Physica C 502 (2014) 36–40

Contents lists available at ScienceDirect

Physica C

journal homepage: www.elsevier.com/locate/physc

Effect of *d*-wave pair coupling on evanescent type of Andreev reflection

H. Goudarzi *, M. Khezerlou, T. Dezhaloud

Department of Physics, Faculty of Science, Urmia University, P.O.Box 165, Urmia, Iran

ARTICLE INFO

Article history:
Received 23 April 2013
Received in revised form 8 April 2014
Accepted 15 April 2014
Available online 4 May 2014

Keywords:
Evanescent wave
d-Wave superconductor
Gapped graphene
Andreev reflection

ABSTRACT

In this paper, we investigate the current resulted from virtual Andreev process, passing through a N/S gapped graphene-based junction, where superconductivity in the S-region is induced by depositing unconventional d-wave superconductor. It is shown that the evanescent type of Andreev reflections occurs above the critical electron incident angle, and needs to take into account its effect when calculating the tunneling conductance in the both conventional and unconventional superconductor junctions. In the evanescent wave regime, the new pure imaginary wavevector of hole-like quasiparticle is obtained, and consequently, the tunneling conductance formalism is modified. We show that due to the nature of pair interaction in d-wave superconductivity, considering the virtual Andreev process affects significantly the behavior of charge carriers in the structure. In particular, the conductance in the virtual regime is more sensitive to the superconductor gap characterized by orbital rotated angle, so that with increasing α the width of zero conductance versus bias energy decreases and above $\alpha = 0.1\pi$ the current in junction is supplied just by virtual Andreev process.

1. Introduction

A relativistic framework of superconductivity was firstly presented by Capelle and Gross [1]. In this theory, using the property of time reversal symmetry of Dirac fermions and representation of a set of 16 bilinear independent matrices it is shown that the proper relativistic generalization of the Bogoliubov–de Gennes equation leads to the Dirac–Bogoliubov–de Gennes (DBdG) equation. Such formalism can effectively be used to investigating a condensed matter structure, concerning superconductivity and relativity. A superconducting electrode on the top of a 2-dimensional atomic layer as graphene may cause to induce superconductivity to the Dirac fermions, via the proximity effect [2–4]. Under this effect, influence of any type of superconductor pair coupling on the relativistic charge carriers can play a noticeable role in transport properties of junctions. By many previous works [5–8], it is found that using various superconducting gaps in junctions leads to the sufficient new results in the electronical behavior of system, specifically in unconventional structures. In particular, superconductor–graphene combinations have been recently considered as an excellent candidate to observe these new effects, i.e. specular Andreev reflections. As we know, graphene as a two-dimensional honeycomb lattice of carbon atoms, which was firstly fabricated by Novoselov et al. [9] represents a new solid state system with a relativistic-like linear dispersion near the Dirac points on the Fermi surface [10,11]. Based on its exotic properties, Beenakker [2] theoretically investigated firstly the Andreev process at the graphene-based normal/superconductor interface. Following that, in the many related works, for example [12–15], the effect of this new physics on the tunneling conductance of junctions has been studied.

The Blonder–Tinkham–Klapwijk (BTK) formalism [16] is an effective method to calculate the conductance of a junction taking into account the contribution of Andreev reflections for various incident angles. In order to have alone actual specular Andreev reflection in the interface of a N/S junction, the reflected angle of hole must be $\theta_h \leqslant \pi/2$. This is an usual condition for having actual Andreev process. So, a maximum value less than $\pi/2$ is resulted for electron incident angle θ_e in the upper limit of BTK formalism, as critical angle θ_c. Therefore, under this condition it is possible to eliminate the contribution of evanescent waves in the conductance, so that, taking condition $\theta_c < \theta_e \leqslant \pi/2$ the virtual Andreev reflection (VAR) may be involved in the structure.

First attempts in this relation were worked out by Kashiwaya and Zutic [17,18] for conventional ferromagnet/superconductor junction, and it was shown that above critical angle the virtual Andreev process occurs at the interface, since the conductance is found indefeasible and the tunneling of quasiparticles goes on, although the state of hole-like wavevector is still pure imaginary. Note that, in non-relativistic junctions the virtual Andreev process

* Corresponding author. Tel.: +98 9144406713; fax: +98 4412753172.
E-mail addresses: goudarzia@phys.msu.ru (H. Goudarzi), m.khezerlou@urmia.ac.ir (M. Khezerlou).

http://dx.doi.org/10.1016/j.physc.2014.04.023
0921-4534/

occurs only in ferromagnetic systems, because, an electron belonging to one of the two spin bands incoming from the ferromagnetic region to the interface will be reflected as a hole in the opposite spin band. The splitting of spin bands by the exchange energy in ferromagnetic materials implies that the quasiparticles carry the different angles of incidence. Consequently, due to this opposite band states of spin in the ferromagnetic section, VAR may take place at the interface for $\theta_e > \theta_c$. Unlike conventional systems, in unconventional one, as graphene-based structures electron and hole states are interconnected, that exhibit properties analogous to the charge-conjugation symmetry in QED. The wavevector and incidence angle of a hole-like fermion may be different from electron-like, and this can lead to new behaviors in the evanescent type of the Andreev reflection. Soodchomshom [19] has shown that the conductance resulted from virtual Andreev process is considerable, and should be governed by the evanescent states of hole-like quasiparticles.

In this paper, we aim to consider the dependence of evanescent waves on *d*-wave superconducting energy gap. As shown in Refs. [5,6], the *d*-wave pairing causes to observe new behaviors of charge carriers in a graphene-based N/S junction, due to orbital interaction of Cooper pairs with orbital rotated angle, α. Actually, detecting various type of pair coupling such as *d*-wave gap has a noticeable importance in high-temperature superconductivity. Experimentally new developments in this area can serve a little bit the motivation of such present work. Recently, Wang et. al. [20] were able to induce superconductivity on the surface states of a $Bi_2\,Se_3$ topological insulator by growing high-quality $Bi_2\,Se_3$ films on a purported *d*-wave superconductor $Bi_2\,Sr_2\,CaCu_2\,O_{8+\delta}$(Bi2212). Like graphene, a topological insulator also has Dirac points, so it is closely related to graphene. By using angle-resolved photoemission spectroscopy, Wang et al. have determined that the proximity-induced gap by purported *d*-wave pairing of $Bi_2\,Sr_2\,CaCu_2\,O_{8+\delta}$ on the surface states is nearly isotropic and consistent with predominant *s*-wave pairing. Correspondingly, in the previously experiments with purported *d*-wave superconductor Bi2212 as seen in Refs. [21–23], it is shown that all experiments can only be understood in terms of a substantial *s*-wave order parameter component. Also, Katterwe and Krasnov [24] experimentally showed in the intrinsic Josephson junction of Bi2212 that the in-plane penetration depth has the BCS temperature dependence of the *s*-wave superconductor.

2. Model and theoretical formalism

In this section, we consider the motion of massive Dirac fermion in a gapped graphene-based normal metal/superconductor junction (NG/SG), see Fig. 1, that is governed by the DBdG equation:

$$\begin{pmatrix} -i\hbar v_F(\sigma_x\partial_x+\sigma_y\partial_y)-E_F+\sigma_z M & \Delta_{+(-)} \\ \Delta^*_{+(-)} & i\hbar v_F(\sigma_x\partial_x+\sigma_y\partial_y)+E_F-\sigma_z M \end{pmatrix}\psi_a = E\psi_a, \tag{1}$$

where v_F represents the Fermi velocity of the quasiparticles in graphene, $\sigma_{x,y,z}$ are the Pauli spin matrices and M is the mass energy gap of graphene. Superconductivity in S region is induced by depositing unconventional *d*-wave superconductor, so the pair potential is taken as:

$$\Delta_{+(-)} = \Delta(T)\cos(2\theta_{Se(h)} - (+)2\alpha)e^{i\varphi}\Theta(x), \tag{2}$$

where $\Theta(x)$ is the unit step function, Δ is the pair potential and φ is the phase of superconductivity. Also, α denotes to the orientation of $L = 1$ orbital with respect to the interface normal vector, and the quasiparticles propagate with angle incidence $\theta_{Se(h)}$ in SG region. The wavevectors in these regions are expressed as:

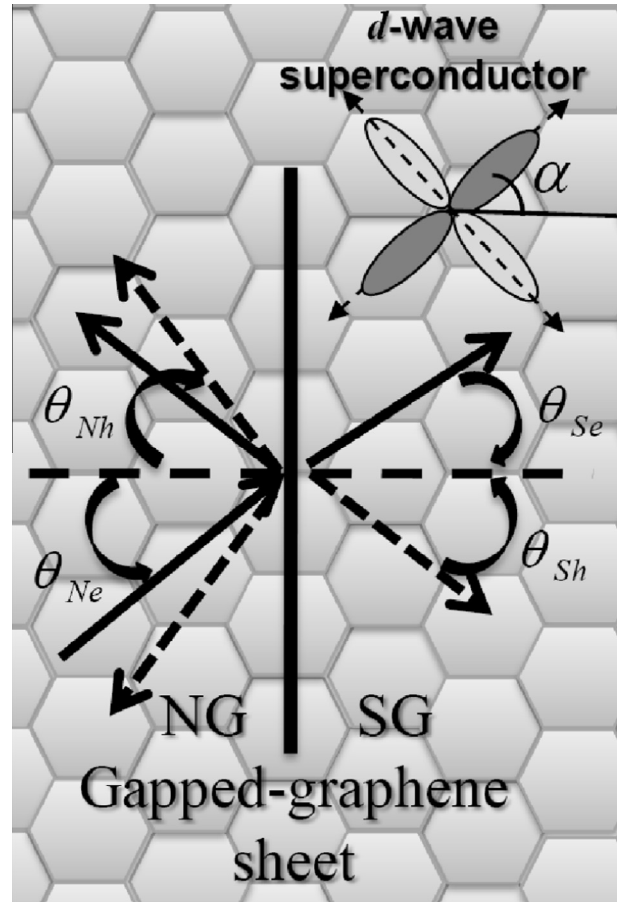

Fig. 1. Sketch of simple model for the N/S graphene-based junction. It illustrates the different scattering processes, which may take place. The orientation of anisotropic *d*-wave gap is presented.

$$k_N^{\pm} = \frac{\sqrt{(E_{FN} \pm E)^2 - M^2}}{\hbar v_F},$$
$$k_S^{\pm} = \frac{\sqrt{(E_{FS} \pm \Omega_{\pm})^2 - M^2}}{\hbar v_F},$$

where

$$\Omega_{+(-)} = \sqrt{E^2 - |\Delta(T)\cos(2\theta_{Se(h)} - (+)2\alpha)|^2}.$$

Note that, the momentum of quasiparticles in y-direction is conserved, so that we have $k_\parallel = k_N^{\pm}\sin\theta_{Ne(h)} = k_S^{\pm}\sin\theta_{Se(h)}$. This condition allows to determine the Andreev reflection angle θ_{Nh} versus electron incident angle θ_{Ne} as, $\theta_{Nh} = \sin^{-1}(\sin\theta_{Ne}\frac{\sqrt{(E_{FN}+E)^2-M^2}}{\sqrt{(E_{FN}-E)^2-M^2}})$. It is reasonable [25] to take a finite superconducting order parameter Δ and large doping, that means $E_{FS} \gg \Delta$, in order to calculate exactly the reflection angle in superconductor region, which is found $\theta_{Se(h)} = \sin^{-1}\left(\sin\theta_{Ne}\frac{\sqrt{(E_{FN}+E)^2-M^2}}{\sqrt{E_{FS}^2-M^2}}\right)$.

The needed condition for occurring actual Andreev reflection in the interface is $\theta_{Nh} \leqslant \pi/2$, consequently the critical value for θ_e is found as following:

$$\theta_c = \sin^{-1}\left(\frac{\sqrt{(E_{FN}-E)^2-M^2}}{\sqrt{(E_{FN}+E)^2-M^2}}\right). \tag{3}$$