Journal of Magnetism and Magnetic Materials 442 (2017) 15–24

Contents lists available at ScienceDirect

Journal of Magnetism and Magnetic Materials

journal homepage: www.elsevier.com/locate/jmmm

Research articles

Valley polarized current and Fano factor in a ferromagnetic/normal/ferromagnetic silicene superlattice junction

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A R T I C L E I N F O

Article history:
Received 26 November 2016
Received in revised form 29 April 2017
Accepted 3 June 2017
Available online 17 June 2017

Keywords:
Silicene superlattice
Landauer Buttiker formula
Electrical transport
Fully valley current
Fano factor

A B S T R A C T

In this paper, based on the transfer-matrix method, we investigate the transport properties of Dirac fermions through a superlattice of ferromagnetic/normal/ferromagnetic (FNF) buckled silicene junction where an electrostatic gate potential U is attached to the normal region. It is found that owing to buckled structure of silicene, the transmission probabilities and consequently valley-resolved conductance of the junction can be turned on or off by adjusting electric field strength, the number of barriers, and electrostatic gate voltage. Remarkably, the fully valley polarized current can be achieved by increasing the number of barriers in the proposed device. The effect of the number of barriers on the total charge conductance G_c of such a junction versus barrier length has also been investigated and it is shown that by increasing the number of barriers the amplitudes of G_c oscillations decrease. It is also found that Fano factor strongly modulated by applying electric field, number of barriers, and gate voltage. In particular, in presence of an electrostatic gate potential, Fano factor reaches the full Poissonian value $F = 1$, which signifies that transport is forbidden ($T \rightarrow 0$) and pure tunneling occurs in this junction.

1. Introduction

Silicene, a hexagonal monolayer of silicon atoms, has been synthesized recently [1]. However its existence in nature was established theoretically for the first time in 1994 [2]. This material has attracted considerable attention due to its unique spin and valley behavior and its potential application in nano-electronic and spintronic devices [3]. Silicene, which is positioned among many known two dimensional materials; such as graphene [4], germanene [5], and transition metal dichalcogenides [6], has similar structural and electronic properties with even more privileges than them. Graphene, in their original forms, are nonmagnetic, but ferromagnetism could be induced in graphene by deposing a ferromagnet on top of its surface [7]. Taking advantage of first principle calculation silicene has the potential to be ferromagnetic under semi-hydrogenation process [8] or transition metal atom decoration [9]. Compared to graphene, silicene has a larger spin-orbit coupling [10] (1000 times greater than the one in graphene) and due to its buckled geometry (for the stable silicene, the buckled height is about 0.44A [11] which is in sharp contrast to the planar sheet of graphene), its energy gap can be further tuned by an electric field perpendicular to the silicene sheet [12]. The large spin-orbit interaction of silicene and controlling the mass terms at the Dirac points leads to several interesting electronics properties such as spin/valley-dependent transport and silicene-based spin-valleytronics application [13]. Note also that opening the energy gap leads to the topological phase transition in silicene by applying an electric field and this gap overcomes the difficulties of graphene in nano-electronic applications [14] (lack of a tunable band gap in the pristine graphene).

Recently, First-principles calculations showed that there are diverse ways in which silicene turns into a large-gap insulator (such as surface functionalization [15,16], point defect patterning [17,18] and silicene edge structure engineering [19,20]). But in these methods, the carrier mobility doesn't remain intact. Low carrier mobility is one of the disadvantages of these methods. An adjustable gap can be opened up in silicene by applying an external electric field [21] or by pairing silicene with a substrate [22,23] without disturbing the carrier mobility of silicene. It is an important feature for the large- efficiency silicene FET devices. First-principles calculations predicted [24] that the electronic properties of silicene modulated by the adsorption of organic molecular species. In addition to these, it is found that molecules having smaller

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http://dx.doi.org/10.1016/j.jmmm.2017.06.023
0304-8853/

adsorption energy have a smaller effective mass, as a result the carrier mobility is high. Using an analytical model in Ref. [25], the combined effects of the intrinsic SOC and an external electric field applied perpendicular to the superlattice have been studied and it is found that by tuning the electric field the quantum phase transition from semimetal to a topological insulator can be achieved.

Yokoyama was the first person who established perfect valley and spin polarized transport through a NFN graphene-based junctions [26]. Rashidian, inspired with this model, extended the Yokoyama's paper by considering valley and spin polarized through an array of NFN junctions [27]. As in graphene, the spin/valley-polarized current is obtained for one barrier or array of ferromagnetic barriers in silicone-based junctions [28–31]. Recently, spintronics and valleytronics applications of the ferromagnetic/nor mal/ferromagnetic (FNF) and normal/ferromagnetic/normal (NFN) silicene junctions have been extensively studied [26–33]. Also Fano factor has been analyzed theoretically in several non-interaction systems [34–37], based on the Landauer Buttiker approach, using a distribution of transmission eigenvalues. Fano factor, which by definition is the normalized shot noise, gives information about the transport of charge carriers in the system which is not obtainable from the conductance.

In mesoscopic systems, shot noise is originated from the granular nature of charge carrier [38]. Depending on the ballistic or disordered silicene strips measuring the Fano factor, the normalized shot noise by average current, leads to a different value as a good tool for identifying the kind of system. For a Poissonian transport where the Fano factor is $F = 1$ (i.e. when transport occurs via electron tunneling), while the ballistic transport occurs for $F = 0$ (i.e. in the perfect transmission) and $F = 1/3$ corresponds to diffusive transport [38,39].

In the present work, we theoretically investigate the electronic transport properties including spin-and-valley- resolved conductances and Fano factor through a superlattice of FNF silicene junction within the Landauer-Buttiker formula. It was found that by increasing the number of barriers, transmission probabilities are strongly suppressed at the specific incident angles. These transmission probabilities can be turned on or off by adjusting applying electric field, the number of barriers and electrostatic gate potential. In particular, the valley polarization can be observed by tuning the electric field strength and the number of barriers. Presence of an electrostatic gate potential causes a stronger valley polarization. The effect of barrier length on the transport properties has also been investigated and it was shown that they have an oscillatory behavior. In this junction, by increasing the electric field strength and by considering an electrostatic gate potential, Fano factor reaches to the full Poissonian value $F = 1$, which signifies that transport is forbidden ($T \to 0$) and pure tunneling occurs in this junction.

2. System and model Hamiltonian

We study a superlattice of two-dimensional FNF silicene junctions in the xy-plane as seen in Fig. 1. In the framework of single-valley transport; for $K(\eta = 1)$ or $K'(\eta = -1)$ valleys, the general effective low-energy Hamiltonian is written as [32,40]

$$H = \hbar v_f(k_x\tau_x - \eta k_y\tau_y) - (\eta\sigma\Delta_{SO} - \Delta_Z)\tau_Z - \sigma h + U, \tag{1}$$

Where $v_f = 5.5 \times 10^5$ m/s represents the Fermi velocity and $\hbar$ is the reduced Plank constant. $\eta(\eta') = +1(-1)$ corresponds to the $K(K')$ valley and τ_x, τ_y and τ_z are the Pauli matrices in the sublattice pseudospin space and $\sigma = +1(-1)$ is for the spin up (down) configuration. The second term is the intrinsic spin-orbit coupling that we take to be [32,40,41] $\Delta_{SO} = 3.9$ mev and Δ_Z is on-site potential difference between A and B sublattices which can be effectively tuned by perpendicular electric field, triggering the emergence of tunable energy gap. h is the magnetization exchange energy in the ferromagnetic regions and U is the electrostatic gate potential in the normal silicene (NS) layers. We assume that the electric field is applied only in the normal regions. It should be noted the Rashba SO interaction associated with the nearest neighbor hopping term and the Rashba SO interaction associated with the next-nearest neighbor hopping, are much smaller than the intrinsic spin-orbit interaction, therefore we have neglected from the Rashba spin-orbit interaction in the Hamiltonian (1) as compared to intrinsic spin-orbit interaction, Δ_{SO} [13].

The eigenvalues of Hamiltonian in the normal silicene and ferromagnetic silicene regions can be easily determined as mentioned in Ref. [32]

$$E_F = \pm\sqrt{(\hbar v_f K_F)^2 + (\eta\sigma\Delta_{SO})^2} - \sigma h, \tag{2}$$

$$E_N = \pm\sqrt{(\hbar v_f K_N)^2 + (\eta\sigma\Delta_{SO} + \Delta_Z)^2} + U. \tag{3}$$

$K^2_{N,F} = k^2_{N_x,F_x} + k^2_{N_x,F_x}$, where K_N and K_F are wavevectors in the normal silicene and ferromagnetic silicene regions, respectively. For a given energy E, the wavefunction for the valley η and spin σ in ferromagnetic silicene Ψ_F and normal silicene Ψ_N regions can be described by

$$\Psi_F = A_F\begin{pmatrix}\frac{\hbar v_f(k_{F_x}+i\eta k_{F_y})}{\Delta_F+\sigma h+E}\\ 1\end{pmatrix}e^{ik_{F_x}x} + B_F\begin{pmatrix}\frac{\hbar v_f(-k_{F_x}+i\eta k_{F_y})}{\Delta_F+\sigma h+E}\\ 1\end{pmatrix}e^{-ik_{F_x}x}, \tag{4}$$

$$\Psi_N = A_N\begin{pmatrix}\frac{\hbar v_f(k_{N_x}+i\eta k_{N_y})}{\Delta_N+E+U}\\ 1\end{pmatrix}e^{ik_{N_x}x} + B_N\begin{pmatrix}\frac{\hbar v_f(-k_{N_x}+i\eta k_{N_y})}{\Delta_N+E+U}\\ 1\end{pmatrix}e^{-ik_{N_x}x}, \tag{5}$$

$$\Psi_1 = \begin{pmatrix}\frac{\hbar v_f(k_{F_x}+i\eta k_{F_y})}{\Delta_F+\sigma h+E}\\ 1\end{pmatrix}e^{ik_{F_x}x} + r_{\eta\sigma}\begin{pmatrix}\frac{\hbar v_f(-k_{F_x}+i\eta k_{F_y})}{\Delta_F+\sigma h+E}\\ 1\end{pmatrix}e^{-ik_{F_x}x}, \tag{6}$$

$$\Psi_n = \begin{pmatrix}\frac{\hbar v_f(k_{F_x}+i\eta k_{F_y})}{\Delta_F+\sigma h+E}\\ 1\end{pmatrix}e^{ik_{F_x}x}, \tag{7}$$

where $\Delta_F = \eta\sigma\Delta_{SO}$ and $\Delta_N = \Delta_Z - \eta\sigma\Delta_{SO}$. Here x-axis is perpendicular to the interfaces and the electron current is evaluated along the x-axis. The subscript F and N refers to FM and NM layer, respectively, and numerical subscripts n refer to the region index.

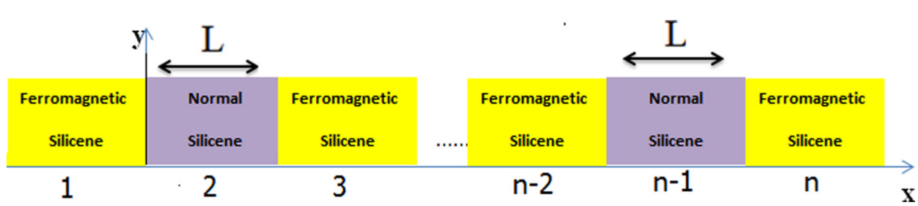

Fig. 1. Schematic picture of a superlattice ferromagnetic/normal/ferromagnetic silicene junction.