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Spin transport through electric field modulated graphene periodic ferromagnetic barriers

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ABSTRACT

Using the transfer matrix method, the spin transmission coefficient and the spin conductivity are studied theoretically through the monolayer and bilayer graphene periodic ferromagnetic barriers modulated by a homogeneous electric field. The spin conductivity of the systems has an oscillatory behavior with respect to the external electric field which depends on the spin state of electron. In addition, the oscillation amplitude of the spin conductivity and spin polarization increase by increasing the number of barriers, but for a monolayer system with number of barriers greater than thirty, also for a bilayer system with the number of barriers greater than four, the oscillation amplitude does not change significantly. Our probes show that for bilayer system unlike monolayer structure the highest value of spin polarization achieved can be 1 or (-1). So, for designing spintronic devices, bilayer graphene is more efficient.

1. Introduction

Graphene is a monoatomic layer of graphite densely packed into a two-dimensional (2D) honeycomb lattice and was first fabricated by Novoselov et al. in 2004 [1]. Charge carriers, i.e., electrons and holes close to the Dirac points K and K', in monolayer graphene are described by the massless Dirac equation where Fermi velocity ($v_F \approx 10^6$ m s^{-1}) plays the role of speed of light [2]. Due to the massless Dirac equation for charge carriers in graphene, tunneling through a barrier in graphene is described by the Klein tunneling mechanism [3,4]. Graphene exhibits numerous novel electronic and transport properties, for example, half-integer and unconventional quantum Hall effect [5], optical effect [6,7], finite minimal electrical conductivity [8,9], special Andreev reflection [10] and so on.

The charge carriers in bilayer graphene have parabolic energy spectrum, which means they are massive quasiparticles similar to conventional nonrelativistic electrons. Based on the arrangement of layers, a bilayer graphene can be categorized into two types, AA and AB. In AA arrangement both graphene layers are stacked directly on top of each other which yields a metastable configuration [11], whereas AB arrangement in which the two layers are stacked alternatively is a more stable structure.

In the past few years, the spin polarized transport of electrons in conventional ferromagnetic nanostructures [12], ferromagnetic monolayer graphene barrier [13–15], double ferromagnetic graphene barrier [16–18], magnetic barrier [19] and ferromagnetic monolayer graphene superlattice [20–23] have been investigated and many interesting results have been achieved. Graphene is not ferromagnetic naturally. However, researchers have recently shown that ferromagnetism state can be induced in graphene layer by different methods such as doping and defect [24], applying an external electric field [25], or depositing a ferromagnetic insulator on top of the graphene. In the latter case graphene is called “ferromagnetic graphene” [13,14]. This deposition induces an exchange splitting in graphene. For instance, a ferromagnetic state with exchange energy of $E_{ex} \sim 5$ meV can be induced by depositing the ferromagnetic insulator *EUO* (Europium oxide) on top of graphene [14]. The ability to manipulate both the charges and the spin of the electrons has led to the development of a new field of application in spintronics. The generation of a spin polarized current is a fundamental prerequisite for the construction of spintronic devices [26]. In the present paper, we study the spin transport in monolayer and bilayer graphene periodic ferromagnetic barriers modulated by a homogeneous electric field, which, to the best of our knowledge, has not already been reported in the literature. We show that the spin conductivity of systems oscillates with respect to external electric field. In spite of the fact that in monolayer graphene there is no cent percent spin polarization, our probes show that there are specific conditions in which we can get pure spin polarized current in the bilayer ferromagnetic graphene barrier structures.

The paper is organized as follows. The model and method are presented in Section 2, the results are discussed in Section 3, and finally we end the paper with a brief conclusion.

2. Model and method

In the present study we consider two kinds of systems, monolayer and bilayer ferromagnetic graphene barrier structures.

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Each system includes N square ferromagnetic barriers modulated by a homogeneous electric field. A schematic of the structures in the presence of an external electric field (E') applied between $x = l_{(1)}$ and $x = l_{(2N)} = L$ is shown in Fig. 1. The potential profile along the growth direction (the x-axis) is given by

$$V'(x) = \begin{cases} V_0 \pm E_{ex} - eE'x & \text{for barrier} \\ -eE'x & \text{elsewhere} \end{cases} \tag{1}$$

Here, V_0 is the electronic potential which is controlled by the metallic gate and E_{ex} is the exchange field. The $+$and $-$ denote the electrons with spin antiparallel or parallel to the exchange field, respectively. In order to neglect the strip edges, we focus on the case where the width of graphene strip (L_y) is much larger than the width of barrier, namely b. In addition we consider the systems at zero temperature in the absence of carrier–phonon and spin–orbit interactions.

2.1. Transport in monolayer ferromagnetic graphene

In the low energy limit, charge carriers in monolayer ferromagnetic graphene barrier structures (MFGBS) are described by noninteracting Hamiltonian $\hat{H} = \hat{H}_0 + V'(x)$, where $\hat{H}_0 = \hbar v_F \hat{\sigma}.\vec{k}$. $\vec{k}$ represents wave vector of quasiparticles, $\hat{\sigma}$ is 2D Pauli matrix and $v_F \approx 10^6$ m s^{-1} is Fermi velocity. In order to study the transport problem in MFGBS, we shall solve the Dirac equation. To solve this equation, we suppose that incident electron from the left comes through the interface with incident angle φ along the x-axis and the spin σ, and therefore, the Dirac spinor components, ψ_1^i and ψ_2^i, which are the solution to the Hamiltonian $\hat{H} = \hat{H}_0 + V'(x)$, in the ith strip can be written in the following form [19,20,27–29]:

$$\begin{aligned} \psi_1^i &= (a_i e^{ik_{ix\sigma}x} + b_i e^{-ik_{ix\sigma}x}) e^{ik_{iy\sigma}y}, \\ \psi_2^i &= s_i (a_i e^{ik_{ix\sigma}x + i\varphi_i} - b_i e^{ik_{ix\sigma}x - i\varphi_i}) e^{ik_{iy\sigma}y}, \\ s_i &= \mathrm{sgn}(E - V'(x)). \end{aligned} \tag{2}$$

Here, a_i and b_i are transmission and reflection coefficients respectively. $k_{ix\sigma}$ and $k_{iy\sigma}$ are wave vectors along the x and y-directions respectively and can be expressed as follows:

$$k_{ix\sigma} = \begin{cases} q_{x\sigma} = \frac{E - V_0 \pm E_{ex} + eE'x}{\hbar v_F} \cos\theta & \text{for barrier} \\ k_x = \frac{E + eE'x}{\hbar v_F} \cos\varphi & \text{elsewhere} \end{cases}. \tag{3}$$

$$k_{iy\sigma} = \begin{cases} q_{y\sigma} = \frac{E - V_0 \pm E_{ex} + eE'x}{\hbar v_F} \sin\theta & \text{for barrier} \\ k_{y\sigma} = \frac{E + eE'x}{\hbar v_F} \sin\varphi, & \text{elsewhere} \end{cases}, \tag{4}$$

where E is the energy of incident electron and σ denotes its spin state. Also $\theta = \tan^{-1}(k_y/q_x)$ is the refraction angle. Because the system in our model is homogeneous in the y-direction, the momentum parallel to the y-axis is conserved [13].

By applying the continuity of wave function at the boundaries for the system, we obtain $b_{1\sigma}$ and $a_{(2N+1)\sigma}$, where $b_{1\sigma}$ and $a_{(2N+1)\sigma}$ represent the reflection and transmission coefficients, respectively. The spin dependent transmission probability can be evaluated by

$$T(\varphi) = \frac{\cos\varphi_n}{\cos\varphi} |a_{(2N+1)\sigma}|^2 \tag{5}$$

Note that φ_n is emergence angle of the electron from the right side in structure, which is different from the incident angle (φ).

2.2. Transport in bilayer ferromagnetic graphene

In low energy regime, the charge carriers in bilayer graphene are described by an off-diagonal Hamiltonian [2,3]:

$$\hat{H} = -\frac{\hbar^2}{2m^*} \begin{pmatrix} 0 & (k_x - ik_y)^2 \\ (k_x + ik_y)^2 & 0 \end{pmatrix} \tag{6}$$

which yields a gapless semiconductor with chiral electrons and holes having finite mass of m^*. Here m^* is $0.035 m_e$, where m_e is the mass of bare electron. Thus, it would be possible to describe the Hamiltonian of charge carriers in the bilayer ferromagnetic graphene barrier structures (BFGBS) under the applied electric field as follows:

$$\hat{H} = -\frac{\hbar^2}{2m^*} \begin{pmatrix} 0 & (k_x - ik_y)^2 \\ (k_x + ik_y)^2 & 0 \end{pmatrix} + V'(x) \tag{7}$$

General solutions to Eq. (7) for the ith strip can be expressed by the following formulation [3,27,30]:

$$\begin{aligned} \psi_1^i(x,y) &= (a_i e^{ik_{ix\sigma}x} + b_i e^{-ik_{ix\sigma}x} + c_i e^{\kappa_{ix\sigma}x} + d_i e^{-\kappa_{ix\sigma}x}) e^{ik_{iy\sigma}y}, \\ \psi_2^i(x,y) &= s_i \left(a_i e^{ik_{ix\sigma}x + 2i\varphi_i} + b_i e^{-ik_{ix\sigma}x - 2i\varphi_i} - c_i h_i e^{\kappa_{ix\sigma}x} - \frac{d_i}{h_i} e^{-\kappa_{ix\sigma}x} \right) e^{ik_{iy\sigma}y}, \end{aligned} \tag{8}$$

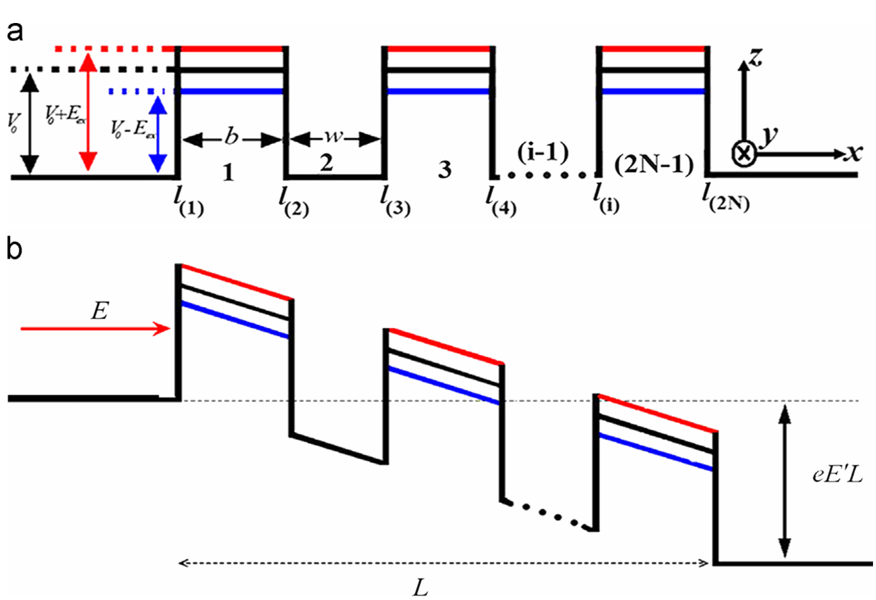

Fig. 1. A schematic view of model with N ferromagnetic barriers of width b, and $(N-1)$ wells of width w, and the system length of $l_{(2N)} = (L)$ (a) without electric field and (b) under the applied electric field E'.