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Spin transport in graphene spin–orbit barrier structure

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ABSTRACT

We studied spin-dependent transport in monolayer graphene with a spin–orbit barrier, a narrow strip in which the spin–orbit interaction is not zero. When the Fermi energy is between the two spin-split bands, the structure can be used to generate spin-polarized current. For a strong enough Rashba strength, a thick enough barrier or a low enough Fermi energy, highly spin-polarized current is generated (polarization ~ 0.7–0.85). Under these conditions, the spin direction of the transmitted electron is approximately perpendicular to the direction of motion. This shows that graphene spin–orbit nanostructures are useful for the development of graphene spintronic devices.

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The spin properties of graphene have attracted a lot of research interest recently because, for its long spin coherence time, it is regarded as a material suitable for spintronic devices [1–4]. However, it has the drawback that the control of spin is not as easy as in semiconductors as spin–orbit interaction in graphene is small [5–8]. Theoretical studies have already been carried out on how to manipulate spin using ferromagnetic proximity effect [9–14]. Nevertheless, these proposals have not been demonstrated experimentally. As a result, the manipulation of spin in graphene is still an open challenge. Recently experimental and theoretical studies [15,16] have shown that it is possible to induce strong spin–orbit interaction (SOI) in graphene, which stimulate the interest in using this effect to manipulate spin. There are already some studies of the electronic structure of graphene with spin–orbit interaction and spin-dependent scattering by SOI nanostructures [17–22]. However, the generation of spin polarization or spin current by SOI in graphene has received little attention despite it is a very important topic in the field of spintronics [23] and the recent strong interest in graphene spintronics. In particular, it is not clear how to generate significant spin-polarized current in bulk graphene and it is our objective here to address this issue. We found that it is possible to generate spin-polarized current using a simple SOI barrier without the assistance of lateral confinement and external magnetic field. We also found that the spin polarization can be maximized by reducing the influence between the evanescent waves in the barrier. These results are very useful as they show that a complicated nanostructure is not required for spin current generation in graphene and relatively simple experimental requirement is sufficient.

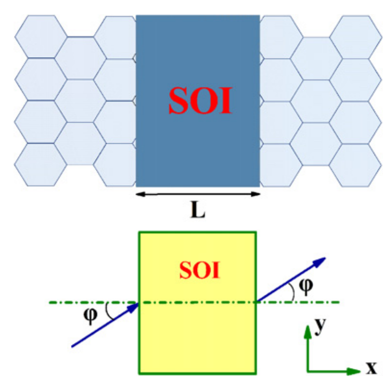

Fig. 1. (Color online.) Top: Schematic diagram of a monolayer graphene sheet with a SOI region which has a thickness L. Bottom: Definition of the incident angle φ.

The system we consider is a monolayer graphene with an SOI barrier, inside which the SOI is non-zero, while it is zero outside the barrier (see Fig. 1 for a schematic diagram and definitions of symbols). When a small bias is applied across the SOI barrier, a spin-polarized current can flow perpendicular to the barrier

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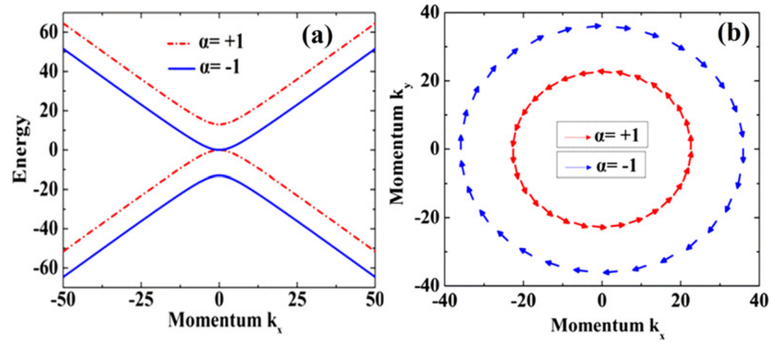

Fig. 2. (Color online.) (a) The energy band structure of graphene with Rashba SOI with a fixed angle $\varphi = \arctan(k_y/k_x) = \pi/6$. The upper ($\alpha = +1$, the dash–dot line) and lower ($\alpha = -1$, the solid line) spin-split branches are shown. (b) The spin direction of the energy eigenstates. The red arrows ($\alpha = +1$, the inner circle) and blue arrows ($\alpha = -1$, the outer circle) show the spin direction of upper and lower spin-split branches respectively. Fermi energy is set to be $E_F = 30$. Here we have set $\hbar = \nu_F = 1$.

along the x-direction, owing to the presence of the SOI barrier, which makes the transmission spin-dependent. The motion of electron in the K valley is described by the Hamiltonian with space-dependent spin–orbit interaction [24] $H_k = \hbar\nu\vec{\sigma}\cdot\vec{k} + \lambda(x)(\vec{\sigma}\times\vec{s})_z/2$, where $\lambda(x) \neq 0$ inside the barrier with thickness L, i.e. $0 < x < L$. The K' valley Hamiltonian is related to the K valley one by the transformation $H_{K'} = \sigma_y H_K \sigma_y^{-1}$.

We have carried out a symmetry analysis as in Ref. [25] and found that the spin-dependent transmissions and the spin-polarized currents are identical for the two valleys in the present system. So, we consider only the K valley. For electrons incident from the left, the spin-dependent conductance of the structure is $G_{s_R s_L} = G_0 \int_{-\pi/2}^{\pi/2} |t_{s_R s_L}|^2 \cos(\theta)\, d\theta$, where $G_0 = \frac{2e^2 E_F L_y}{h\pi \nu_F}$ and $t_{s_R s_L}$ is the spin-dependent transmission between spin S_L and S_R. E_F is the Fermi energy and L_y is the transverse dimension of the sample. We used the following definitions of spin polarization given in Refs. [25] and [26] to determine the degree of polarization of the current in terms of the spin-dependent conductance $P_x = \mathrm{Re}[2G_{xy}/G]$, $P_y = \mathrm{Im}[2G_{xy}/G]$, $P_z = (G_{\uparrow\uparrow} + G_{\uparrow\downarrow} - G_{\downarrow\uparrow} - G_{\downarrow\downarrow})/G$, where $G_{xy} = G_0 \int_{-\pi/2}^{\pi/2} (t_{\downarrow\uparrow} * t^*_{\uparrow\uparrow} + t_{\downarrow\downarrow} * t^*_{\uparrow\downarrow}) \cos(\theta)\, d\theta$ and G is the total conductance

$$G = \sum_{s_R, s_L} G_{s_R s_L} = G_{\uparrow\uparrow} + G_{\uparrow\downarrow} + G_{\downarrow\uparrow} + G_{\downarrow\downarrow}.$$

To find the conductance and the transmission of the structure we first find the scattering wave function by matching the wave function across the boundary as in Bercioux and De Martino [17]. For this purpose, we need the energy dispersion and electron wave functions in different regions, and in the SOI barrier they are given by (with $\hbar = 1$ and $\nu_F = 1$):

$$E_{\alpha\beta} = \frac{\alpha\lambda}{2} + \beta\sqrt{k^2 + \left(\frac{\lambda}{2}\right)^2},$$

$$\psi_{\alpha\beta} = \frac{1}{\sqrt{N_{\alpha\beta}}}\left(\frac{(k_x - ik_y)}{k}\frac{1}{\sqrt{\xi_{\alpha\beta}}},\ \sqrt{\xi_{\alpha\beta}},\ i\alpha\sqrt{\xi_{\alpha\beta}},\right.$$
$$\left. i\alpha\frac{(k_x + ik_y)}{k}\frac{1}{\sqrt{\xi_{\alpha\beta}}}\right)^T$$

where $\alpha = \pm 1$ and $\beta = \pm 1$. $\beta = +1$ (-1) is for conduction (valence) band and the two values of α are for the two spin-split bands of the conduction and valence bands. $\xi_{\alpha\beta} = E_{\alpha\beta}/k$ and $N_{\alpha\beta} = 2(\xi_{\alpha\beta} + 1/\xi_{\alpha\beta})$ is the normalization constant. Without SOI, the energy dispersion is spin-degenerate. Under SOI it is split into two branches and the spin direction of the eigenstate is perpendicular to the k vector, but opposite in the two branches as the expectation of the spin operator is $\langle\psi_{\alpha\beta}|\vec{s}|\psi_{\alpha\beta}\rangle = (-2\alpha k_y, 2\alpha k_x, 0)/kN_{\alpha\beta}$ (see Fig. 2 for the dispersion and spin orientation under SOI). Different from semiconductors with SOI, there is a gap between the two spin-split bands and this gap can be used to generate spin-polarized current.

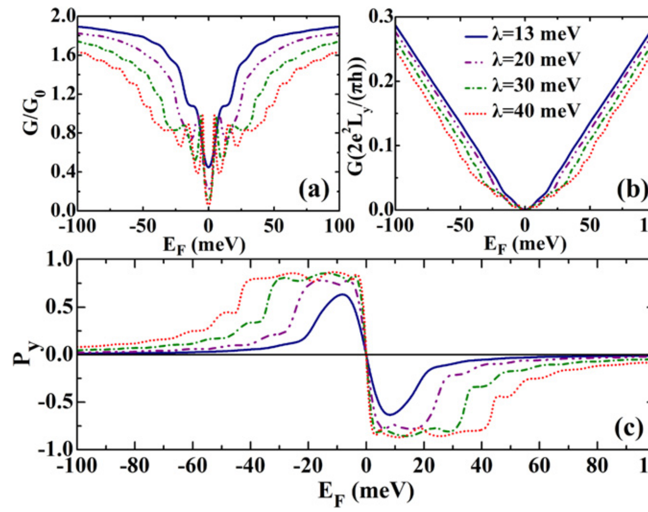

Fig. 3. (Color online.) (a) Normalized conductance G/G_0, (b) total conductance G in unit of $2e^2L_y/(h\pi)$ and (c) spin polarization along the y-axis plotted as functions of Fermi energy under several values of Rashba SOI strength $\lambda = 13$, 20, 30, 40 meV. The thickness of the SOI region $L = 150$ nm.

In Fig. 3, the conductance and the spin polarization of the current produced by applying a small bias across the SOI barrier are shown. Only P_y is shown as polarizations along the x- and z-directions are zero. We found that the x-direction polarization of the transmitted electrons denoted by p_x is an odd function of the incident angle φ (see Figs. 5 and 6 below), so P_x involving an average over the angle is zero. The z-direction polarization of the transmitted electrons, denoted by p_z, is zero for all incident angles, and thus P_z is zero. The y-direction polarization of the transmitted electrons is an even function of the incident angle. To explain these properties of p_x and p_y, we consider the relation between the Hamiltonian for $\vec{k} = (k_x, -k_y)$, $H' = H(k_x, -k_y)$, and the Hamiltonian for $\vec{k} = (k_x, k_y)$, $H = H(k_x, k_y)$. They are related by the transformation $H' = RHR^{-1}$ where $R = \sigma_x s_y$. So the scattering wave function of H' with energy E, denoted by ψ', is related to the scattering wave function of H, denoted by ψ, by $\psi' = R\psi$. The expectation values of the spin current operators $\nu^s_{yx} = \nu[\sigma_x s_y + s_y\sigma_x]/2$ and $\nu^s_{xx} = \nu[\sigma_x s_x + s_x\sigma_x]/2$ have the following relation for these two eigenstates. $\langle\psi'|\nu^s_{yx}|\psi'\rangle = \langle\psi|R^{-1}\nu^s_{yx}R|\psi\rangle = \langle\psi|\nu^s_{yx}|\psi\rangle$ and $\langle\psi'|\nu^s_{xx}|\psi'\rangle = \langle\psi|R^{-1}\nu^s_{xx}R|\psi\rangle = -\langle\psi|\nu^s_{xx}|\psi\rangle$.

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