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Enhanced nonlocal Andreev reflection in F|S|F graphene spin-valve

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ABSTRACT

In this paper crossed Andreev reflection (CAR) conductance is calculated in graphene-based Ferromagnetic-Superconductor-Ferromagnetic heterostructure. In this spin-valve system, the ferromagnetic semi-infinite layers act as leads. The leads are assumed to be half-metallic, i.e. the respective shift of the two spin sub-bands at each lead is such that the electronic states of just one spin sub-band are present near the Fermi level. In this graphene-based system, as in the corresponding metallic structures, if the leads are in anti-parallel configuration, direct Andreev reflection (AR) and electron cotunneling(CT) are weak while crossed Andreev reflection is considerable. The CAR reaches the maximum probability amplitude for thickness of the superconducting layer that is comparable to the superconducting coherence length. The behavior of the system at parallel configuration of the leads, contradicts with metallic FSF structures, so that an appreciable amount of CAR probability is obtained. This is provided in graphene by the combination of CAR and spin-dependent Klein tunneling through p-n barrier between different spin sub-bands of the two leads. In the case that the Fermi energy of the first lead is in Dirac point the result is the enhanced CAR due to blocking CT channels in both parallel and anti parallel configurations. The resulting nonlocal conductance oscillates with L exhibiting a π-phase shift between the two configurations.

1. Introduction

Hybrid structures of ferromagnetic (F) and superconductors (S) show very peculiar properties by providing possibility of controlled interplay of ferromagnetism and induced superconducting correlations [1–3]. Most of the peculiarities are attributed to the ferromagnetic exchange field, h, that in Andreev reflection of an electron (hole) from the ferromagnetic-superconductor interface – FS – to the hole (electron) excitation of opposite spin, induces momentum change of amount $2h/v_F$ where v_F is the Fermi velocity [4]. This momentum shift of the correlated electron-hole is responsible for suppression of the proximity effect at FS contacts [1,3] and spatially evanescent amplitude of the induced superconducting correlations in F [1,5]. The proximity effect in F may be altered significantly by the inhomogeneous (anisotropic) exchange field direction. Enhanced induction of the superconducting correlations in F by two domains with AP exchange fields [1] and the generation of long range triplet superconducting correlations by the non-collinear configuration of the exchange field [6] have been demonstrated both experimentally and theoretically.

The nonlocal proximity effect takes place in FSF structures. This is the superconducting counterpart of the spin-valve in spintronics, in which the relative orientation of the exchange field of the lateral ferromagnetic leads can be controlled by e.g. an external magnetic field [7–9]. If the thickness of S layer is of the order of superconducting coherence length, ξ,the proximity effect which gives rise to AR, is not the only process involved. Under this situation, a nonlocal process, named crossed AR, occurs by which an electron excitation at one FS interface is reflected as a hole at the distant second SF interface [9–12]. This results in the absorption of a Cooper pair into the superconductor which is formed by two distant electrons from the two (ferromagnetic) leads. Such a FSF setup is ideal for producing spatially separated entangled electrons that beside being an outstanding aspect of quantum physics, it is also of potential applications in quantum communication (information) [13] and quantum computation [14,15].

In this paper, we study the nonlocal quantum transport in FSF structures based on graphene [16–18]. Graphene is a semimetal with conical valance and conduction bands in which the charge carriers behave like 2D massless Dirac fermions with a pseudo-relativistic chiral property [17–21]. The carrier type, (electron-like (n) or hole-like(p)) and its density can be tuned by applying electrical gate or doping the underlying substrate. An intriguing effect which arises from such a Dirac like spectrum, is the reflectionless transmission of an electron through a wide and high graphene p-n barrier called Klein tunneling in analogy with the corresponding effect in quantum relativistic theory [22–25]. Currently intriguing properties of graphene have been the subject of intense studies [26–28]. Among the

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others, peculiarity of the AR in graphene-based FS junctions has been reported [29].

In this work, we show that the graphene-based FSF structure provides possibility for a unique combination of the nonlocal Andreev reflection and spin-dependent Klein tunneling, which makes this structure ideal for realizing entangled massless chiral electrons. To make a comparison between graphene and common (metallic) spin-valve structures with superconducting contact, we first notice that in most of the theoretical models for NSN and FSF structures [10], point contacts are assumed between S and lateral non-superconducting leads in order to consider the superconducting pair potential, Δ, constant inside S. However, the chirality of quasi particles in graphene permits a large Fermi energy-difference between S and F leads that removes the need for point contact [30]. Highly doped superconducting strips of different widths can be produced by depositing superconducting metallic electrodes on top of the graphene sheet [31]. In this circumstance, the large Fermi energy-mismatch between S and F regions plays the role of a barrier in the interfaces that due to reflectionless tunneling at normal incidence, manifest itself only at large incidence angles.

The amplitude of CAR in graphene NSN [32] has very small contribution to the nonlocal conductance owing to the presence of chirality conserving processes which are AR and CT. To achieve remarkable CAR, in ref. [33] the pseudo-diffusive transport through undoped graphene has been employed to make CAR as large as CT. Like in metallic FSF, in graphene FSF structures, the exchange potential can partially or totally suppress CT and/or AR channels which are competing phenomenon with CAR.

We realize that in contrast to the behavior of a metallic FSF structure in which only anti-parallel (AP) configuration favors CAR, the corresponding graphene spin-valve, depending on the doping of F regions, would allow appreciable CAR process for both parallel (P) and anti-parallel configurations. When both of F regions are of the same type of doping, say n-type, AP alignment of the exchange fields for half metal case ($h = E_F$) blocks the competing processes of CT and direct AR, thus the transport becomes pure CAR at zero energy. On the other hand when ferromagnetic electrodes are of different n and p types, the similar situation happens for P configuration. In both configurations we suggest a spin-diode property for this device because the situation is the same for the other spin-specie incident electron from other F to the superconducting interface if an inverse voltage ($-V$) is applied say to F_2 while F_1 and S are grounded. We further demonstrate the situation that one of the electrodes is undoped at the Dirac point. In this case, we find that when the first electrode is undoped the CAR with excitation energy,ε, has an appreciate amplitude for both P and AP configurations for $h = \mp(\varepsilon + E_F)$, because the CT is blocked. Under this condition, for $\varepsilon/E_F = 0$ in AP configuration the CAR is of retro type and in P configuration it is of specular type. The resulting conductance oscillates with varying the thickness of S, which have relative π phase shift at AP and P cases which is a result of the pseudo-spin reversal of the incident electron when hitting the F_1S interface.

2. Model and theory

We consider a planar spin-valve structure, shown schematically in Fig. 1, in which a wide superconducting strip, S, of length L connects two semi-infinite ferromagnetic leads F_1 and F_2. The whole system is embedded on graphene. The ferromagnetic leads are characterized in the Stoner model by the exchange potential $h(\vec{r}) = \Theta(-x) \pm \Theta(x-L)$ for P (+) and AP (−) alignments, respectively, where $\Theta(x)$ is the Heaviside step function. Such a ferromagnetic region can be produced by depositing ferromagnetic metal electrodes, like Co [34], on top of the graphene sheet or by doping the substrate by magnetic atom impurities [35]. In addition to the proximity-induced correlations [36], intrinsic ferromagnetism was also predicted to exist in graphene sheets

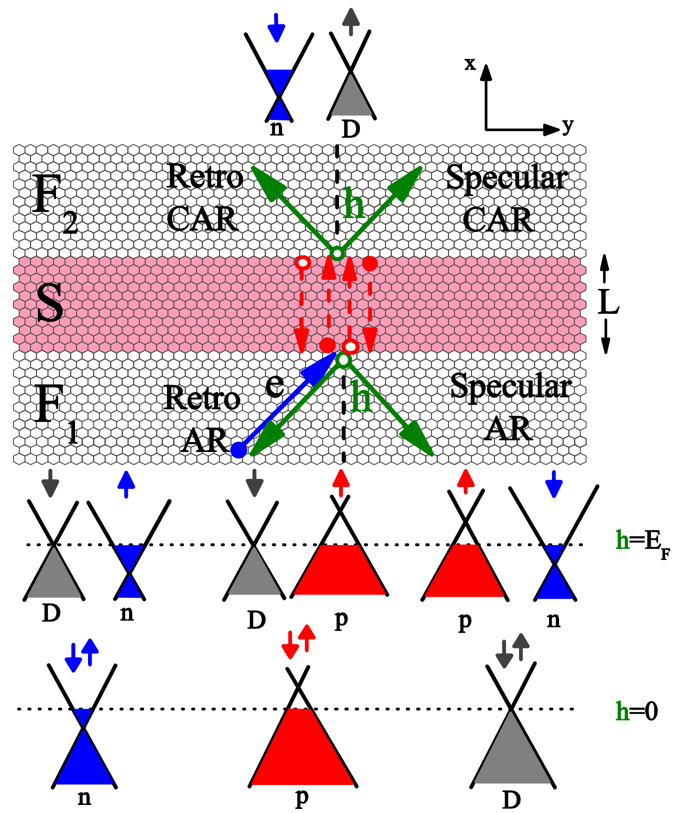

Fig. 1. All on graphene model consists of two ferromagnetic leads connected by superconducting layer.CAR may be of retro or specular types. n-S-n, p-S-n and D-S-n band structures are shown.

[37] and nanoribbons [38]. The Fermi energy in S and F leads can be modulated by doping or using several electrostatic local gates. We consider S strip to be highly doped with a Fermi energy, E_{Fs} much larger than in leads, $E_{F1,2}$. This coincides with the condition of the reported experiment [31] in which the superconductivity is induced by the proximity to AlTi metallic superconductor. The condition $E_{Fs} \gg E_{F1,2}$ justifies the assumption of a step-like variation of the superconducting pair potential $\Delta(\vec{r}) = \Delta\Theta(x)\Theta(-x+L)$ [30].

We employ scattering formalism to study transport properties of quasi-particles in this spin-valve structure. Within this formalism, resonant states between two wide SF_1 and SF_2 interfaces are also taken into account properly. The quasi-particles' wave functions are the eigenfunctions of Dirac Bogoliubov de Gennes (DBdG) equation that describes superconducting correlation between massless Dirac fermions with different valley indices. Due to the valley degeneracy, only one set of the four-dimensional (for 2 components of each electron-like and hole-like pseudo-spins) equations will be considered that describes coupling of a spin σ ($\sigma = \pm 1$) electron from one valley to a spin $\bar{\sigma}$ ($\bar{\sigma} = -\sigma$) hole from the other valley. In the presence of one-particle exchange interaction, it takes the following form;

$$\begin{pmatrix} \hat{H}_0 - \sigma h\hat{I} & \Delta\hat{I} \\ \Delta\hat{I} & -\left(\hat{H}_0 - \bar{\sigma} h\hat{I}\right) \end{pmatrix} \begin{pmatrix} u^{\sigma} \\ v^{\bar{\sigma}} \end{pmatrix} = \varepsilon^{\sigma} \begin{pmatrix} u^{\sigma} \\ v^{\bar{\sigma}} \end{pmatrix} \tag{1}$$

where $\hat{H}_0 = i\hbar v_F(\hat{\sigma}_x\partial_x + \hat{\sigma}_y\partial_y) - E_F\hat{I}$ is the Dirac Hamiltonian and u_σ and $v_{\bar{\sigma}}$ are the BCS coherence factors belonging to different valleys of the k-space and $\varepsilon_\sigma > 0$ is the excitation energy measured from the Fermi energy, denoted by $E_F = E_{Fs,1,2}$ in S and $F_{1,2}$ respectively; $\hat{\sigma}_x$ and $\hat{\sigma}_y$ are Pauli matrices in the pseudo spin space of the two sublattices and $\hat{I}$ is2-dimensional unit matrix. By diagonalizing Hamiltonian the energy eigenvalues are obtained. In F_1 and F_2 the excitation energy as a function of the two dimensional wave vector $\boldsymbol{k}^{\sigma} = (k^{\sigma}, q^{\sigma})$ depends