T) for the observation of ZBCP as it makes Zeeman splitting harder to achieve. However it has one distinction compared to the other depairing terms; it retains the ‘hard gap’ at lower fields (figures 3(c) and (d)). Some of these characteristic responses are also seen in experiments, however with the interest in probing the response of induced superconductivity in the TM layer (device B in figure 1(b)). In our simulation, with a low $g_{\text{eff}}$ of about 2, for most other TM materials, we no longer observe the ZBCP which also corroborates with the fact that such ZBCP features have not been convincingly observed, experimentally, in 3D TI surfaces or 2D TI edges. Therefore, our analysis calls for careful scrutiny in interpretation of experimental studies using differential tunneling conductance measurements. We would like to emphasize that for Zeeman energy (primarily due to large $g_{\text{eff}}$), approaching $\Delta$, our model assumes the ground state of the interface state to have a homogeneous order parameter. Transition to in-homogeneous superconducting state, such as Fulde, Ferrell, Larkin and Ovchinnikov (FFLO) states [28] is not considered since these states are very sensitive to disorder and are expected to occur only in very clean systems [21].

Next, we probe the ZBCP state in applied field and simulate the response of the SC layer in the hybrid SC/TM interface (with $g_{\text{eff}}$ of 10) to the modulations in $b_{\text{so}}$. Experimentally, gate voltage modulation on the TM layer may also indirectly affect the strength of the SO scattering potential in the SC film due to the adjacent TM layer (see figure 1(b)). Figure 4(a) shows the variation in the differential conductance contour taken at an applied field of 0.85 T. Interestingly, we observe the ZBCP (and its weak splitting) to gradually disappear, with the reappearance of soft gap and eventually a hard gap (see figure S2). Additionally, recent work in 1D nanowire systems has suggested a strong anisotropy of $\delta_{\text{nanowire}}$ depending on the direction of the applied magnetic field with respect to the nanowire axis [24]. Furthermore, it is proposed that the gate voltage modulation can also affect the value of $\delta_{\text{nanowire}}$. Hence, in figure 4(b), we model such a scenario by varying the value of $g_{\text{eff}}$ from 2 (lower limit as in bulk SC) to 10 that may suggest variation in the $g$ value sensed by the SC condensates due to the proximity with the nanowire. Interestingly, we observe a similar trend of disappearance of the ZBCP with reducing $g_{\text{eff}}$, implying angular or gate-modulation dependence, primarily due to lower Zeeman energy that reduces the spin splitting of the quasiparticle states.

Thus our model, provide a good fitting tool with a focus to understand the microscopic origin of depairing effects that limit superconductivity in the hybrid superconducting interface. Additionally, we also propose that by simulating device B (TM/TB/NM2 in figure 1(b)), our model as a fitting routine can also help identify the dominant depairing mechanisms that strongly suppress induced superconductivity in the TM layer. This interest is driven by the fact that in many systems, these PIS states are observed to disappear at relatively small magnetic fields [5, 6]. Here, the role of the atomic SO interaction to the depairing effects may be investigated. Recent studies on the superconducting phase of Nb-doped-SrTiO$_3$ thin films using differential tunneling conductance spectroscopy have shown that the intrinsic atomic SO scattering lifetimes can be short and
comparable to the Rashba or the bulk SO effects [29]. Hence, a systematic study, in this direction, to probe the depairing properties of induced superconductivity in TM layers is still missing.

4. Summary

In conclusion, our work highlights the distinct characteristic response of different depairing interactions to differential tunneling conductance measurements in presence of external stimulus. Importantly, our study reveals that ZBCP can be observed in a topologically-trivial SC state, especially in systems with high SO and large \( g_{\text{eff}} \) such as 1D- semiconducting nanowires but disappear in systems with low \( g_{\text{eff}} \). We expect that our model as a fitting routine can help understand a number of exotic interface studies such as co-existence of proximity induced superconductivity and ferromagnetism [30] by considering an internal exchange field acting on the SC condensates [31] (see figure S4), interface proximity study with ferromagnetic insulator where magnetic impurity governed depairing effects (parameter \( d_{\text{ex}} \)) may play a dominant role. Such a method may allow designing better systems that can enhance PIS to higher fields. We expect future developments in the present model, especially in developing a unified formalism covering barrier-less to weak-barrier conductance for point contact spectroscopy measurements, will advance our understanding of PIS in these classes of hybrid interfaces.

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