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Electric-field strength and doping level controlled spin-valley transport in a silicene *np* junction

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ABSTRACT

The performance of *np* junction, as the basic unit of electronic devices, often determines the prospect of a material. We here investigate the spin- and valley-polarized transport in a silicene *np* junction, where a ferromagnetic field and a perpendicular electric field are applied in the *p*-doped region. It is found that pure spin current with valley polarization can be obtained under the control of electric-field strength and doping level, arising from the specific dispersion with spin- and valley-polarizations. By tuning the electric field properly, one can even realize a controllable state that supports 100% spin- and valley-polarized transport. At fixed electric field, we also demonstrate that the ferromagnetic field can greatly affect the ratios of spin- and valley-polarizations. These findings suggest that silicene is a promising material for application in future spintronics and valleytronics devices.

1. Introduction

One-atom-thick silicene, a new two-dimensional Dirac material after graphene, provides a platform for future devices based on spintronics and valleytronics because it fuses multiple degrees of freedom including spin, sublattice pseudospin and valley [1,2,4,3,5]. As a new type Dirac material, silicene has mainly two advantages: one is that its band gap may be tuned by applying a perpendicular electric field owing to the buckled structure [6,7]; the other is that silicene could be incorporated easily into the silicon-based nanotechnology [8]. Previous studies have shown that silicene has a relatively large spin-orbit gap, compared with graphene, and thus serves as a good candidate to realize the quantum spin Hall state with gapless edge states [9]. Under the control of external fields, many exotic states in silicene have been theoretically found, including the quantum anomalous Hall state driven by ferromagnetic field [10,11], topological superconductivity induced by antiferromagnetic exchange field and *s*-wave superconducting proximity effect [12].

Like in graphene, there also exist two inequivalent valleys in silecene. The difference between two valleys might lead to valley polarization [10,11]. So far, valley has become a nontrivial degree of freedom in studying silicene, just as electron real-spin and sublattice pseudospin [12–14]. Notably, the valley polarization has been recently confirmed experimentally in graphene mono- and bi-layers [15–18], and is also believed to be verified in silicene. In the aspect of silicene application, the first silicene field effect transistor has been successfully fabricated in experiment [24]. Although much efforts have been spent on studying the transport properties of silicene multiple junctions [19–23], but the spin- and valley-dependent transport for a silicene *np* junction, as the basic unit of electronic devices, has not got sufficient discussions in detail until now. Motivated by this, we investigate the spin-valley transport in a silicene *np* junction, where a ferromagnetic field and a perpendicular electric field are applied in the *p*-doped region. It is found that pure spin current can be obtained under the control of the electric-field strength and doping level, arising from the specific dispersion. By tuning the electric field properly, one can even observe the phenomenon of 100% spin-valley polarized transport. We also demonstrate that the ferromagnetic field could greatly affect the spin- and valley-polarizations when the electric field is fixed. Our findings provide basic and useful information for silicene applied in future spintronics and valleytronics devices. The rest of this paper is organized as follows. In Section 2, we introduce the model Hamiltonian and electronic states in silicene. In Section 3, we discuss the spin- and valley-polarized transport in a normal-ferromagnetic *np* junction. A summary is presented in Section 4.

2. Silicene Hamiltonian

We begin our study with an effective silicene Hamiltonian [10,19–23] which is described by Dirac electrons near valleys K ($\eta = +$) and K' ($\eta = -$) and reads

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$$H_\eta = \hbar v_{\mathrm{F}}(\eta\tau_x k_x + \tau_y k_y) + \eta\lambda_{\mathrm{SO}}\tau_z\sigma_z - \lambda_V\tau_z + \lambda_{\mathrm{F}}\sigma_z, \tag{1}$$

where the Pauli matrices τ_i and σ_i $(i = x, y, z)$ describe the sublattice pseudospin and electron spin, respectively. The first term represents the massless Dirac fermion, where $v_{\mathrm{F}} = \sqrt{3}at/2\hbar$ is the Fermi velocity, $a = 3.86$ Å denotes the lattice constant and $t = 1.6$ eV is the nearest-neighbor hopping energy. The second term represents the spin–orbit coupling with $\lambda_{\mathrm{SO}} = 3.9$ meV [7–10]. The third term indicates the perpendicular electric field with $\lambda_V = \ell E_z$, where $\ell = 0.23$ Å is half of the interlayer distance and E_z is the electric-field strength that can be tuned by the top and bottom gates experimentally [25–27]. The last term is the ferromagnetic exchange field with λ_{F}, which can be provided by a ferromagnetic substrate [12,28]. Note that Rashba-type spin–orbit couplings [10,3], as weak perturbations, will be discussed at the end of this paper.

For simplicity, we here set $\hbar = 1$, $v_{\mathrm{F}} = 1$. By diagonalizing the Hamiltonian (1), the energy dispersion is obtained as

$$E_\eta^{m,s} = s\lambda_{\mathrm{F}} + m\sqrt{k^2 + (\lambda_V - s\eta\lambda_{\mathrm{SO}})^2}, \tag{2}$$

where m is the band index that takes the value $+(-)$ for the conduction (valence) band, and s is the spin index that takes the value $+(-)$ for spin up (down). The ferromagnetic field λ_{F} here plays the role of moving up (down) the spin-up (down) subbands. When both λ_{F} and λ_V are zero, the energy dispersion becomes spin degenerate and valley independent. If λ_{F} or λ_V takes a nonzero value, the dispersion may become spin or valley polarized [10,29]. Meanwhile, the spin- and valley-dependent energy gap, between the conduction and valence subbands, is obtained as

$$\left(E_g\right)_\eta^s = 2|V - s\eta\lambda_{\mathrm{SO}}|. \tag{3}$$

Because spins are decoupled in Hamiltonian (1), the electronic states can be expressed by any one spin as

$$\psi_\eta^{m,s}(\varphi) = \nu_\eta^{m,s}\left(f_\eta^{m,s}\cdot\eta e^{-i\eta\varphi}, 1\right)^{\mathrm{T}}, \tag{4}$$

where $\nu_\eta^{m,s}$ is the normalized constant determined by $\nu_\eta^{m,s} = 1/\sqrt{1 + (f_\eta^{m,s})^2}$ with $f_\eta^{m,s} = (E_\eta^{m,s} - \lambda_V + s\eta\lambda_{\mathrm{SO}} - s\lambda_{\mathrm{F}})/k$. Note that $\nu_\eta^{m,s}$ as well as $f_\eta^{m,s}$ depends on not only the spin, valley and band indexes but also external fields.

3. Spin- and valley-polarized transport in an *np* junction

Our studied silicene *np* junction is shown on the top of Fig. 1, where a ferromagnetic exchange field provided by substrate and an external perpendicular electric field E_z controlled by dual gates, i.e., the top gate (TG) and bottom gate (BG), are applied in the p-doped region. The electron-doping level μ_n (positive) in region n can be tuned by injecting electrons from electrode, while the hole-doping level μ_p (negative) in the p-doped region can be controlled by dual gates, as well as E_z [26,27]. At the bottom of Fig. 1, we also show the definitions of incident, reflected and transmitted angles in the *np* junction, where normal-incidence states $|1\rangle$-$|3\rangle$ are labeled in the energy dispersions when parameters $\lambda_V, \lambda_{\mathrm{F}}, \mu_n, -\mu_p$ take one and the same value $2\lambda_{\mathrm{SO}}$. The symbols η and s of these states is omitted for convenience. In region p, the band gap between conduction and valence subbands with the same spin, denoted by the numbers in unit of λ_{SO}, agrees with Eq. (3). Notably, spin and valley should always be conserved in electron tunneling because no spin-flipping or intervalley scattering is included in Hamiltonian (1).

In the n-doped region, the incident states locate in the two spin-degenerate conduction subbands $(m = +, s = \uparrow, \downarrow)$. Due to $\lambda_{\mathrm{F}} = \lambda_V = 0$, the modulus of spin-independent wave vector is solved as $k = \sqrt{\mu_n^2 - \lambda_{\mathrm{SO}}^2}$ from Eq. (2). The incident state, determined by $\psi_\eta^{+,s}(\phi)$ in Eq. (4), is given as $|1\rangle_\eta^s = \nu_n\left[f_n\cdot\eta e^{-i\eta\phi}, 1\right]^{\mathrm{T}} e^{i(k_x x + k_y y)}$, Here, $\phi = \arctan(k_y/k_x)$, $k_x = k\cos\phi$, $k_y = k\sin\phi$, $f_n = (\mu_n + s\eta\lambda_{\mathrm{SO}})/k$, $\nu_n = 1/\sqrt{f_n^2 + 1}$. By replacing ϕ with $\pi - \phi$, the reflected state is obtained as $|2\rangle_\eta^s = \nu_n\left[-f_n\cdot\eta e^{i\eta\phi}, 1\right]^{\mathrm{T}} e^{i(-k_x x + k_y y)}$. In the p-doped region, the modulus of spin-dependent wave vector is solved as $q = \sqrt{(\mu_p - s\lambda_{\mathrm{F}})^2 - (\lambda_V - s\eta\lambda_{\mathrm{SO}})^2}$ from Eq. (2). Corresponding to the incident state $|1\rangle$, the transmitted state $|3\rangle$ needs to satisfy two conditions [14]: (i) momentum conservation in the y-direction, i.e. $q_y = k_y$; (ii) invariable sign of group velocity in the x-direction, i.e. $(\partial E/\partial q_x)\cdot(\partial E/\partial k_x) > 0$. Then the state $|3\rangle$, determined by $\psi_\eta^{-,s}(\theta)$ in Eq. (4), reads $|3\rangle_\eta^s = \nu_p\left[f_p\cdot\eta e^{-i\eta\theta}, 1\right]^{\mathrm{T}} e^{i(q_x x + k_y y)}$, where $\theta = \pi - \arcsin(k_y/q)$ if $|3\rangle$ is located in the conduction subbands, and $\theta = \arcsin(k_y/q)$ if $|3\rangle$ is located in the valence subbands. Other

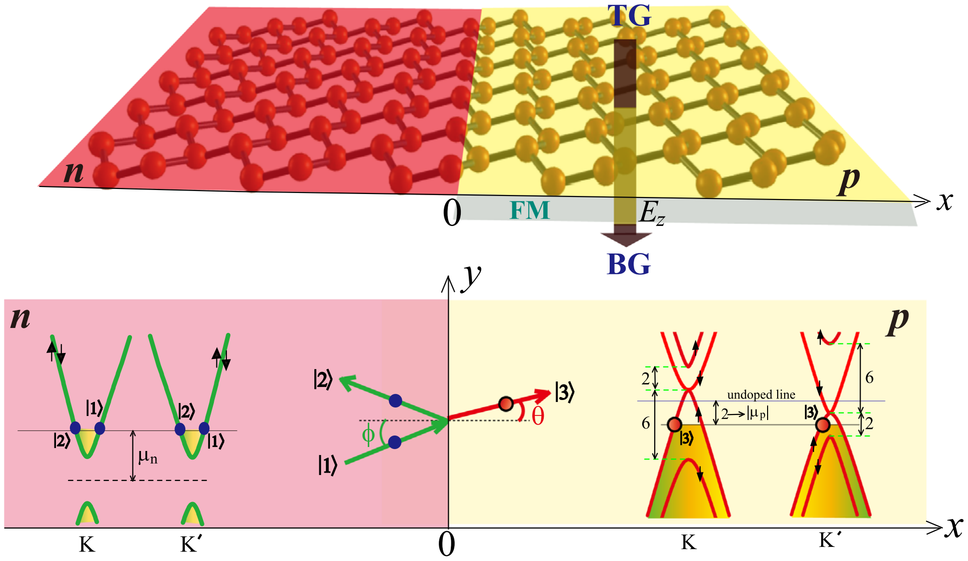

Fig. 1. (Color online) Construction of our studied silicene *np* junction. Top: Real-space lattice structure, where the p-doped region is supported by a substrate that provides a ferromagnetic exchange field, and meanwhile tuned by a perpendicular electric field E_z between the top gate (TG) and back gate (BG). Bottom: Definitions of incident, reflected and transmitted angles, where the insets show the transport states in energy dispersions when parameters $\lambda_V, \lambda_{\mathrm{F}}, -\mu_p$ take the same value $2\lambda_{\mathrm{SO}}$. The band gap between subbands with the same spin is labeled by numbers in unit of λ_{SO}.