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# Spin transport and wavevector-dependent spin filtering through magnetic graphene superlattice

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ABSTRACT

We investigate the spin transport properties of magnetic graphene superlattice in the presence of Rashba spin–orbit interaction (RSOI). We consider two types of magnetic profiles: a sequence of $N$ square magnetic barriers and a sequence of delta magnetic barriers. In the first case it is found that the angular range of the spin transmission through magnetic graphene superlattice can be efficiently controlled by the number of barriers and this renders the structure's efficient wavevector-dependent spin filters. As the number of magnetic barriers increases, the angular range of the spin transmission decreases, the gaps in transmission and conductivity versus energy become wider. In the second case, when the magnetic field is present, the spin polarization increase with increasing the magnetic field. In both cases, the magnetoresistance ratio shows a strong dependence on the number of magnetic barriers.


## 1. Introduction

Graphene, a two-dimensional material with a monolayer honeycomb lattice of carbon atoms, has been fabricated experimentally by Novoselov et al. [1]. In graphene, the energy dispersion relation is approximately linear in the proximity of the Dirac points (often referred to as $K$ and $K'$) where the electron and hole bands touch. Such a peculiar band structure results in many interesting phenomena, including the observer of half-integer quantum hall effect [2], special Andreev reflection [3], Klein tunneling [4] and many others. To circumvent the Klein tunneling effect, it has been suggested that a magnetic barrier can effectively block Klein tunneling and achieve confinement for such massless Dirac fermions for graphene [5]. The required magnetic structures in graphene can be realized by depositing ferromagnetic stripes on the graphene layer [6,7]. In past few years, transport properties through magnetic graphene barriers [5,8–10] and magnetic graphene superlattice [11–15] have been investigated and many interesting results have been achieved, e.g. wavevector filtering and an angular confinement of the transmission. In all these works the spin degree of freedom has been completely neglected. This is justified because of the smallness of Zeeman splitting in graphene [16]. On the other hand, the study of spin transport is one of the most active fields in graphene research. The generation of a spin-polarized current is a fundamental prerequisite for the construction of spintronic devices [17]. Meanwhile, Dedkov et al. have shown experimentally that, if graphene is grown directly onto the Ni (111) substrate the Rashba spin–orbit interaction (RSOI) strength $\lambda_R$ can reach values up to 200 meV at room temperature [18]. However, Rader et al. later argued that the splitting observed by Dedkov et al. was not related to RSOI [19]. In an experimental study, Varykhalov et al. have reported that the interaction of Au atoms between the graphene and Ni substrate can enhance the Rashba spin splitting to a large value of the order of 13 meV [20]. Recently, Gierz et al. have also observed a large RSOI strength up to 200 meV in a graphene monolayer at the sample temperature of 100 K where the graphene epitaxially grows on the substrate of SiC [21]. In graphene the RSOI originates from the interaction of carbon atoms with the substrate electric field or presence of a perpendicular external electric field (generated by a gate) [22,23]. The purpose of this paper is to study the spin-transport properties through magnetic graphene superlattice in the presence of the RSOI by using the transfer matrix method. The effect of the number of barriers on the spin transmission probability and spin conductivity is taken into account. We show that the angular range of spin transmission through magnetic graphene superlattice can be efficiently tuned by controlling incident energy, RSOI strength or by increasing the number of barriers. Our probe shows that when a magnetic field is present, the spin polarization can be observed, whereas for the RSOI alone it is zero. In addition, the dependence of the magnetoresistance ratio to the number of barriers, Fermi energy, and RSOI strength is investigated.

The paper is organized as follows. Theory and method are presented in Section 2, the results are discussed in Section 3, and a brief summary and conclusion are given in Section 4.

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## 2. Model and theory

In this paper, we consider two kinds of systems. In both cases, a monolayer graphene covered by a thin insulating layer and parallel ferromagnetic (FM) stripes are deposited on the top of the dielectric layer [6,7]. Further, a gate voltage is applied to the FM stripes in order to produce a controllable Rashba coupling [24,25]. In the first case FM stripes have magnetization perpendicular to the graphene in the $x$–$y$ plane. In the second case FM stripes with magnetization parallel ($P$) or antiparallel ($AP$) to the growth direction (the $x$ axis) are deposited on top of the dielectric layer. Thus, the systems under consideration are magnetic graphene superlattice consisting of $N$ barriers, where the barrier region with the RSOI is separated by a normal graphene (NG) in which RSOI is absent. The magnetic field $B(x)$ emerging from the FM stripes will influence locally the motion of Dirac electrons in the graphene $x$–$y$ plane and is assumed to be homogeneous in the $y$ direction, but varies along the $x$ direction. The schematic of the structures is shown in Fig. 1.

According to the above discussion, we shall consider two types of magnetic field profiles. In the first case, illustrated in Fig. 1 (b) and (c), the profile consists of a sequence of $N$ magnetic barriers of equal height $B$ and width $b$, separated by well regions (nonmagnetic regions) of width $w$. In the second case, illustrated in Fig. 1(e) and (f), each magnetic barrier can be approximated by several delta functions. Here, the effects of electron–electron and electron–phonon interactions are neglected by considering a single electron transmission at zero temperature. Therefore, the charge carriers in our model are described by the following Hamiltonian:

$$H = H_0 + H_{RSO}, \tag{1}$$

in which,

$$H_0 = \hbar v_F \sigma(\vec{p} + e\vec{A}), \quad H_{RSO} = \frac{\lambda_R}{2}(\sigma \times s)_z, \tag{2}$$

where $\vec{p}$ is the quasiparticle momentum, $\sigma$ is the 2D Pauli matrix, $v_F \approx 10^6\ \mathrm{ms}^{-1}$ is the Fermi velocity, $\vec{A} = [0, A_y(x), 0]$ is the vector potential with $\partial_x A(x) = B(x)$ in the Laudau gauge. The vector $s = (s_x, s_y)$ acts in spin space. It is necessary to mention that the term $H_{RSO}$ contains the RSOI in magnetic graphene superlattice with the strength of $\lambda_R$. For simplicity, we express all the quantities in the dimensionless form by rescaling: the magnetic field $B(x) \to B_0 B(x)$, the vector potential $A(x) \to B_0 l_B A(x)$ with the magnetic length $l_B = \sqrt{\hbar / e B_0}$, the wavevector $k \to k/l_B$, the electron energy $E \to E\hbar v_F / l_B$, RSOI strength $\lambda_R \to \lambda_R \hbar v_F / l_B$, the barrier of width $b \to b l_B$ and well of with $w \to w l_B$. For a realistic value $B_0 \approx 0.1$ T [26,27] we find $l_B = 80$ nm and $\hbar v_F / l_B \approx 7$ meV, which set the typical length and energy scales. To solve Eq. (1), we suppose that an incident electron from the left will go towards the interface with incident angle $\phi$ and spin $s$. The general solution to the Hamiltonian $H$ can be expressed in the following form [20,28].

$$\begin{cases} \Psi = a\psi_{Ns}^{+} + b\psi_{Ns}^{-} + c\psi_{Ns'}^{+} + d\psi_{Ns'}^{-}, \\ \Psi = a'\psi_{s}^{+} + b'\psi_{s}^{-} + c'\psi_{s'}^{+} + d'\psi_{s'}^{-}. \end{cases} \tag{3}$$

where $s(s') = +1(-1)$ corresponds to the expectation value of the spin projection. $a, b, c, d$ and $a', b', c', d'$ represent the ampliudes of quasiparticles in the well and barrier regions, respectively. Also $\psi_{Ns}^{\pm}$ and $\psi_{s}^{\pm}$ are the wave functions traveling along the $\pm x$ in the well and barrier region respectively, and can be expressed by the following form:

$$\begin{aligned} &\psi_{N\uparrow(\downarrow)}^{\pm} = (1(0), \pm e^{\pm i\phi}(0), 0(1), 0(\pm e^{\pm i\phi})) e^{i(\pm k_x x + k_y y)} / \sqrt{\cos\phi}, \\ &\psi_{s'(s)}^{\pm} = ((\pm k_{s'(s)} - i k_y), E, \ -is'(s)E, \ -is'(s)(\pm k_{s'(s)} + i k_y)) \\ &\qquad \times e^{i(\pm k_{s'(s)} x + k_y y)} D_{s'(s)}, \\ &D_{s'(s)} = 1 / \sqrt{2(|k_{s'(s)}|^2 + k_y^2 + E^2)}. \end{aligned} \tag{4}$$

where $E$ is the energy of incident electron, $k_{s'(s)} = \sqrt{(E)(E - s'(s)\lambda_R) - k_y^2}$ and $k_x = E\cos\phi$ are the wave vectors along the $x$ direction in the barrier and well regions respectively, while $k_y = E\sin\phi + A(x)$ is the wave vectors along the $y$ axis. By appling the continuity of wave functions at the boundaries for a system consisting of $N$ barriers and using the transfer-matrix method, we obtain the $t_{s's}$ and $r_{s's}$, where $t_{s's}$ is the transmission coefficient for

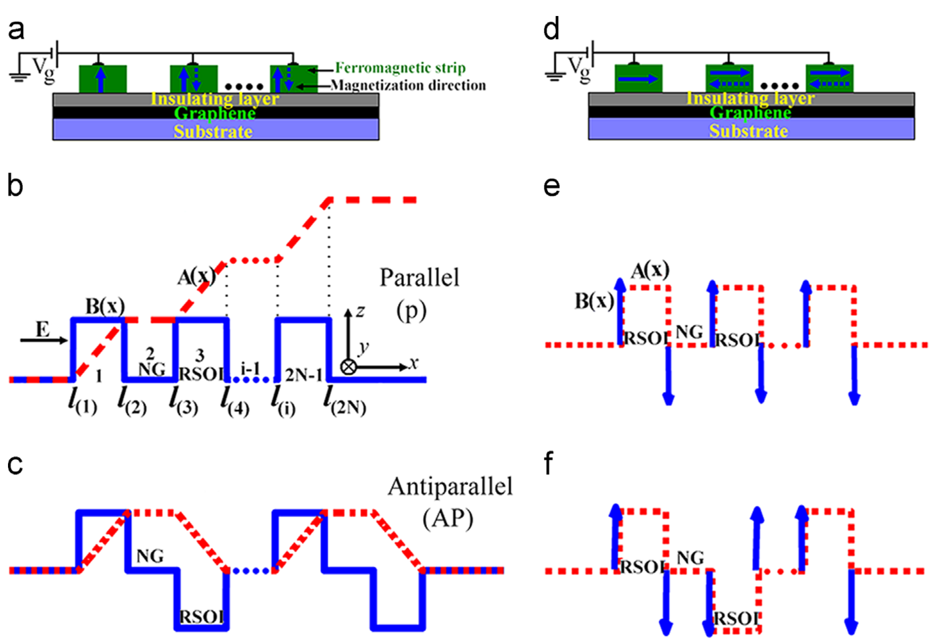


**Fig. 1.** (Color online) Schematic illustration of the monolayer graphene covered by a thin insulating layer; parallel FM stripes are deposited on top of the insulating layer. The gate voltage $V_g$ applied on the FM stripes controls the Rashba coupling. (a) FM stripes have magnetization parallel ($P$) or antiparallel ($AP$) to the $z$ axis. (d) Each FM stripe has a magnetization $P$ or $AP$ to the $x$ axis. (b) Magnetic field profile $B(x)$ and corresponding vector potential $A(x)$ when FM stripes have magnetization parallel to the $z$ axis. (e) $B(x)$ and $A(x)$ when FM stripes have magnetization parallel to the $x$ axis. (c) The same as in (b) but in the $AP$ alignment. (f) The same as in (e) but in the $AP$ alignment.