Spin-valve effect on superconducting graphene

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Abstract

We calculate crossed Andreev reflection(CAR) conductance in graphene ferromagnetic (F)-superconducting (S)- ferromagnetic spin-valve. Contrary to metallic FSF structures the probability for p-doped graphene allows combination of CAR and spin-dependent Klein tunneling through p-n barrier between different spin sub-bands of two F leads that results in appreciable CAR probability in parallel (P) configuration too. The situation with the Fermi energy of incident ferromagnetic in Dirac point, D, is considered to enhance CAR by blocking CT channels in both P and AP configurations.

We study the nonlocal quantum transport in FSF structures which are realized in graphene, the two-dimensional (2D) lattice of carbon atoms [1-3]. The obtained amplitude of CAR in graphene NSN [4] has very small contribution to the nonlocal conductance of the system because in the presence of the competing effect of AR and CT, chirality conservation prohibits pronounced amount of CAR. To achieve remarkable CAR, in ref. [5] the pseudo-diffusive transport through undoped graphene has been employed to make CAR as large as CT. However like metallic FSF, in graphene FSF structures exchange potential may partially or totally suppress CT and/or AR channels resulting in enhanced CAR probability. We find that in contrast to the behavior of a metallic FSF structure which only its 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 antiparallel (AP) 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 of $h = E_F$ blocks the competing CT and direct AR processes and the transport becomes pure CAR at zero energy. On the other hand when F electrodes are of different n and p types, the similar situation happens for P configuration. In both above configurations 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 a voltage $-V$ is applied to F2while F1 and S are grounded.

We consider a planar graphene-based spin-valve structure, shown schematically in Fig. 1, in which a wide superconducting strip, S of length L connects two ferromagnetic leads F1 and F2. 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. We consider S strip to be highly doped with a Fermi energy, E_{Fs} much larger than in F leads, $E_{F1,2}$.

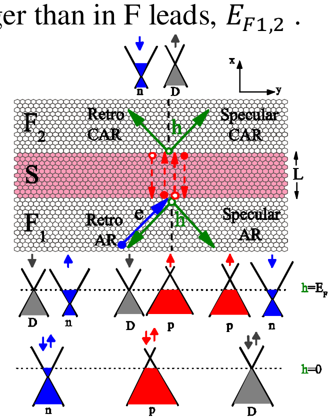

Fig. 1: CAR may be of retro or specular types. n-S-n, p-S-n and D-S-n band structures are shown.

We employ scattering formalism to study transport properties of quasiparticles in this spin-valve structure. 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:

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

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. The solutions of Eq. (1) inside leads F1 and F2 are written, respectively, as:

$$\Psi_{F1}^{\sigma} = \psi_{1+}^{e\sigma} + r^{e\sigma}\psi_{1-}^{e\sigma} + r^{h\sigma}\psi_{1-}^{h\bar{\sigma}}\,, \qquad \Psi_{F2}^{\sigma} = t^{e\sigma}\psi_{2+}^{e\sigma} + t^{h\sigma}\psi_{2+}^{h\bar{\sigma}} \tag{2}$$

where $\psi_{n\pm}^{e\sigma} \sim e^{iqy \pm ik_n^{e\sigma}x} \times (e^{\mp i\varphi_n^{e\sigma}}, \pm 1, 0, 0)$ and $\psi_{n\pm}^{h\bar{\sigma}} \sim e^{iqy \pm ik_n^{h\bar{\sigma}}x} \times \left(0, 0, e^{\mp i\varphi_n^{h\bar{\sigma}}}, \mp 1\right)$ $(n = 1, 2)$ are the eigenstates of Hamiltonian (1) in Fn. Inside S the wave function $\psi_S^{\sigma} = a^{\sigma}\psi_{S+}^{e} + b^{\sigma}\psi_{S-}^{e} + c^{\sigma}\psi_{S+}^{h} + d^{\sigma}\psi_{S-}^{h}$ consists of four superconducting quasi-particle excitations, $\psi_{S\pm}^{h} = e^{iqy+ik_{S\pm}^{h}x} \times (e^{-i\beta}, \mp e^{-i\beta}, 1, \mp 1)$, $\psi_{S\pm}^{e} = e^{iqy+ik_{S\pm}^{e}x} \times \left(e^{i\beta}, \pm e^{i\beta}, 1, \pm 1\right)$. $\beta = \text{acos}\,(\varepsilon/\Delta)$, $k_{S\pm}^{e} = \pm(k_0 + ik)$, $k_{S\pm}^{h} = \mp(k_0 - ik)$ and $k = \sin\beta/\xi$, $k_0 = E_{Fs}/\hbar v_F$. Coefficients a^σ, b^σ, c^σ, d^σ are the amplitudes of different quasiparticle wave functions in S; $r^{e\sigma}$ and $r^{h\sigma}$ are respectively amplitudes of electron normal and Andreev reflections in F1; $t^{e\sigma}$ and $t^{h\sigma}$ are the amplitudes of reflection as electron and hole into F2 which describe CT and CAR processes, respectively. Solving the system of equations one obtains scattering amplitudes; $r^{e\sigma}$, $r^{h\sigma}$, $t^{e\sigma}$, $t^{h\sigma}$. Normalized Differential conductance and the contribution of CAR to the nonlocal differential conductance of the system is calculated by the generalized Blonder-Tinkham-Klapwijk formula [6] as:

$$\frac{G}{G_F} = \frac{1}{G_F}\sum_{\sigma} G^{\sigma} \int_0^{\frac{\pi}{2}} d\varphi_1^{e\sigma} \cos\varphi_1^{e\sigma} (1 - |r^{\sigma}|^2 + |r^{h\sigma}|^2),$$

$$\frac{G_{CAR}}{G_F} = \frac{1}{G_F}\sum_{\sigma} G^{\sigma} \int_0^{\frac{\pi}{2}} d\varphi_1^{e\sigma} \cos\varphi_1^{e\sigma} |t^{h\sigma}|^2 \tag{3}$$

$G^{\sigma} = (2e^2/h)N_1^{e\sigma}(eV)$ is the spin-σ normal-state conductance that takes into account the valley degeneracy and $G_F = G^+ + G^-$. Density of states is determined by $N_1^{e\sigma}(\varepsilon) = \frac{|\varepsilon + E_{F1} + \sigma h| W}{\pi\hbar v_F}$ where W is the width of the junction. $r^{h\sigma}$ and $t^{h\sigma}$ are set equal to zero for $\varphi_1^{e\sigma} > \varphi_{1c}^{h\sigma}$ and $\varphi_1^{e\sigma} > \varphi_{2c}^{h\sigma}$, respectively. In Fig. 2 G_{CAR} is shown to have an oscillatory behavior with L/ξ with an amplitude which reaches a maximum around 1 and decays almost exponentially for $L \gg \xi$ as well as $L \ll \xi$. The oscillations are due to the quantum interference whose period is inversely proportional to the Fermi energy, E_{Fs}, in S. Inset of Fig. 2 compares the total differential conductance and the contribution of CAR to the nonlocal differential conductance. Inset of Fig. 3 is the $\frac{\varepsilon}{E_F} - \frac{h}{E_F}$ space for spin-up incident electron within an angle φ_1^{e+} of such P, p-S-n configuration. In all points of this phase space $\varphi_2^{h-} = \varphi_1^{e+}$. In this structure lines of CT=0 and AR=0 coincide. On this line, with large CAR probability, point A at $h = -E_F$, $\varepsilon/E_F \ll 1$, has corresponding point at $h = E_F$, $\varepsilon/E_F \ll 1$, for which CAR vanishes equally. This manifests a fully spin-polarized transmission through pure specular CAR. The only other point on this line having zero AR and CT for two spin species (and hence large CAR) is the point B at $h = 0, \varepsilon = -E_F$. This point is again the aforementioned non-ferromagnetic n-S-p structure.

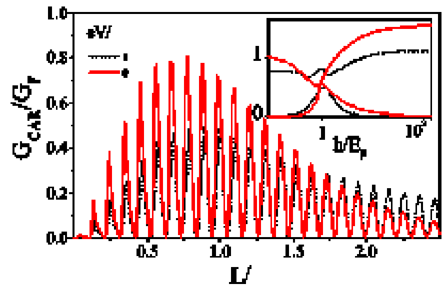

Fig. 2: G_{CAR}/G_F. Inset shows $G_{CAR}/G_F$and G/G_F, having maximum and minimum at $h/E_F = 1$, respectively, for the same values of eV/Δ.

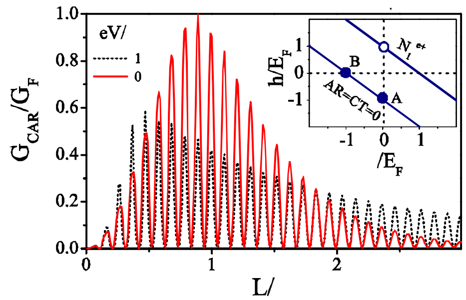

Fig. 3: G_{CAR}/G_F in P, p-S-n. Inset is the phase space of φ_2^{h-} for this structure.

Exchange-induced vanishing amplitudes of CT and AR in point A has high advantage over point B because it modifies the condition $\varepsilon = -E_F$, robust for experiment, that is required for observing CAR in point B. In Fig. 3, G_{CAR}/G_F in ferromagnetic point A is plotted as a function of L/ξ for two values of $\frac{eV}{\Delta} = 0, 1$. It reaches the maximum equal to 1 for $\frac{eV}{\Delta} = 0$ just half of the value for local specular AR in graphene; because CAR implies transmission of one electron from each of F1 and F2 to S.

Conclusions

We have modeled graphene-based FSF transistor in which applying voltage between one ferromagnetic and superconducting regions, induces a voltage to the other distant ferromagnetic through crossed Andreev refection. In its n-S-n case with AP alignment, large amount of retro crossed Andreev reflection is obtained for one spin specie at h/E_F irrespective of eV/Δ in high doping of Fs. In P-type p-S-n alternate, large spin-polarized specular CAR is obtained. So in both cases a large voltage is measurable at F2 that in some $L/\xi \approx 1$ at $\frac{eV}{\Delta} = 0$ for P-type p-S-n, with specular CAR and at $\frac{eV}{\Delta} = 1$ for AP-type n-S-n with retro CAR, equals exactly the applied voltage to F1. D-S-n and n-S-D structures are studied too.

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