Physica E 56 (2014) 227–230

Contents lists available at ScienceDirect

Physica E

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

Anisotropic quantum transport in monolayer graphene in the presence of Rashba spin–orbit coupling

Kobra Hasanirokh, Hakimeh Mohammadpour *, Arash Phirouznia

Azarbaijan Shahid Madani University, 53714-161 Tabriz, Iran

HIGHLIGHTS

- The studied model system is a ferromagnetic–normal–ferromagnetic structure on graphene.
- Rashba spin–orbit interaction is assumed in the normal region.
- The electronic transport is studied for different SOI strength and incidence angles and other parameters.
- Quantum oscillation, non-symmetry of the transport in the incident angle and etc. are observed.

ARTICLE INFO

Article history:
Received 13 March 2013
Received in revised form
17 July 2013
Accepted 3 September 2013
Available online 23 September 2013

Keywords:
Spin transport
Graphene
Rashba
Magnetic tunnel junctions

ABSTRACT

We have studied spin-dependent electron tunneling through the Rashba barrier in a monolayer graphene lattices. The transfer matrix method, have been employed to obtain the spin dependent transport properties of the chiral particles. It is shown that graphene sheets in the presence of Rashba spin–orbit barrier will act as an electron spin-inverter.

1. Introduction

Graphene with quasi relativistic energy spectrum of Dirac fermions [1,2] and unconventional quantum Hall effect (QHE) [3–5] has attracted attention from the electronic transport and spintronic research community. Experimental studies in graphene have revealed a long spin relaxation length (1 μm at room temperature) [6,7]. So, graphene is a promising candidate for spintronic devices as well as of prospective applications in nano-elecronics.

Spin-dependent electron transport have been studied extensively in grapheme [8,9]. Applications in spintronics depend on the control of spin–orbit (SO) coupling [10–12]. This interaction comprises of two different types; intrinsic and Rashba (extrinsic) couplings [13,14]. The former is induced by the carbon intra-atomic spin–orbit interaction and may open a gap in graphene energy dispersion This interaction can convert graphene to a topological insulator and induce some other interesting effects like the fractional spin Hall effect [15,16]. The intrinsic SOI is very weak in graphene and can be ignored in the calculations [17]. Theoretical calculations demonstrate that the strength of the extrinsic spin–orbit coupling can be remarkably higher than the intrinsic spin–orbit interaction [17,18]. Rashba spin–orbit interaction that arises from the structure inversion asymmetry (SIA), is introduced by a substrate surface or an external electric field [19].

The ferromagnetic layer in magnetic tunnel junctions (MTJ) [20–22] splits the energies of the electrons into two spin-resolved sub-bands. Therefore this splitting leads to spin-dependent current passing through the junctions. Manipulating the spin degree of freedom is the key point of spintronics.

Spin inversion has been studied vastly in the common as well as in nano-scale semiconductors [23,24]. It has been shown that a triple quantum dot in dc and ac magnetic fields in the presence of tunable gate voltages, acts as a spin-inverter. In Ref. [24], it has been shown that graphene sheets in the presence of Rashba spin–orbit barrier will act as an electron spin-inverter.

2. Model and approach

In this work, spin transport of the electrons has been studied in grapheme in which Dirac equation governs dynamics of the

* Corresponding author. Tel.: +98 9144076401.
E-mail address: mhmdpour@azaruniv.ac.ir (H. Mohammadpour).

1386-9477/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.physe.2013.09.002

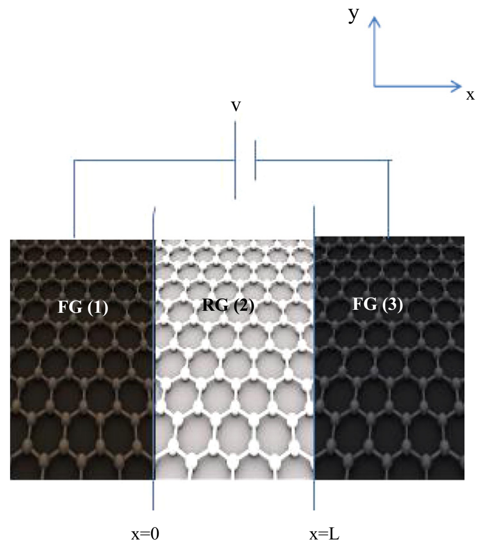

Fig. 1. Schematic illustration of the Rashba spin–orbit barrier with height λ_R and length L.

carriers. The system considered here is a ferromagnetic–Rashba barrier–ferromagnetic (FG/RG/FG) junction constructed in the x–y plane of graphene depicted in Fig. 1. RG refers to the non-magnetic graphene layer which is affected by Rashba spin–orbit interaction generated by a gate voltage placed on top of the sheet. The width of the graphene sheet is assumed to be large enough, so that we can ignore the edge effects.

The Hamiltonian in regions (1) and (3) which are assumed to be of different ferromagnetic strength is

$$H_{1(3)} = H_0 + H_{\sigma 1(3)} \tag{1}$$

H_0 is Dirac Hamiltonian for massless fermions

$$H_0 = -i\hbar v_F(\sigma_x \partial_x + \sigma_y \partial_y) \tag{2}$$

$\hbar$ is Planck constant, v_F denotes the Fermi velocity in graphene and σ is Pauli matrice in pseudospin space.

The exchange Hamiltonian $H_{\sigma 1(3)}$ is defined as

$$H_{\sigma 1(3)} = h^{(')}\sigma \tag{3}$$

where $h^{(')}$ is the exchange interaction magnitude in region 1 (3).

The Hamiltonian in the central region with Rashba interaction is

$$H = H_0 + H_R \tag{4}$$

H_R is the Rashba (SO) interaction, and is written as [25,26]

$$H_R = \lambda_R/2(\sigma_y s_x - \sigma_x s_y) \tag{5}$$

where λ_R is the strength of Rashba (SO) interaction and s_i denotes Pauli matrix in the spin space.

We have considered a spin up electron with the given energy E that propagates from the left ferromagnetic contact to the interface with Rashba region.

The wave functions of the electrons exhibit the chiral properties of the graphene. The solutions of the Dirac Eqs. (1) and (4), are in the following spinor form:

$$\psi(x \le 0) = \exp(ikx\cos\varphi)\begin{pmatrix} e^{-i\varphi/2} \\ e^{i\varphi/2} \\ 0 \\ 0 \end{pmatrix} + r\exp(-ikx\cos\varphi)\begin{bmatrix} e^{-i(\pi-\varphi)/2} \\ e^{i(\pi-\varphi)/2} \\ 0 \\ 0 \end{bmatrix} + r'\exp(-ik'x\cos\varphi')\begin{bmatrix} 0 \\ 0 \\ e^{-i(\pi-\varphi')/2} \\ e^{i(\pi-\varphi')/2} \end{bmatrix}$$

$$k' = \frac{E-h}{\hbar v_F}, \quad k = \frac{E+h}{\hbar v_F}, \quad \varphi' = \sin^{-1}(k\tan\varphi/k'). \tag{6}$$

We have assumed an incidence and reflection angle with the normal to the interface of magnitude φ (for spin up) and φ' (for spin down) in region 1, angles φ_1, φ_2, φ_3 and φ_4, in region 2 and $\overline{\varphi}$ (for spin up) and $\overline{\varphi}'$(for spin down) in region 3.

$$\psi(0 \le x \le L) = \sum_{j=1}^{4} A_j \exp(ik_j x\cos\varphi_j) \times \begin{pmatrix} \frac{\hbar v_f k_j}{E} e^{-i\varphi_j} \\ 1 \\ \left(E - \frac{\hbar^2 v_f^2 k_j(x)^2}{E}\right)\frac{1}{i\lambda_R(x)}, \\ \frac{\hbar v_f k_j}{E} e^{-i\varphi_j}\left(E - \frac{\hbar^2 v_f^2 k_j(x)^2}{E}\right)\frac{1}{i\lambda_R(x)}, \end{pmatrix} \tag{7}$$

where

$$\begin{aligned} \varphi_1 &= \tan^{-1}(k\tan\varphi/k_1), \\ \varphi_2 &= \tan^{-1}(k\tan\varphi/k_2), \\ \varphi_3 &= \pi - \varphi_1, \quad \varphi_4 = \pi - \varphi_2 \end{aligned} \tag{8}$$

r, t, r', t' are the scattering amplitudes in ferromagnetic regions (1) and (3) and A_j are the coefficients of the electronic wave function in Rashba region.

$$\psi(x \ge L) = t\frac{e^{i\bar{k}x\cos\overline{\varphi}}}{\sqrt{\cos\overline{\varphi}}}\begin{pmatrix} e^{-i\overline{\varphi}/2} \\ e^{i\overline{\varphi}/2} \\ 0 \\ 0 \end{pmatrix} + t'\frac{e^{-i\bar{k}'x\cos\overline{\varphi}'}}{\sqrt{\cos\overline{\varphi}'}}\begin{pmatrix} 0 \\ 0 \\ e^{-i\overline{\varphi}'/2} \\ e^{i\overline{\varphi}'/2} \end{pmatrix} \tag{9}$$

where

$$\begin{aligned} k_1 &= \frac{\sqrt{(E+V)^2 - \lambda_R(E+V)}}{\hbar v_F}, \\ k_2 &= \frac{\sqrt{(E+V)^2 + \lambda_R(E+V)}}{\hbar v_F} \\ k_3 &= -k_1, \quad k_4 = -k_2 \\ \bar{k}' &= \frac{E-h'}{\hbar v_F}, \quad \bar{k} = \frac{E+h'}{\hbar v_F} \end{aligned} \tag{10}$$

The factors $(1/\sqrt{\cos\varphi})$, $1/\sqrt{\cos\varphi'}$, $1/\sqrt{\cos\overline{\varphi}}$ and $1/\sqrt{\cos\overline{\varphi}'}$ in above equations ensure that all of the four states carry the same particle current density.

From the conservation of momentum along y-axis, we have

$$k\sin\varphi = k_1\sin\varphi_1 = \ldots \tag{11}$$

At the interfaces, the pseudo-spinor wave functions have to be continuous [27], so

$$\psi(0^-) = \psi(0^+), \psi(L^-) = \psi(L^+) \tag{12}$$

We obtain the scattering amplitudes by applying the boundary conditions at the interfaces.

3. Results

A numerical study of spin-transport properties in FG/RG/FG is presented in this section. The Fermi energy is taken to be E_F=1 meV and all the energies are written in units of E_F [28].

The incoming electron is assumed to be spin up polarized and the length of the Rashba spin–orbit interaction region is taken to be L=2 nm.

In Fig. 2, the transmission probability (normalized to the unit incoming electron probability) of the incoming spin up electron to the transmitted spin down state ($T_{\uparrow\to\uparrow}$) is plot as a function of the