Controllable spin and valley polarized current through a superlattice of normal/ferromagnetic/normal silicene junction

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A B S T R A C T

The spin and valley transports in a superlattice of normal/ferromagnetic/normal silicene junction are studied theoretically. Transport properties in particular valley-resolved conductance, spin and valley polarization have been computed by the Landauer Buttker formula. We achieve fully valley and spin polarized current in the superlattice N/F/N structure. Our findings also imply that by increasing the number of ferromagnetic barriers, the onset of fully spin and valley polarized current always occur for lower values of staggered potential(\(\Delta z\)) and length of the ferromagnetic region \((K, L)\) in the silicene superlattice structure as compared with N/F/N silicene junction. Fully spin and valley polarizations make silicene superlattice a suitable candidate for spin-valleytronics applications.

1. Introduction

Silicene, a single layer of silicon atoms on a two-dimensional (2D) honeycomb lattice [1] has currently been synthesized with superior compatibility with current silicon-based technology [2–9]. Silicene, a counterpart of graphene [10], the first experimentally realized monolayer material, due to its exotic physical properties resulting from the slightly buckled two-dimensional atomic structure [11–13] has attracted enormous attention in the field of physics. The low-energy excitations in silicene are the Dirac fermions [11,12,14]. In contrast to graphene, silicene has a large spin–orbit coupling [12] which leads to massive Dirac electrons and due to its buckled structure, the mass of Dirac electrons can be control by an external electric field [13,15,16].

The valley physics aims to control valley transport of electrons in 2D-materials and has been developed in graphene [17–19]. The valley-valve and valley-filter effect was originally proposed in graphene nanoribbons with zigzag edge [17,19]. The valley degree of freedom is similar to the spin degree of freedom and provides another probe to control electron. Due to the strong spin–valley coupling and the tunability of the spin-splitting band gap by external electric filed in silicon, it is worth studying the valleytronics in silicon and comparing the results with those for graphene in which the spin–orbit interaction is weak.

Currently, the transport properties of silicene-based magnetic tunneling junction has attracted much attention. Yokoyama has predicted that the current through the normal/ferromagnetic/normal (NFN) silicene junction is valley and spin polarized due to the coupling between valley and spin degrees of freedom [14]. Fully spin and valley polarized current were found to be controllable by electric and exchange field in the ferromagnetic silicene layer [14,20,21]. In this regard, by aligning the spin and valley-resolved confined states in magnetic well, remarkable spin and valley polarization can be accessed through the spinor relying resonant tunneling mechanism [22]. Also, it was shown that the presence of ferromagnetic barrier in the NFN silicene junction induced exchange splittings in the charge conductance and the charge conductance is a periodic function of the barrier potential and exchange field [23–25].

The superlattice model for the graphene-based sequence of N/F/N junction has been done. It is found that this junction, due to turning the unpolared current to polarize one, could act as a polarizer [26], the prediction of which will contribute to the development of spintronics devices. Also a giant charge thermoelectric coefficient in a graphene superlattice [27] and the thermoelectric transport in a magnetic silicene superlattice has been reported [28]. So, due to importance of superlattice structure, here we theoretically study the spin and valley transport in a superlattice of N/F/N silicene junctions. Since for two-dimensional materials with honeycomb lattice structure, there is valley degree of freedom in addition to spin and charge, manipulating valley degree of freedom motivates us to following ways for producing controllable valley polarized current. In this paper we achieve this goal with increasing the number of barriers.

Actually, we employ the superlattice model to study the spin and valley conductance and also spin and valley polarization in the concerned silicene junction. Here, we mainly focused on how the...
transport properties of the junction evolve upon varying the number of NFN barriers and how the reported effects for single NFN silicene junction [14] carry over to superlattice of barriers. We achieve fully valley and spin polarized current in the superlattice structure. Our findings also imply that by increasing the number of barriers, the onset of fully spin and valley polarized current always occurs for the lower staggered potential ($\Delta_g$) and length of the ferromagnetic region ($s$) in a superlattice structure as compared with N/F/N structure [14]. Our theoretical calculations show that a superlattice of N/F/N silicene junction could act as a spin-valve and spin-filter (100% valley and spin-polarized current) which is suitable for spintronics and nano-electronics potential devices.

2. System and model hamiltonian

We consider a superlattice of two dimensional N/F/N silicene junction in the xy plane as schematically shown in Fig. 1. The normal and ferromagnetic silicene regions have the same length as L. In the framework of single-valley transport for $K (\eta = 1)$ or $K' (\eta = -1)$ valleys, the effective low-energy Hamiltonian is given by [12,14]

$$H = \hbar v_F (k_x \tau_x - \eta k_y \tau_y) - (\eta\sigma\Delta_g - \Delta_z) \tau_z - \eta h,$$

where $v_F = 5.5 \times 10^5$ m/s represents the Fermi velocity, $\tau_z$ are the spin Pauli matrices of the sublattice pseudospin and $\sigma = \pm 1$ denotes spin up (↑) and spin down (↓) states in the ferromagnetic regions. $h$ is the reduced Plank constant and $(k_x, k_y)$ are the in-plane wavevectors. The second term describes the spin-orbit coupling that we take to be [12,14,29] $\Delta_g = 3.9$ meV and $\Delta_z$ is the staggered sublattice potential between silicon atoms at A and B sites that can be effectively tuned by perpendicular electric field, triggering the emergence of tunable energy gap $\Delta$ and $h$ is the exchange field in the ferromagnetic regions. The eigenvalues of Hamiltonian (1) in the normal and ferromagnetic regions can be easily determined as

$$E_{F,N} = \pm \sqrt{\left(\hbar v_F k_{F,N}\right)^2 + (\eta\sigma\Delta_g - \Delta_z)^2} - \eta h,$$

$$K_{i,N}^2 = K_{F,N}^2 + K_{i,N}^2, \quad K_{F,N} \text{ and } K_{i,N} \text{ are wavevectors in the ferromagnetic and normal regions, respectively. For a given energy } E, \text{ the wavefunction for the valley } \eta \text{ and spin } \sigma \text{ in the ferromagnetic(\eta) and normal(\eta) regions and also in the first and the last region can be read as [14]:}$$

$$\psi_{\eta} = e^{iK_{F,N}x} \left( \begin{array}{c} \psi_{\eta,F} \\ \psi_{\eta,N} \end{array} \right),$$

$$\psi_{\eta} = e^{iK_{F,N}x} \left( \begin{array}{c} \psi_{\eta,F} \\ \psi_{\eta,N} \end{array} \right),$$

$$\psi_{\sigma} = e^{iK_{F,N}x} $$

$$\psi_{\eta} = e^{iK_{F,N}x} \left( \begin{array}{c} \psi_{\eta,F} \\ \psi_{\eta,N} \end{array} \right),$$

$$\psi_{\eta} = e^{iK_{F,N}x} \left( \begin{array}{c} \psi_{\eta,F} \\ \psi_{\eta,N} \end{array} \right),$$

and

$$\psi_{\eta} = \left( \begin{array}{c} \psi_{\eta} \pm K_{F,N} + i\Delta \tau_z \\ \hbar \tau_z + \Delta \end{array} \right) e^{iK_{F,N}x}.$$

$h$ and $\Delta_z$ are zero in normal regions. $\Delta_f = \sigma\Delta_{s,f} - \Delta_z$ and $\Delta_h = \sigma\Delta_{h,f}.$

Here x-axis is perpendicular to the interfaces and the electron current is evaluated along the x-axis.

Applying continuity of wavefunctions at each interface between adjacent regions, we obtain transmission coefficient, $t$, through the superlattice consisting of n potential barriers and adopting landauer Buttiker formula [30], the ballistic conductance in the zero-temperature regime derived by integrating overall incident angles as below

$$G_{n,0}(E_F) = G_0 \int_{-\pi/2}^{\pi/2} t_{an}^{\pi} e^{i\theta} d\theta.$$

where $E_F$ is the system Fermi energy, $G_0 = \frac{\alpha}{L}$ is the conductance with $L$ the system transverse size and $\theta$ is the incident angle. We have numerically calculated the transmission coefficient through the nth region, however it could be computed by the transfer matrix method [31] as is used in the superlattice paper [28].

The valley-resolved conductance is defined as

$$G_{k,k'1} = \frac{\sum_{z=\pm1} G_{k,k',z}}{2}.$$

Also the valley and spin polarizations $G_n, G_v$ are written as:

$$G_n = \frac{G_k - G_k}{G_k + G_k},$$

and

$$G_v = \frac{G_{k1} + G_{k1} - G_{k1} - G_{k1}}{G_{k1} + G_{k1} + G_{k1} + G_{k1}}.$$

3. Discussions

In the following calculations, we have assumed the structure parameters as $\hbar = 0.3$, $\Delta_s/E = 0.5$ and Fermi wave vector $k_F = \frac{1}{L}$. As a check of validity of our calculations we emphasized that our results in Figs. 2–6 for one N/F/N silicene junction (n=1) coincide with [14].

In Fig. 2, we show the dependence of the valley resolved conductance $G_k(E_F)$ on the ferromagnetic length L of the N/F/N superlattice silicene junction by taking $\Delta = 0.5E$ (in Figs. 2a and b) and $\Delta = 1E$ in Figs. 2c and d). It is clearly seen that the number of N/F/N silicene junction has strong impact on the amplitude of the valley resolved conductance $G_k(E_F)$ curves and by increasing the number of barriers, the valley resolved conductance $G_k(E_F)$ decays oscillatory with higher amplitude as compared to n=1 case as a function of the thickness of the ferromagnetic layer for $\frac{\Delta}{E} = 0.5$ and $\frac{\Delta}{E} = 1.5$. The oscillatory behaviour is a direct manifestation of the Klein tunneling that occurs for Massless Dirac fermions [32]. It is worth mentioning that at the

Fig. 1. Schematic representation of a sequence of normal/ferromagnetic silicene junctions that make a superlattice of normal/ferromagnetic/normal junction.