Physics Letters A ••• (••••) •••–•••

Contents lists available at ScienceDirect

Physics Letters A

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Electrical control of valley and spin polarized current and tunneling magnetoresistance in a silicene-based magnetic tunnel junction

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ARTICLE INFO

Article history:
Received 17 April 2014
Accepted 28 June 2014
Available online xxxx
Communicated by R. Wu

Keywords:
Silicene
Magnetic tunnel junction
Valley polarization
Spin polarization
Vertical electric field

ABSTRACT

We investigate the electronic transport in a silicene-based ferromagnetic metal/ferromagnetic insulator/ferromagnetic metal tunnel junction. The results show that the valley and spin transports are strongly dependent on local application of a vertical electric field and effective magnetization configurations of the ferromagnetic layers. In particular, it is found that the fully valley and spin polarized currents can be realized by tuning the external electric field. Furthermore, we also demonstrate that the tunneling magnetoresistance ratio in such a full magnetic junction of silicene is very sensitive to the electric field modulation.

Silicene [1–4], the graphene counterpart for silicon, has been successfully synthesized and has attracted considerable experimental and theoretical researches because of its exotic physical properties resulting from the slightly buckled two-dimensional hexagonal structure. The low-energy electronic properties can be well described by massive Dirac fermions with relatively large intrinsic spin–orbit coupling compared to graphene, which leads to a gap between the conduction and valence bands [5,6]. Especially, due to the buckled structure, its energy band gap can be further tuned by an electric field perpendicularly applied to the silicene plane [7–10].

It has been known that the spin-filter effect mainly focuses on the spacer-controlled different currents with different spins, while the tunneling magnetoresistance (TMR) effect is concerned with the electrode-controlled different currents under different magnetizations. Recently, the valley and spin transports in a normal/ferromagnetic/normal (N/FM/N) silicene junction have been explored [9], and the transport property of *pn* and *npn* junctions made of silicene has also been analyzed under the local application of a gate voltage [10]. In this Letter, we study the valley and spin transports and the TMR effect in a silicene-based ferromagnetic metal/ferromagnetic insulator/ferromagnetic metal (FM/FI/FM) tunnel junction, which is actually the combination of spin- and valley-filter effect and TMR effect in the full magnetic tunnel junction of silicene.

We consider a general spintronic and valleytronic tunneling model for a silicene-based FM/FI/FM tunnel junction, as depicted schematically in Fig. 1(a). For simplicity, it is assumed here that the magnetization directions of two FM electrodes are same and fixed, while that of the FI spacer can be reversed, so that there are two effective magnetization configurations. Note that for silicene, the on-site potential difference between the A and B sublattices can be produced and modulated by an external electric field perpendicular to the sample plane [7–10], which is similar with the case for bilayer graphene [11–17]. Also, the exchange fields can be induced by the magnetic proximity effect stemming from magnetic insulators deposited on the silicene, which were proposed for graphenes [18,19] and conventional two-dimensional electron gas [20–24].

According to the symmetry, the low-energy effective Hamiltonian derived from the tight binding model around Dirac point in silicene can be described by [5,6,9,10]

$$\mathcal{H}_{\eta,\nu} = \begin{pmatrix} \Delta_\nu - \sigma_\nu h_\nu & \hbar v_{\mathrm{F}}(k_{\nu x} + i\eta k_{\nu y}) \\ \hbar v_{\mathrm{F}}(k_{\nu x} - i\eta k_{\nu y}) & -\Delta_\nu - \sigma_\nu h_\nu \end{pmatrix} \tag{1}$$

with $\nu = 1, 2, 3$ denoting the three regions, where

$$\Delta_\nu = \sigma\eta\lambda_{\mathrm{so}} - \delta_{\nu,2}\Delta_z, \tag{2}$$

and the relative spin indices

$$\sigma_\nu = \theta_\nu \sigma. \tag{3}$$

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http://dx.doi.org/10.1016/j.physleta.2014.06.044

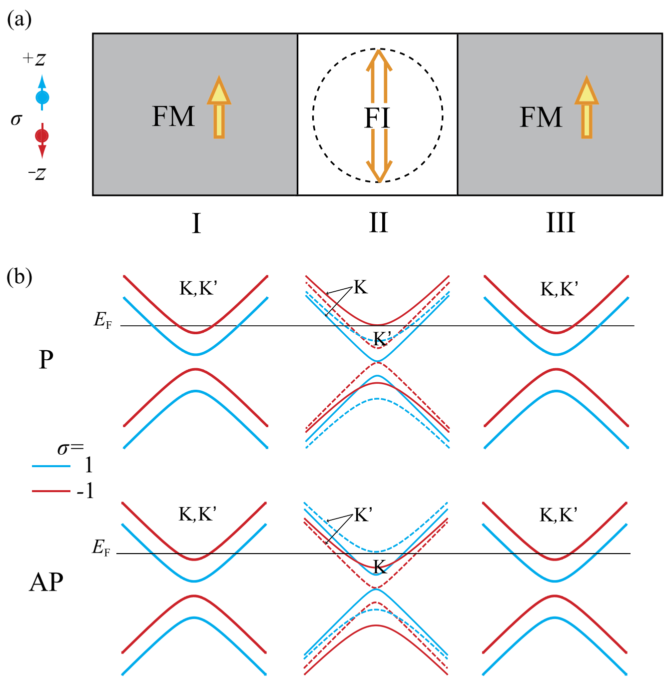

Fig. 1. (Color online.) (a) Schematic diagram of a silicene-based FM/FI/FM tunnel junction with different magnetization configurations. (b) Band structures near the K and K′ points in each region for the parallel and antiparallel magnetization configurations.

Here, $\eta = \pm 1$ distinguishes the two valleys (K and K′). λ_{so} represents the effective spin–orbit coupling. Δ_z is the on-site potential difference between the A and B sublattices induced by the vertical electric field, and h_ν is the exchange field induced by the magnetic proximity effect in each region. $\delta_{\nu,2}$ is the Kronecker delta function. $\sigma = +1(\uparrow)$ or $-1(\downarrow)$ means spin-up or spin-down with respect to the positive z direction. $\theta_\nu = +1(\Uparrow)$ or $-1(\Downarrow)$ represents the magnetization direction in the ν region, parallel or antiparallel to the positive z direction. In our case, we fix $\theta_1 = \theta_3 = +1(\Uparrow)$ for simplicity, and only let the direction of magnetization in the FI spacer vary, i.e., $\theta_2 = \pm 1$.

The eigenvalues and normalized eigenstates of the Hamiltonian in Eq. (1) are derived as

$$E = \pm\sqrt{(\hbar v_F k_\nu)^2 + \Delta_\nu^2} - \sigma_\nu h_\nu, \tag{4}$$

$$\varphi_\nu^\pm = N_\nu \begin{pmatrix} \hbar v_F(\pm k_{\nu x} + i\eta k_{\nu y}) \\ E + \Delta_\nu + \sigma_\nu h_\nu \end{pmatrix}, \tag{5}$$

with the normalized parameter

$$N_\nu = \frac{1}{\sqrt{2(E + \sigma_\nu h_\nu)(E + \Delta_\nu + \sigma_\nu h_\nu)}}. \tag{6}$$

Due to the translational invariance in the y direction, the momentum parallel to the y axis is conserved. We assume that the electron in the system ballistically transports from the left to the right of the FM/FI/FM tunnel junction. The interfaces between the FM and the FI are located at $x = 0$ and $x = L$, where L is the length of the FI spacer in region II.

If the incident electron propagates at an angle with respect to the x axis from the left of this junction, then the wavefunctions in each region should respectively take the following forms:

$$\psi_I = \varphi_1^+ e^{ik_1 \cos\phi_1 x} + r_{\eta,\sigma}\varphi_1^- e^{-ik_1 \cos\phi_1 x}, \tag{7a}$$

$$\psi_{II} = a_{\eta,\sigma}\varphi_2^+ e^{ik_2 \cos\phi_2 x} + b_{\eta,\sigma}\varphi_2^- e^{-ik_2 \cos\phi_2 x}, \tag{7b}$$

$$\psi_{III} = t_{\eta,\sigma}\varphi_3^+ e^{ik_3 \cos\phi_3 x}, \tag{7c}$$

where

$$k_\nu = \frac{1}{\hbar v_F}\sqrt{(E + \theta_\nu \sigma h_\nu)^2 - \Delta_\nu^2}, \tag{8}$$

and

$$\phi_{2(3)} = \arcsin\frac{k_1 \sin\phi_1}{k_{2(3)}}. \tag{9}$$

By matching the boundary conditions on ψ_I and ψ_{II} at $x = 0$ and ψ_{II} and ψ_{III} at $x = L$, one can obtain the transmission coefficients $t_{\eta,\sigma}$. Correspondingly, the transmission probability through such a full magnetic silicene junction is then expressed as [25]

$$T_{\eta,\sigma}^{\theta_2}(\phi_1) = |t_{\eta,\sigma}|^2 \frac{\cos\phi_3}{\cos\phi_1}. \tag{10}$$

The ballistic conductance of the junction at zero temperature can be evaluated for the different magnetization arrangements by using the Landauer–Büttiker formalism,

$$G_{\eta,\sigma}^{\theta_2} = G_0 \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} T_{\eta,\sigma}^{\theta_2}(\phi_1)\cos\phi_1 d\phi_1, \tag{11}$$

where $G_0 = 4e^2 L_y k_{F\sigma}/(2\pi h)$ with L_y being the width of the silicene sheet in the y direction. Note that the Fermi wavevector in the ferromagnetic silicene $k_{F\sigma} = \sqrt{(E_F + \sigma h_1)^2 - \lambda_{so}^2}/(\hbar v_F)$ is spin-dependent, so the conductance $G_{\eta,\sigma}^{\theta_2}$ explicitly depends on the spin.

The valley resolved conductance is defined as

$$G_\eta^{\theta_2} = \frac{1}{2}(G_{\eta\uparrow}^{\theta_2} + G_{\eta\downarrow}^{\theta_2}). \tag{12}$$

We also introduce the valley and spin polarizations $\mathcal{P}_v^{\theta_2}$ and $\mathcal{P}_s^{\theta_2}$ for the different magnetization configurations [26,27]:

$$\mathcal{P}_v^{\theta_2} = \frac{G_K^{\theta_2} - G_{K'}^{\theta_2}}{G_K^{\theta_2} + G_{K'}^{\theta_2}}, \tag{13}$$

$$\mathcal{P}_s^{\theta_2} = \frac{G_{K\uparrow}^{\theta_2} - G_{K\downarrow}^{\theta_2} + G_{K'\uparrow}^{\theta_2} - G_{K'\downarrow}^{\theta_2}}{G_{K\uparrow}^{\theta_2} + G_{K\downarrow}^{\theta_2} + G_{K'\uparrow}^{\theta_2} + G_{K'\downarrow}^{\theta_2}}. \tag{14}$$

The TMR ratio in the system is usually defined as the normalized difference of the conductances for the two magnetization configurations, i.e.,

$$\mathrm{TMR} = \frac{G_K^{\Uparrow} + G_{K'}^{\Uparrow} - G_K^{\Downarrow} - G_{K'}^{\Downarrow}}{G_K^{\Uparrow} + G_{K'}^{\Uparrow}}. \tag{15}$$

We now apply the above formulation to calculate the valley and spin transports and the TMR in a silicene-based FM/FI/FM tunnel junction with the local electric field modulation. In the following calculations, we employ the dimensionless units for simplicity, in which energy and length are measured in units of E and $\hbar v_F/E$, respectively. Other parameters are $\lambda_{so} = 0.5$, $h_1 = h_3 = 0.3$, and $h_2 = 0.2$ (except for Fig. 4).

The valley resolved conductance, valley polarization and spin polarization in the case of the different magnetization arrangements are presented in Fig. 2 as functions of the length of the FI spacer L for the two different values of Δ_z. In Fig. 2(a), it is easy to see that for a smaller Δ_z, the valley conductances $G_K^{\theta_2}$ and $G_{K'}^{\theta_2}$ always show an oscillatory dependence on L, the values of which are distinct for the parallel and antiparallel magnetization configurations. In contrast, for a larger Δ_z, the valley conductances