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Valley-dependent electron transport in ferromagnetic/normal/ferromagnetic silicene junction

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ABSTRACT

The electron transport through ferromagnetic/normal/ferromagnetic silicene junction with an induced energy gap is investigated in this work. The energy gap can be tuned by applying electric field or exchange fields due to the buckled structure of silicene. We analyze the local electric field, exchange field, length of normal region-dependence transmission probabilities of four groups and valley conductance. These transmission probabilities and valley conductance can be turned on or off by adjusting the local electric field and exchange field. In particular, a fully valley polarized conductance with 80% transmission is found in this junction, which can be caused by the interplay of valley-dependent massive Dirac electron, the exchange potential and the on-site potential difference of sublattices. Our findings will benefit applications in silicene-based high performance nano-electronics.

1. Introduction

Valleytronics, which was firstly developed in graphene [1,2], have recently attracted great interests due to its prominent applications on electric control [3–7], magnetic control [8,9] and information carrier [10,11]. The independence and degeneracy of the valley degree of freedom in graphene suggest it might be a candidate for valleytronics. However, it is hard to realize valleytronics in experiment due to the zero gap in graphene [12,13], because a key point for valleytronics would be only one single valley current dominated in graphene.

Silicene, a single layer of silicon atoms arranged in a two dimensional honeycomb lattice, has been successfully synthesized in 2010 [14–16]. This material has a large spin–orbit gap compared to graphene and buckled sublattices made of A and B sites [17,18], which become a new playground of valleytronics. The buckled structure of silicene implies an intriguing possibility that we can control the electron transport properties by applying an electric field [19,20] or exchange field [21,22]. Recently, there has been considerable attention drawn to study the electronic transport in silicene-based tunnel junction. N. Nagaosa and co-workers investigate charge transport of pn junction made from silicene and show that the conductance is almost quantized to be 0, 1, and 2 by external electric field [23]. Also, the topological phases of silicene, characterized by spin-valley structure, are studied by introducing different exchange fields on the A and B sites in 2013 [22]. Subsequently, a fully spin-valley polarized is found in the silicene-based normal/ferromagnetic/normal, normal/superconductor/normal, and ferromagnetic metal/Ferromagnetic insulator/ferromagnetic metal tunnel junction [24–26]. These works have offered a possibility to a realization of valleytronics. However, the maximum transmittance for single spin or valley conductance is no more than 40% in these papers [24,26].

In this paper, we theoretically investigate the electron transport properties through ferromagnetic/normal/ferromagnetic junction in silicene. The electrons are perfectly transmitted with more angles for a longer normal region. Each spin and valley transmission probability can be strongly restricted for a larger electric field. However, the transmission probability for K' valley electron with spin down is turned on by adjusting the exchange field. In particular, an efficiency conductance with near 80% transmittance for single K' is found in this junction.

2. Model and theoretical method

The schematic picture of the model is shown in Fig. 1. We assume the single layer silicene sheet in the $k_x k_y$ plane, the electrons with Femi energy E_F propagate at an angle ϕ with respect to the k_x axis, the angle of refraction in the normal region is θ and the transmission angle is still ϕ. The length of the normal region is L.

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The low-energy effective Hamiltonian acquired from tight binding model around Dirac point in silicene can be described by [22,23].

$$H = \begin{pmatrix} -(\eta\sigma\lambda_{SO} - \Delta_z) - \sigma h & \hbar v_F(k_x + i\eta k_y) \\ \hbar v_F(k_x - i\eta k_y) & \eta\sigma\lambda_{SO} - \Delta_z - \sigma h \end{pmatrix} \quad (1)$$

where λ_{SO} represents the effective spin–orbit coupling (SOC) at the Dirac points, Δ_z denotes the on-site potential difference between the A and B sublattices, which can be tuned by an local electric field. $\eta = +1/-1$ is the valley K and K'. $\sigma = +1/-1$ distinguishes the spin-up and spin-down. $v_F \sim 5.5 \times 10^5$ m/s is the Fermi velocity. h is the exchange field induced by the magnetic proximity effect in ferromagnetic region. The magnetization directions of region I and III are parallel to the positive k_y direction. $k_x = k\cos\phi$ and $k_y = k\sin\phi$ are the perpendicular and parallel wave vector components of the incidence electron with $k = \sqrt{(E_F + \sigma h)^2 - (\eta\sigma\lambda_{SO})^2}/\hbar v_F$.

Assuming the electric field is applied perpendicular to the $k_x k_y$ plane in the normal region, the $\Delta_z = 0$ in ferromagnetic region and $h = 0$ in the normal region, the wavefunctions of three regions can be written as.

$$\Psi_I = \frac{1}{\sqrt{2\varepsilon_f(E_F + \sigma h)}} \begin{pmatrix} \hbar v_F(k_x + i\eta k_y) \\ \varepsilon_f \end{pmatrix} e^{ik_x x} + \frac{r_{\eta\sigma}}{\sqrt{2\varepsilon_f(E_F + \sigma h)}} \begin{pmatrix} -\hbar v_F(k_x - i\eta k_y) \\ \varepsilon_f \end{pmatrix} e^{-ik_x x} \quad (2)$$

$$\Psi_{II} = \frac{a_{\eta\sigma}}{\sqrt{2E_F E_N}} \begin{pmatrix} \hbar v_F\left(k'_x + i\eta k'_y\right) \\ E_N \end{pmatrix} e^{ik'_x x} + \frac{b_{\eta\sigma}}{\sqrt{2E_F E_N}} \begin{pmatrix} -\hbar v_F\left(k'_x - i\eta k'_y\right) \\ E_N \end{pmatrix} e^{-ik'_x x} \quad (3)$$

$$\Psi_{III} = \frac{t_{\eta\sigma}}{\sqrt{2\varepsilon_f(E_F + \sigma h)}} \begin{pmatrix} \hbar v_F(k_x + i\eta k_y) \\ \varepsilon_f \end{pmatrix} e^{ik_x x} \quad (4)$$

with $\varepsilon_f = E_F + \sigma h + \eta\sigma\lambda_{SO}$ and $E_N = E_F + \eta\sigma\lambda_{SO}\text{-}\Delta_z$, k'_x and k'_y are the perpendicular and parallel wave vector components of the transmitted electron with $k' = \sqrt{E_F^2 - (\eta\sigma\lambda_{SO} - \Delta_z)^2}/\hbar v_F$. $r_{\eta\sigma}$ and $t_{\eta\sigma}$ are reflection and transmission coefficients. The parallel wave vector component is conserved due to the translational invariance in the k_y direction. Using continuity condition of wave function at the boundary, we acquire the following set of equations:

$$\Psi_I(x=0) = \Psi_{II}(x=0), \quad \Psi_{II}(x=L) = \Psi_{III}(x=L). \quad (5)$$

The transmission coefficients through such a silicene junction can be calculated as:

$$t_{\eta\sigma} = \frac{A[X\cos(kL\cos\phi) + Y\sin(kL\cos\phi)] - iA[X\sin(kL\cos\phi) - Y\cos(kL\cos\phi)]}{X^2 + Y^2} \quad (6)$$

where

$$A = 4k'_x k\cos\phi\,\varepsilon_f E_N,$$

$$X = 4k'_x k\cos\phi\cos(k'_x L)\varepsilon_f E_N,$$

$$Y = \left(2k'^2\varepsilon_f^2 - 4\eta^2 k^2\sin^2\phi\,\varepsilon_f E_N + 2k^2 E_N^2\right)\sin k'_x L.$$

The transmission probability can be given by $T_{\eta\sigma} = A^2/(X^2 + Y^2)$ for the electrons traveling through the normal region. Under the zero-temperature regime. The spin and valley resolved ballistic conductance can be calculated using Landauer–Büttiker formula [27] by integrating overall the incident angles:

$$G_{\eta\sigma} = \frac{4e^2 kW}{2\pi h}\int_{-\pi/2}^{\pi/2} T_{\eta\sigma}\cos\phi\, d\phi = G_0 g_{\eta\sigma}. \quad (7)$$

where $G_0 = 4e^2 kW/\pi h$ with W being the width of the silicene sheet in the k_y direction and k is the wave vector of ferromagnetic silicene.

We define the normalized valley resolved and valley polarization conductance as.

$$g_\eta = \frac{1}{2}\left(g_{\eta,1} + g_{\eta,-1}\right), \quad (8)$$

$$\Delta g = \frac{g_{1,1} + g_{1,-1} - g_{-1,1} - g_{-1,-1}}{g_{1,1} + g_{1,-1} + g_{-1,1} + g_{-1,-1}}. \quad (9)$$

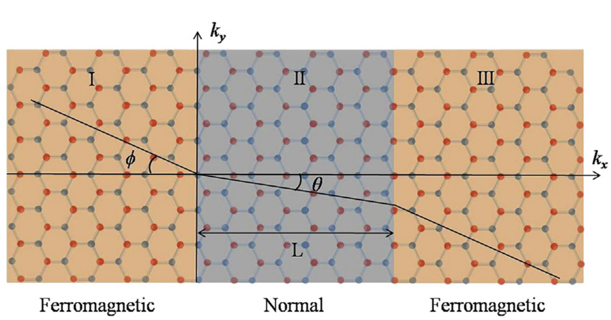

Fig. 1. (Color online) Schematic picture of the model. There is a tuned electric field fixed in the normal region of $0 \le x \le L$. ϕ denotes the incidence angle of electrons and θ is the refraction angle.

3. Results and discussion

After some tedious algebras, we obtain the transmission probability as a function of the incident angle ϕ at different conditions shown in the Fig. 2. From Fig. 2(a), we can see that the structure remains high transmission probability for each $T_{\eta\sigma}$ with a wide range of incident angles, especially at some special angles, it's perfect transparent. In fact, this transmission is related to the thickness of normal region, the positions and numbers of resonant peaks increase as the thickness of normal region in Fig. 2(b), it is the feature unique to the tunneling effect due to the chiral nature of their quasiparticles, which is qualitatively different from the case of normal non-relativistic. For a larger $\Delta_z = 1.4\,E_F$ in Fig. 2(c) compared with Fig. 2(a), the $T_{1,-1}$ and $T_{-1,1}$ are strongly restricted to 0, while