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Dirac-fermions in graphene d-wave superconducting heterojunction with the spin orbit interaction

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ABSTRACT

In this study, based on the Dirac–Bogoliubov–de Gennes equation, we theoretically investigate the interaction effect between the anisotropic d-wave pairing symmetry and the spin orbit interaction (the Rashba spin orbit interaction (RSOI) and the Dresselhaus spin orbit interaction (DSOI)) in a graphene superconducting heterojunction. We find that the spin orbit interaction (SOI) plays a critical role on the tunneling conductance in the pristine case, but minimally affecting the tunneling conductance in the heavily doped case. As for the zero bias state, in contrast to the keep intact feature in the heavily doped case, it exhibits a distinct dependence on the RSOI and the DSOI in the pristine case. In particular, the damage of the zero bias state with a slight DSOI results in the disappearance of the zero bias conductance peak. Moreover, the tunneling conductances also show a qualitative difference with respect to the RSOI when both the RSOI and the DSOI are finite. These remarkable results suggest that the SOI and the anisotropic superconducting gap can be regarded as a key tool for diagnosing the specular Andreev reflection.

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1. Introduction

In general, the modern semiconductor industries mainly rely on the three-dimensional (3D) semiconductor material such as silicon, germanium, and gallium arsenide. However, the two-dimensional (2D) crystals which are materials of atomic thickness exhibit unique physical and enormous oddball features that strongly differ from their 3D counterparts [1]. In another hand, as a result of their reduced dimensionality, the 2D crystals typically exhibit dramatic changes in their physical properties too. The first truly 2D crystal, graphene, has been isolated by Geim and Novoselov in 2004 [2–4]. Since the pioneering work of Novoselov et al., the study of 2D crystal graphene flakes has progressed rapidly in theory and application field [2–4]. Since its carriers behave as massless relativistic electrons, graphene displays various novel phenomena such as, unconventional quantum Hall effects [5], sub-Poissonian shot noise [6], valley-dependent Brewster angles [7], Klein tunneling [8] and so on.

Due to the light atomic mass of carbon and the second order effect, the strength of the intrinsic Desselhaus spin orbit interaction (DSOI) in flat graphene is estimated by many studies with energies in the range of μeV [9–12]. However, the enhancement of the SOI (both the DSOI and the Rashba spin orbit interaction (RSOI)) in graphene may lead to various topological phenomena and also find applications in spintronics [1–3,13]. In fact, realizing a large DSOI in graphene may be possible by an interface with a tungsten disulfide substrate very recently [14]. It is suggested that two to three orders of magnitude enhancement of the DSOI (up to 17 meV) can be achieved in experiment [14,15]. Moreover, the RSOI induced by structure inversion asymmetry can also be tuned by the external gate voltages [9–12], adatoms [16], and substrate emerging [17]. Essentially, depending on the interaction between the two materials, the RSOI can be increased up to 200 meV at room temperature [17]. Since the SOI strengths can be tuned to a notable value, we thus open the possibilities for the realization of the quantum spin Hall effect in graphene and the SOI-resolved graphene electronic device application [18–20].

In graphene, in addition to the retro- Andreev reflection (RAR) [21], a specular Andreev reflection (SAR), one of the peculiar hallmarks of the superconducting physics, occurs [22,23]. The RAR refers to the reflected hole traveling along the same path of the incident electron. While the SAR corresponds to the reflected hole travels along the specular path of the incident electron. Following the pioneering work in graphene [22], the physical properties of superconducting heterojunction have attracted great interest due to its novel features and potential applications in future electronic circuits [3,4]. It is reported that the specular Andreev reflection

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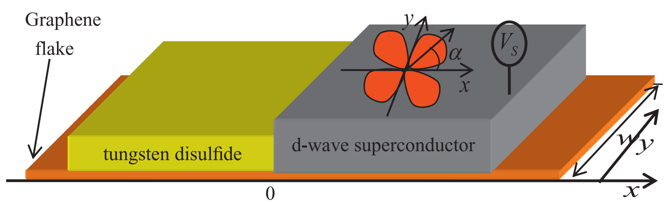

Fig. 1. Sketch of the superconducting heterojunction. V_S is the voltage applied to the superconducting lead. The yellow lead represents a tungsten disulfide lead which causes a notable strength of the DSOI in graphene. The light grey lead represents an unconventional d-wave superconducting lead which gives rise to an anisotropic d-wave superconductivity in graphene via the proximity effect.

can be also found in a graphene ferromagnet/superconductor junction [23,24], a graphene SOI/superconductor junction [25], and in a four-terminal graphene superconducting heterojunction [26]. Furthermore, the SAR effect on magnetoresistance, shot noise, spin-valves effect, and Josephson supercurrent has also been extensively investigated by many authors [27–30].

In fact, pristine graphene is not a natural superconductor. However, the experimentally observed Josephson supercurrent in graphene suggests that the superconducting pairing can be evoked in graphene by means of an external superconducting lead [31–35]. Moreover, Chapman et al. experimentally show that the robust superconductivity can be induced in graphene crystals by decorating with Ca [36]. On the other hand, a complete investigation of the possible pairing symmetries on a hexagonal lattice up to *f*-wave superconducting pairing has been given by Mazin and Johannes [37]. Therefore, besides the conventional *s*-wave superconducting pairing, the unconventional pairing in graphene could be achieved by the proximity effect through an unconventional superconductor lead, such as high-Tc superconductor lead. Consequently, some studies have focused on the unconventional *d*-wave pairing effect on the sub-superconducting gap quantum transport in graphene superconducting heterojunction [38,39]. Indeed, the zero-bias conductance peak and the weakly-damped Josephson current indicate that the effect of anisotropic *d*-wave pairing symmetry on the quantum transport properties in this junction is of considerable importance.

It is thus important to ask the question if anisotropic *d*-wave pairing symmetry catch up with the SOI (both the DSOI and the RSOI) in the atomically thin graphene superconducting heterojunction. This critical question has been overlooked up to now. Here, we investigate how the spin-resolved transport properties change in the presence of the SOI in the graphene superconducting heterojunction with the *d*-wave pairing symmetry.

2. Model and basic formula

We consider that a spin-resolved relativistic electron knocks on a two-terminal graphene normal metal/superconductor heterojunction. Here the normal metal lead is with the SOI and the superconductor lead is with a *d*-wave superconducting pairing symmetry. The sketch of the superconducting heterojunction is shown in Fig. 1. The normal metal lead with the SOI extends from $x = -\infty$ to $x = 0$ and the superconducting region occupies $x > 0$. In experiment, the RSOI can be tuned by either a Ni surface or a SiC surface [17,40]. While the DSOI can be modulated largely by a tungsten disulfide flake [14,15]. In the region $x > 0$, we assume that it is kept close to a unconventional superconducting lead so that a *d*-wave superconductivity is induced via the proximity effect [38,39]. Note that, in this study, we only focus on the case where the width (along y direction) of the graphene strip, *w*, is very large. Therefore, the details of the microscopic description of the strip edges become irrelevant, and can be realistically created in experiments [2–4].

In this study we assume a defect-free graphene flake in the xy-plane. For T< 100 K, the electron-electron and electron-phonon inelastic scatterings can be ignored [41,42]. Thus, the essential physics can be elucidated by a single particle Hamiltonian. The low energy quasiparticles in the present system can be described by the following Dirac-Bogoliubov–de Gennes (DBdG) equation [22–30]

$$\begin{pmatrix} H_a - E_F & \Delta(x) \\ \Delta^*(x) & E_F - H_a \end{pmatrix} \Psi_a = \varepsilon \Psi_a \quad (1)$$

Here, $\Psi_a = (\Psi_{\uparrow Aa}, \Psi_{\uparrow Ba}, \Psi_{\downarrow Aa}, \Psi_{\downarrow Ba}, \Psi^*_{\uparrow A\bar{a}}, \Psi^*_{\uparrow B\bar{a}}, -\Psi^*_{\downarrow A\bar{a}}, -\Psi^*_{\downarrow B\bar{a}})^{Tr}$ is the 8 component wave function for the Bogoliubov quasiparticle, where Tr represents transpose. The arrow index (↑, ↓) stands for real spin, the index a denotes K or K' for electrons or holes near K and K' points in the Brillouin zone, $\bar{a}$ takes values $K'(K)$ for $a = K(K')$, A and B denote the two inequivalent sites in the real space hexagonal lattice, E_F is the Fermi energy, $\Delta(x)$ is taken in the form $\Delta(x) = \Delta_0 \cos(2\theta_S - 2\alpha)e^{i\varphi}\theta(x)$, where Δ_0 and ϕ are the amplitude and the phase of the induced superconducting order parameters, respectively, α models the orientation of the superconducting gap in k-space with regard to the interface, θ_S is the transmission angle between the momentum of the Bogoliubov quasiparticle and the x axis, and $\theta(x)$ is the Heaviside step function, and the spin- and valley-resolved Hamiltonian H_a is given by

$$H_a = -i\hbar v_F[\sigma_x \tau(a)\partial_x + \sigma_y \partial_y] + ((\lambda/2)(\sigma_x \tau(a) s_y - \sigma_y s_x) + \beta \sigma_z \tau(a) s_z)\theta(-x) + U(x)$$

where $v_F \approx 10^6$ ms^{-1} is the Fermi velocity, the Pauli matrice $\vec{\sigma} = (\sigma_x, \sigma_y)$ [$\vec{s} = s_x, s_y$] corresponds to the inequivalent sublattice [the physical spin] degree of freedom, $\tau(a)$ is the valley index ($\tau(a)$ is $1(-1)$ for $a = K(K')$), the parameters λ and β describe the strength of the RSOI and the DSOI, respectively, and the potential profile $U(x)$ across the heterojunction may be adjusted independently by a gate voltage or doping. Moreover we also assume that the potential change is sharp on the scale of the Fermi wavelength in the interfaces. Since the zero of potential is arbitrary, the chirality-resolved scattering with an abrupt potential can be defined by the following form $U(x) = -V_S \Theta(x)$.

In order to solve the chirality-resolved transport problem in our two-terminal graphene normal metal/superconductor heterojunction (sketched in Fig. 1), we assume that an electron or a hole is incident from the left normal metal lead along x axis. For a chirality-resolved electron with energy ε, incident angle θ, and chirality γ, the envelope functions in the two regions, taking into account both the normal reflection and the Andreev reflection, can be written as

$$\begin{cases} \Psi_L = \Psi^{e+}_{\gamma} + r_1 \Psi^{e-}_{\gamma} + r_2 \Psi^{e-}_{\bar{\gamma}} + r_{A1} \Psi^{h-}_{\gamma} + r_{A2} \Psi^{h-}_{\bar{\gamma}}, & x < 0 \\ \Psi_R = t_1 \Psi^{e+}_{S1} + t_2 \Psi^{e+}_{S2} + t_3 \Psi^{h+}_{S1} + t_4 \Psi^{h+}_{S2}, & x > 0 \end{cases} \quad (2)$$

where r_1 and r_2 are the amplitudes of normal reflections, r_{A1} and r_{A2} are the amplitudes of Andreev reflections, and t_1, t_2, t_3, and t_4 are the amplitudes of electron and hole quasiparticles in the superconducting lead. The chirality $\bar{\gamma}$ is − for γ is +. ± denotes the envelope functions traveling along the ± x directions. The specific form of the envelope functions can be obtained by the Eq. (1), and written in a compact form. Due to the translational invariance along the y direction, the momentum along the y axis, q, can be regarded as a good quantum number and the factor e^{iqy} can be omitted in the specific envelope functions accordingly.

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