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# Quantum transport in ferromagnetic graphene super lattice in the presence of Rashba spin–orbit coupling

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ABSTRACT

Using the transfer matrix method, we study the electron transport through a single-layer graphene superlattice with alternating layers of ferromagnetic and normal regions with Rashba spin–orbit coupling. We show that the transport properties of the system depend strongly on the superlattice parameters. As another result, Rashba spin–orbit coupling manifests to be of crucial importance in controlling the transmission probabilities and Giant Magneto Resistance (GMR).



## 1. Introduction

Recently the unique properties of graphene, a zero-gap semiconductor constructed by a one-atom-thick carbon atoms, have drawn vast attention from the research community [1–8]. Manipulating the spin degree of freedom of the transmitted carriers has high importance in the field of spintronics.

In the spintronics, spin–orbit interaction is a possible ingredient that controls the spin current with intriguing behaviors such as anomalous Hall effect [9]. Rashba effect (extrinsic spin–orbit interaction) [11,12,20] arises by breaking the structure inversion symmetry, possibly caused by ripples [10], perpendicular external electric fields [10–13], adsorbed adatoms [14–16], the substrate [17–19], etc.

Ferromagnetism in graphene has also been studied extensively [21]. The spin-resolved energy sub-band splitting in graphene-based ferromagnetic multi-layer structure [22,26] leads to spin-dependent conductance.

In Ref. [23], the conductance of the chiral particles through graphene superlattice has been studied and shown that the conductance depends strongly on the spin–orbit interaction strength.

In this paper, by employing the transfer matrix method, we have studied the electronic transport through a graphene-based ferromagnetic superlattice structure in the presence of Rashba spin orbit coupling and calculated the transmission coeffcient and GMR, for different amounts of Rashba coupling. The results reveal that the transport properties of the system depend strongly on the superlattice parameters and the spin–orbit coupling strength.

## 2. The model and calculating method

At the low-energy limit, charge carriers near Dirac points are described by Dirac Hamiltonian as follows:

$$H_0 = -i\hbar v_F(\partial_x\sigma_x + \partial_y\sigma_y)s_0$$

Where $\hbar$ and $\boldsymbol{\sigma}$ are Planck constant and Pauli matrices in the pseudospin space, respectively. $s_0$ is a unit matrix at the real spin space and Fermi velocity in graphene is $v_F = 10^6$ m/s.

We consider a one dimensional lattice made of alternating ferromagnetic and normal regions in which Rashba spin–orbit coupling is present at the normal regions. The Hamiltonian of the structure reads as

$$H = H_0 + H_1, \tag{1}$$

$$H_1 = \begin{cases} H_h = h\sigma_0 s_z, \\ [i(d+\Delta) < x < (i+1)d + i\Delta \quad (i = 0, 2, 4, 6, \ldots)] \\ H_R = \lambda_R/2(\vec{\sigma} \times \vec{s})_z, \\ [id + (i-1)\Delta < x < i(d+\Delta) \quad (i = 1, 2, 3, \ldots)] \\ H_{h'} = h\sigma_0 s_z, \\ [i(d+\Delta) < x < (i+1)d + i\Delta \quad (i = 1, 3, 5, \ldots)] \end{cases} \tag{2}$$

$H_{h(h')}$ is the exchange Hamiltonians in the alternating ferromagnetic regions and $H_R$ denotes Rashba spin–orbit interaction (SOI)

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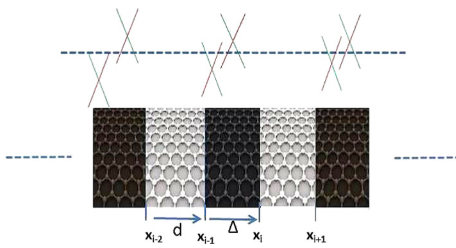


**Fig. 1.** Graphene superlattice with Rashba spin–orbit coupling.

with $\lambda_R$ standing for the Rashba SOI strengths (or Rashba constant). $\sigma_0$ is unit matrix at the pseudospin space and $s_z$ is the Pauli matrix in $z$ direction in the spin subspace. A schematic of the monolayer graphene superlattice is shown in Fig. 1.

We have considered $N$ double-layer cells each composed of one ferromagnetic layer and one Rashba layer (barrier) and then there is $(N-1)/2$ barriers.

Consider a spin-up electron with energy $E$ and wave vector $\mathbf{k}$, incident from the left ferromagnetic graphene with angle $\varphi$ to the interface with the Rashba SOI region. The general solution of the Dirac equation (Eq. (1)), results in the following spinor forms for the $i$-th ferromagnetic region:

$$\psi(x) = A_1 \exp(ikx\cos\varphi)\begin{pmatrix} e^{-i\frac{\varphi}{2}} \\ e^{i\frac{\varphi}{2}} \\ 0 \\ 0 \end{pmatrix} + A_2 \exp(ik'x\cos\varphi')\begin{bmatrix} 0 \\ 0 \\ e^{-i\varphi'/2} \\ e^{i\varphi'/2} \end{bmatrix} + A_3 \exp(-ikx\cos\varphi)\begin{bmatrix} e^{-i(\pi-\varphi)/2} \\ e^{i(\pi-\varphi)/2} \\ 0 \\ 0 \end{bmatrix} + A_4 \exp(-ik'x\cos\varphi')\begin{bmatrix} 0 \\ 0 \\ e^{-i(\pi-\varphi')/2} \\ e^{i(\pi-\varphi')/2} \end{bmatrix}. \tag{3}$$

In which, $i(d+\Delta) < x < (i+1)d + i\Delta$ $(i = 0, 2, 4, 6, \ldots)$ and $k = \frac{E+h}{\hbar v_f}$, $k' = \frac{E-h}{\hbar v_f}$, $\varphi' = \sin^{-1}(k\tan\varphi/k')$.

$A_i$s are the transmission and reflection amplitudes for up and down spins. In the Rashba layers, we have:

$$\psi(x) = \sum_{j=1}^{4} B_j \exp(ik_j x\cos\varphi_j)\begin{pmatrix} W_j \\ 1 \\ X_j \\ Y_j \end{pmatrix} id + (i-1)\Delta < x < i(d+\Delta) \quad (i = 1, 2, 3, \ldots), \tag{4}$$

$$W_j = \frac{\hbar v_f k_j}{E} e^{-i\varphi_j}, \qquad X_j = \left(E - \frac{\hbar^2 v_f^2 k_j^2}{E}\right)\frac{1}{i\lambda_R},$$
$$Y_j = W_j \times X_j, \tag{5}$$

$$k_1 = \frac{\sqrt{E^2 - \lambda_R E}}{\hbar v_f}, \qquad \vec{k}_3 = -\vec{k}_1,$$
$$k_2 = \frac{\sqrt{E^2 + \lambda_R E}}{\hbar v_f}, \qquad \vec{k}_4 = -\vec{k}_2, \tag{6}$$

$\varphi_j = \tan^{-1}(k\tan\varphi/k_j)$, $B_j$ denotes coefficients of the electron wave function in the Rashba regions.

$$\psi(x) = C_1 \exp(i\bar{k}x\cos\bar{\varphi})\begin{pmatrix} e^{-i\frac{\bar{\varphi}}{2}} \\ e^{i\frac{\bar{\varphi}}{2}} \\ 0 \\ 0 \end{pmatrix} + C_2 \exp(i\bar{k}'x\cos\bar{\varphi}')\begin{bmatrix} 0 \\ 0 \\ e^{-i\bar{\varphi}'/2} \\ e^{i\bar{\varphi}'/2} \end{bmatrix} + C_3 \exp(-i\bar{k}x\cos\bar{\varphi})\begin{bmatrix} e^{-i(\pi-\bar{\varphi})/2} \\ e^{i(\pi-\bar{\varphi})/2} \\ 0 \\ 0 \end{bmatrix} + C_4 \exp(-i\bar{k}'x\cos\bar{\varphi}'')\begin{bmatrix} 0 \\ 0 \\ e^{-i(\pi-\bar{\varphi}')/2} \\ e^{i(\pi-\bar{\varphi}')/2} \end{bmatrix},$$
$$i(d+\Delta) < x < (i+1)d + i\Delta \quad (i = 1, 3, 5, \ldots),$$
$$\bar{k} = \frac{E+h'}{\hbar v_f}, \qquad \bar{k}' = \frac{E-h'}{\hbar v_f}. \tag{7}$$

From the conservation of the $y$-component of the wave vector we have:

$$k_F \sin\varphi = k_F^i \sin\varphi_i. \tag{8}$$

The scattering amplitudes (transfer matrix components) are extracted by applying the pseudo-spin wave function continuity at the interfaces [24] as

$$\psi(x_i^-) = \psi(x_i^+), \quad i = 1, 2, 3, \ldots, N. \tag{9}$$

The total transfer matrix (T-Matrix) which makes relations between incident and transmitted wave functions will be a series product of the transfer matrices that arise from each interface.

Therefore, based on the T-Matrix method, we have obtained the transmission amplitudes for the up and down spins. The GMR for the incident spin up electrons is defined by

$$GMR = \frac{T^{(\uparrow\to\uparrow)} - T^{(\uparrow\to\downarrow)}}{T^{(\uparrow\to\uparrow)} + T^{(\uparrow\to\downarrow)}}, \tag{10}$$

where $T^{(\uparrow\to\uparrow)} = t^*t$ and $T^{(\uparrow\to\downarrow)} = t'^*t'$ are spin-dependent transmissions with $t$ and $t'$, the transmission amplitude as spin up and spin down, respectively.

## 3. Results and discussion

The calculated spin transport properties in the model graphene superlattice are indicated in this section. It should be noted at the outset that the incoming electrons are polarized in up spin state and all energies are written in terms of the Fermi energy, $E_F$, that we take it as $E_F = 1$ meV [25].

Let us first present the spin-dependent transmission probabilities. Probabilities of the transmission of the electrons with incidence amplitude normalized to 1, as up ($T$) and down ($T'$) spins, are plot as a function of the incidence angle, $\varphi$, in Fig. 2. We assume $h' = 0.1$, $h = -0.1$ and $\lambda = 0.1$ (in units of $E_F$) and $d = 0.2$, $\Delta = 0.3$ (in units of $\lambda_F$) in which $d$ and $\Delta$ are the lengths of the Rashba and ferromagnetic regions, respectively.

We take a FG/NG/FG/NG/FG junction ($N = 5$) as a unit cell of the superlattice (Fig. 2(top)) where FG and NG denote the ferromagnetic and Rashba barrier regions, respectively and a case with $N = 21$ is explored in Fig. 2(bottom).

Fig. 2(top) demonstrates that for $\varphi \ll \frac{\pi}{2}$, $T' \approx 0$ $(\equiv T^{\uparrow\to\downarrow})$, so the spin current can be effectively controlled. As shown in these