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Gate tunable spin transport in graphene with Rashba spin-orbit coupling

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Recently, it attracts much attention to study spin-resolved transport properties in graphene with Rashba spin-orbit coupling (RSOC). One remarkable finding is that Klein tunneling in single layer graphene (SLG) with RSOC (SLG + R for short below) behaves as in bi-layer graphene (BLG). Based on the effective Dirac theory, we reconsider this tunneling problem and derive the analytical solution for the transmission coefficients. Our result shows that Klein tunneling in SLG + R and BLG exhibits completely different behaviors. More importantly, we find two new transmission selection rules in SLG + R, i.e., the single band to single band ($S \rightarrow S$) and the single band to multiple bands ($S \rightarrow M$) transmission regimes, which strongly depend on the relative height among Fermi level, RSOC, and potential barrier. Interestingly, in the $S \rightarrow S$ transmission regime, only normally incident electrons have capacity to pass through the barrier, while in the $S \rightarrow M$ transmission regime the angle-dependent tunneling becomes very prominent. Using the transmission coefficients, we also derive spin-resolved conductance analytically, and conductance oscillation with the increasing barrier height and zero conductance gap are found in SLG + R. The present study offers new insights and opportunities for developing graphene-based spin devices.

1. Introduction

Spin transport and control are of fundamental and practical importance in future graphene-based spintronic devices [1]. Klein tunneling is one of the most supernatural and counterintuitive transport phenomena in which an incoming electron can penetrate through a potential barrier even if its energy is lower than the barrier height [2]. Observation of this exotic phenomenon is quite difficult, because it requires extremely high energy in experiment [3]. Graphene, a single atomic layer of graphitic carbon, exhibits the liner spectrum near the Dirac points, where the carriers behave like massless Dirac fermions. This unique property makes it possible to test the relative quantum tunneling in graphene experimentally. Thus, it arouses

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intense interest to investigate Klein tunneling in graphene-based systems [4–13]. Most theoretical works focused mainly on the case of spin-independent tunneling, while spin-orbit coupling (SOC) was less considered.

The SOC in graphene comprises intrinsic and extrinsic components, which play a key role in generating a topological insulating state and manipulating electron spins. However, the intrinsic SOC in graphene is extremely weak. Thus, various methods to induce the large extrinsic SOC have been proposed theoretically [14–16] and explored experimentally [17–19]. Rashba SOC (RSOC) originating from the space inversion symmetry breaking, has attracted tremendous research interest in various field of physics and materials science [20], owing to its controllability via an external gate voltage [21]. Marchenko et al. reported a large RSOC in the Au-intercalated graphene-Ni system [17]. Such enhancement is crucial for the development of graphene-based devices such as the Das-Datta spin field effect transistor (FET) [22]. Motivated by the experimental development, recently much attention has paid to investigate the effect of RSOC on spin transport properties of graphene [23–28]. Among these works, one remarkable finding was that Klein tunneling in single layer graphene (SLG) with RSOC (SLG + R for short below) behaves as in bi-layer graphene (BLG) [25]. Considering the early work by Katsnelson et al. [4], such fantastic behavior seems somewhat surprising.

As demonstrated in Ref. [4], chiral tunneling in SLG and BLG exhibits completely different behaviors. So, why does the appearance of RSOC repaint a new tunneling picture in SLG? Admittedly, the low-energy spectrum of SLG + R and BLG has the same mathematical form [25], but this is not enough to declare that low-energy physics in SLG + R and BLG behaves similarly. First, the interlayer coupling parameter γ_1 in BLG and the Rashba coupling λ in SLG are two fundamentally different interactions. RSOC in SLG comes from the $\pi-\sigma$ hybridization [29], and unlike conventional semiconduction 2D electron gases, it is independent of the momentum. The parameter γ_1 in BLG characterizes the nearest-neighbor hopping between the two graphene layers, and almost has no effect on SOC as demonstrated in Refs. [30,31]. Furthermore, to the best of our knowledge, carriers in BLG are massive and similar to conventional non-relativistic quasiparticles [32], which are quite different from massless Dirac fermions in SLG. In fact, it requires different equations to describe electrons in BLG and SLG + R. As a result, for tunneling problems in BLG, there are four possible solutions for a given energy, and two of them correspond to evanescent waves [4] which do not exist in SLG + R. Combining these facts, we think that it is necessary to reexamine whether Klein tunneling in SLG + R behaves as in BLG.

In this paper, we reconsider the tunneling problem in SLG + R based on the effective Dirac theory. We show that the tunneling in SLG + R and BLG exhibits different behaviors. In BLG, normally incident electrons are always completely reflected by the potential barrier [4], but this is not always true for SLG + R case. In SLG + R, normally incident electrons are allowed some tunneling, but are not always perfectly transmitted, consistent with the previous report in Ref. [23]. Interestingly, when the Fermi lever in SLG + R is less than the strength of RSOC ($0 < E_F < \lambda$), the tunneling only occurs in normally incident electrons. We analyze this case and obtain the analytical solution for the transmission coefficient, revealing the properties of spin polarization independent of the height of potential barrier. We also discuss the case of $E_F > \lambda$ in more detail, and intriguing behaviors of the tunneling and the spin-resolved conductance oscillations will be shown.

This paper is organized as follows. In Sec. 2 we describe our model and solve it analytically. In Sec. 3 we investigate the subband-dependent transmission coefficients in SLG + R. Then, we derive and discuss the spin-resolved conductance in Sec. 4. In Sec. 5 we discuss the dependence of spin polarization on the barrier height. Based on the spin transport properties discussed above, in Sec. 6 we propose a conceptive graphene-spin device. Our conclusions are summarized in Sec. 7.

2. Model

Near the Dirac points K and K', the effective Hamiltonian of SLG + R is described by Ref. [33].

$$H_\tau^0 = -i\hbar v_F\left(\tau\sigma_x\frac{\partial}{\partial x} + \sigma_y\frac{\partial}{\partial y}\right) + \frac{1}{2}\lambda(\tau\sigma_x S_y - \sigma_y S_x), \tag{1}$$

where S_i and σ_i $(i = x, y)$ are Pauli matrices denoting the real spin and the pseudospin, respectively.$v_F \approx 10^6$m/s is the Fermi velocity, and λ represents RSOC strength. $\tau = \pm 1$ describes two inequivalent Dirac cones (K and K'). Considering the RSOC, the electronic bands near K point are given by

$$E_{\nu\mu} = \frac{\nu\times\mu}{2}\left[\sqrt{\lambda^2 + 4(\hbar v_F k)^2} - \mu\lambda\right], \quad \nu,\ \mu = \pm 1, \tag{2}$$

where the product $\nu\times\mu$ specifies electron and hole subbands. The corresponding eigenstates are

$$|\nu\mu\rangle = \frac{1}{\sqrt{2\left(1+\chi_{\nu\mu}^2\right)}}\begin{bmatrix} \nu e^{-i2\phi} \\ \chi_{\nu\mu}e^{-i\phi} \\ i\nu\chi_{\nu\mu}e^{-i\phi} \\ 1 \end{bmatrix}, \tag{3}$$