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Spin-dependent transport and current-induced spin transfer torque in a disordered zigzag silicene nanoribbon

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ABSTRACT

We study theoretically the spin-dependent transport and the current-induced spin transfer torque (STT) for a zigzag silicene nanoribbon (ZSiNR) with Anderson-type disorders between two ferromagnetic electrodes. By using the nonequilibrium Green's function method, it is predicted that the transport property and STT through the junction depend sensitively on the disorder, especially around the Dirac point. As a result, the conductance decreases and increases for two electrode in parallel and antiparallel configurations, respectively. Due to the disorder, the magnetoresistance (MR) decreases accordingly even within the energy regime for the perfect plateau without disorders. In addition, the conductance versus the relative angle of the magnetization shows a cosine-like behavior. The STT per unit of the bias voltage versus the angle of the magnetization exhibits a sine-like behavior, and versus the Fermi energy is antisymmetrical to the Dirac point and exhibits sharp peaks. Furthermore, the peaks of the STT are suppressed much as the disorder strength increases, especially around the Dirac point. The results obtained here may provide a valuable suggestion to experimentally design spin valve devices based on ZSiNR.

1. Introduction

Silicene, the graphene equivalent for silicon, has a low buckled honeycomb structure [1–3]. It has been synthesized on different substrates [4–6], which exhibits various physical properties such as quantum spin Hall (QSH) effect [7,8], quantum anomalous Hall effect [9–11], etc. It can also undergo a topological phase transition by irradiating circular polarized light in the presence of electric field [12,13]. Moreover, silicene field-effect transistor has been fabricated at room temperature very recently, by using a specific growth-transfer-fabrication process [14]. Silicene has Dirac points similar to graphene and shares almost every remarkable property with graphene [15]. However, silicene has a buckled structure and its relatively strong spin–orbit coupling (SOC) opens a gap between the conduction and valence bands, and may lead to detectable QSH effect [1], which can realize dissipationless spin currents along the edges of a silicene. While the QSH effect can occur in graphene only at unrealistically low temperature due to its rather weak SOC gap [7,16,17].

Meanwhile, the silicene nanoribbon (SiNR) has been fabricated on Ag surface in experiment [18,19], and a strong resistance of SiNR to oxidation has been reported [20]. Theoretical investigations have demonstrated that the band gap of an armchair SiNR oscillates with a period of 3 dimers as its width increases [21,22], and a zigzag SiNR (ZSiNR) becomes half metal modulated by an external electric field [21]. The charge and spin transport in ZSiNRs has also been studied vastly. Based on the first-principles calculation, for example, Kang et al. [23] have found that a ZSiNR shows symmetry-dependent transport property similar to those of zigzag graphene nanoribbons (ZGNRs) [24–26], although the σ mirror plane is absent for any ZSiNR due to the buckled structure of silicene [27]. Recently, Farokhnezhad et al. [28] have shown that a ZSiNR can work as a perfect spin filter by applying two ferromagnetic (FM) strips on both edges of the ZSiNR and an electric field. By using the tight-binding formalism, Shakouri et al. [29] have found that a ZSiNR can act as a controllable high-efficiency spin polarizer in the presence of external field.

On the other hand, an important application in spintronics is the spin valve effect [30], where the resistance of devices can be changed by manipulating the relative orientation of the magnetization in two electrodes. The spin-polarized electrons passing from the left FM electrode into the right one in which the magnetization deviates the left by an angle may exert a torque, which is called the spin transfer torque (STT) [31,32]. From our knowledge, up to now a great deal of attentions have been attracted on the FM/graphene/FM magnetic junctions [33–36]. However, the

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investigation of spin-dependent transport through a FM/silicene/FM junction, particularly in STT, is sparsely reported. And we address this issue here.

In this paper we present a theoretical investigation on the spin-dependent transport and the STT for a FM/ZSiNR/FM junction. We consider the ZSiNR with Anderson-type disorder since imperfects always exist to a certain degree in a real silicene sample. By using the nonequilibrium Green's function (NEGF) method [34,37,38], we found a perfect MR plateau for the junction without the disorder, which indicates that it is a good candidate for the spin valve device. However, the Anderson disorder influences sensitively on the electron transport through the junction, especially around the Dirac point. This is because that the disorder can destroy the definite parity of π and π^* band wavefunctions in the central ZSiNR region, which results in the decrease and increase of conductance around the Dirac point for parallel (P) and antiparallel (AP) configurations of magnetization in two electrodes, respectively. Due to the disorder, the MR decreases accordingly even within the energy regime for the perfect plateau without disorders. Besides, the conductance versus the relative angle of the magnetization shows a cosine-like behavior, and the conductance increases slightly as the magnetization strength increases. Furthermore, a sinelike behavior is shown for the STT per unit of the bias voltage as a function of the magnetization angle, and the STT is enhanced as the magnetization strength increases. It is predicted that the STT versus the Fermi energy shows sharp peaks which is antisymmetric to the Dirac point, and it is determined by the difference between the magnitudes of torques exerted by spin-up and -down electrons. Finally, the STT depends sensitively on the Anderson disorder, especially around the Dirac point.

The rest of the paper is organized as follows. In Section 2, we introduce the Hamiltonian for the junction and the corresponding formalism based on the NEGF method. Some numerical examples and the discussions on the results are demonstrated in Section 3. Finally, Section 4 concludes the paper.

2. Model and method

The device model considered here is a silicene-based FM/ZSiNR/FM junction depicted in Fig. 1, where the hardwall condition is imposed on two edges of the ZSiNR, The number N of A (B) sites in a unit cell is used to denote ZSiNR with different width. Therefore, a ZSiNR with N Si–Si chains is named as N-ZSiNR. The magnetization of the left FM electrode is $\mathbf{M}_L = M_L(0, 0, 1)$, which is parallel to the z-axis, and that of the right FM electrode is $\mathbf{M}_R = M_R(\sin\theta, 0, \cos\theta)$, deviating from the z-direction by a relative angle θ in the x–z plane relative to $\mathbf{M}_L$. It seems worthwhile

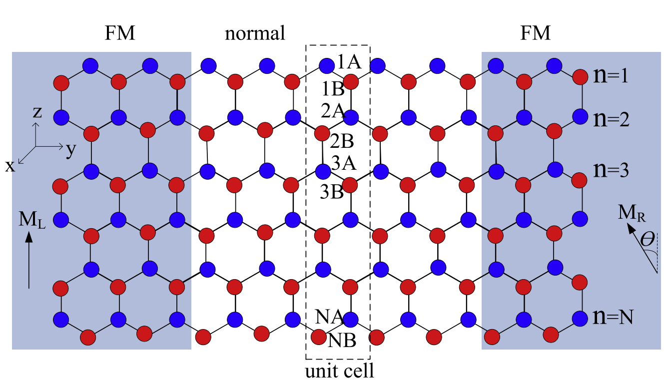

Fig. 1. Schematic of a FM/ZSiNR/FM junction, where a unit cell represented by (black) dashed rectangular frame contains N numbers of A and B sites labeled as 1A, 1B, …, NA, NB. The magnetic moment between the two FM electrodes is aligned at a relative angle θ.

to note that the FM graphene electrode can be realized by growing the graphene on a FM insulator (e.g., EuO) [39] or by applying an in-plane magnetic field parallel to the graphene layer [40], and here we propose that the FM silicene electrode can also be realized by using similar methods in experiment. The tunneling current flows along the y-axis (see Fig. 1). For simplicity, we neglect the influence of magnetic ordering in electrodes on the central region.

The total Hamiltonian for the system considered can be written as $H = H_C + H_\alpha + H_{T\alpha}$, where

$$H_C = \sum_{i\in C} w_i c_i^\dagger c_i - t\sum_{\langle ij\rangle\in C} c_i^\dagger c_j + \mathrm{i}\frac{\lambda_{SO}}{3\sqrt{3}}\sum_{\langle\langle ij\rangle\rangle\in C} \nu_{ij} c_i^\dagger \sigma^z c_j - \mathrm{i}\frac{2}{3}\lambda_R \sum_{\langle\langle ij\rangle\rangle\in C}\mu_{ij} c_i^\dagger (\boldsymbol{\sigma}\times\mathbf{d}_{ij}^0)^z c_j \tag{1}$$

is the Hamiltonian for the central ZSiNR in the tight-binding approximation [2], where the Anderson-type disorder with random distributed on-site energy w_i in the range $[-W/2, W/2]$ is introduced with the disorder strength W. The second term of the total Hamiltonian

$$H_{\alpha=L/R} = -t\sum_{\langle ij\rangle\in\alpha} c_i^\dagger c_j - \sum_{i\in\alpha} c_i^\dagger\left(\boldsymbol{\sigma}\cdot\mathbf{M}_\alpha\right)c_i + \mathrm{i}\frac{\lambda_{SO}}{3\sqrt{3}}\sum_{\langle\langle ij\rangle\rangle\in\alpha}\nu_{ij} c_i^\dagger\sigma^z c_j - \mathrm{i}\frac{2}{3}\lambda_R\sum_{\langle\langle ij\rangle\rangle\in\alpha}\mu_{ij} c_i^\dagger(\boldsymbol{\sigma}\times\mathbf{d}_{ij}^0)^z c_j \tag{2}$$

for the left/right FM-stripe-covered ZSiNR electrode [27], and the third term

$$H_{T\alpha} = -t\sum_{\langle ij\rangle,(i\in C, j\in\alpha)} c_i^\dagger c_j + \mathrm{i}\frac{\lambda_{SO}}{3\sqrt{3}}\sum_{\langle\langle ij\rangle\rangle,(i\in C, j\in\alpha)}\nu_{ij} c_i^\dagger\sigma^z c_j - \mathrm{i}\frac{2}{3}\lambda_R\sum_{\langle\langle ij\rangle\rangle,(i\in C, j\in\alpha)}\mu_{ij} c_i^\dagger(\boldsymbol{\sigma}\times\mathbf{d}_{ij}^0)^z c_j \tag{3}$$

for the coupling between the central region and the electrodes. In the above Hamiltonians, $c_i = (c_{i\uparrow}\ c_{i\downarrow})^T$ for short, $c_i^\dagger\,(c_i)$ creates (annihilates) an electron with spin-up $(\uparrow)$ and -down $(\downarrow)$ on site i, respectively, $\boldsymbol{\sigma} = (\sigma_x, \sigma_y, \sigma_z)$ is the Pauli matrix, $\langle ij\rangle$ stands for the nearest-neighbor pair and $\langle\langle ij\rangle\rangle$ for the next-nearest-neighbor one which is not included in our previous work [27]. Moreover, $\nu_{ij}=1$ (-1) for the next-nearest-neighbor hopping anticlockwise (clockwise) with respect to the positive x-axis, $\mu_{ij}=1\ (-1)$ for the A (B) site, and $\mathbf{d}_{ij}^0 = \mathbf{d}_{ij}/|\mathbf{d}_{ij}|$ with vector $\mathbf{d}_{ij}$ connecting two sites i and j in the same sublattice.

To proceed the NEGF, we need to take a unitary transformation with $\tilde{c}_{is} = Uc_{is}$ for all sites in the right FM electrode [27,35,36,41], where the unitary matrix U contains the relative angle of the magnetization θ. Under this unitary transformation, the Hamiltonians H_C, H_L and H_{TL} remain unchanged, but H_R and H_{TR} become treatable for NEGF. In this case the magnetization direction of the right FM electrode is along the direction of z-axis, and then H_R is diagonal in the spin space after this unitary transformation.

Further, to analyze the spin-dependent transport property for the junction we have to firstly calculate the energy band for an infinitely long ZSiNR. Actually, Hamiltonian (1) is only for a 2D silicene, and so we need to apply the hard-wall boundary condition and establish an effective difference equation analogous to the case of an infinite one-dimensional chain for the ZSiNR (for details see Ref. 27). Once the electron energy is determined and after performing the NEGF formulism [27], the spin-dependent electronic transmission probability as a function of E through the junction can be obtained from the Landauer–Büttiker formula [42] $T_\sigma(E) = \mathrm{Tr}[\Gamma_{L\sigma}(E)G_\sigma^r(E)\Gamma_{R\sigma}(E)G_\sigma^a(E)]$, where $G_\sigma^r(E) = [G_\sigma^a(E)]^\dagger = [EI - H_C - \Sigma_{L\sigma}^r - \Sigma_{R\sigma}^r]^{-1}$ is the retarder Green's function with spin index σ and the left/right electrode retarded self-energy