Journal of Magnetism and Magnetic Materials 452 (2018) 407–414

Contents lists available at ScienceDirect

Journal of Magnetism and Magnetic Materials

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

Research articles

Large magnetoresistance dips and perfect spin-valley filter induced by topological phase transitions in silicene

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ARTICLE INFO

Article history:
Received 13 July 2017
Received in revised form 15 December 2017
Accepted 2 January 2018
Available online 4 January 2018

Keywords:
Silicene
Topological phase transition
Spin-valley filter
Magnetoresistance

ABSTRACT

Spin-valley transport and magnetoresistance are investigated in silicene-based N/TB/N/TB/N junction where N and TB are normal silicene and topological barriers. The topological phase transitions in TB's are controlled by electric, exchange fields and circularly polarized light. As a result, we find that by applying electric and exchange fields, four groups of spin-valley currents are perfectly filtered, directly induced by topological phase transitions. Control of currents, carried by single, double and triple channels of spin-valley electrons in silicene junction, may be achievable by adjusting magnitudes of electric, exchange fields and circularly polarized light. We may identify that the key factor behind the spin-valley current filtered at the transition points may be due to zero and non-zero Chern numbers. Electrons that are allowed to transport at the transition points must obey zero-Chern number which is equivalent to zero mass and zero-Berry's curvature, while electrons with non-zero Chern number are perfectly suppressed. Very large magnetoresistance dips are found directly induced by topological phase transition points. Our study also discusses the effect of spin-valley dependent Hall conductivity at the transition points on ballistic transport and reveals the potential of silicene as a topological material for spin-valleytronics.

1. Introduction

After the discovery of graphene [1], two-dimensional (2D) materials beyond graphene have drawn great interest in the field of condensed mater [2,3]. Silicene, a novel two-dimensional silicon allotrope akin to graphene, has been both theoretically predicted [4–7] and experimentally synthesized [8–13]. It has become one of promising materials for modern electronic devices, such as spin-valleytronics [14–16]. The first silicene-based field effect transistor operated at room temperature has been recently fabricated [11]. Silicene is a monolayer of silicon with atoms arranged in honeycomb lattice. Its atomic structure is buckled related to mixed $sp^2 - sp^3$ hybridizations [17] and has strong spin orbit interaction (SOI) [6], unlike that in graphene which is planar and has weak spin orbit interaction [18]. Buckled structure leads to tunable energy gap by perpendicular electric field [19,20], due to A- and B-sublattices placed in different positions. The carriers in silicene are governed by Dirac fermions with spin-valley-dependent mass controlled by external fields. The presence of SOI may give rise to quantum spin Hall (QSH) Effect which was firstly proposed by Kane and Mele [21] in graphene including effect of intrinsic SOI. Unfortunately, the subsequent work found that in SOI in graphene is rather weak [18]. In contrast to graphene, strong SOI in silicene leads to prediction of rich phase [6,15,22–26]. It undergoes a topological phase transition from QSH state, 2D topological insulator, to a trivial (or band) insulator, quantum valley Hall (QVH) insulator, by varying perpendicular electric field [22]. Quantum anomalous Hall (QAH) Effect occurs in silicene induced by magnetization and SOI [23,24]. Spin polarized quantum anomalous Hall (SQAH) insulator and anti-ferromagnetic (AF) phase are induced by interplay of electric field and magnetization [15]. The various types of topological phase transitions are classified by spin-valley Chern numbers due to spin and valley degrees of freedom in silicene. The trivial insulator phases are related to the first and spin-Chern numbers (C, C_s) are zeroes (0, 0) while topological insulator phases occur when (C, C_s) are not zeroes [25]. Quantum spin-valley Hall conductivities may be given associated with spin-valley Chern numbers.

Recently, ballistic spin-valley transport properties in silicene junctions have been investigated by several works [16,27–34]. Charge transport in *pn* and *npn* junctions in silicene were investigated, to show the conductance being almost quantized 0, 1 and 2 [27]. Spin-valley polarized currents have been investigated [28–30]. Defect enhanced spin and valley polarizations are possible in silicene superlattices [28,29]. The spin-valley-polarized Andreev reflection at the interface silicene-based normal/superconducting junction is found to be fully controlled by external electric field

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https://doi.org/10.1016/j.jmmm.2018.01.004

[30]. Perfect spin-valley filtering controlled by electric field has been proposed in a ferromagnetic silicene junction [16] when A and B sublatices are induced into ferromagnetism by different exchange fields. Control of spin-valley currents by circularly polarized lights have also been investigated [31,32], since it can induce valley-dependent-Dirac mass into silicene [33].

In this paper, we investigate spin-valley currents and magnetoresistance in silicene-based N/TB/N/TB/N junction where N and TB are normal silicene and topological-phase-transition barriers, respectively. We assume that in the two TB-barriers, perpendicular electric field [22], staggered exchange field [15,16] and circularly polarized lights are applied [33]. The effect of topological phase transitions in silicene on spin-valley transport and magnetoresistance is the main objective of our work. The effect which is directly due to topological phase transitions in the barriers has not been studied by previous works. Spin-valley quantum Hall conductivities in barriers are taken into consideration. The topological phase transition in the barriers can be tuned by varying electric field, exchange energy and frequency of circularly polarized light, controlling species of electron carriers to transport in the junctions.

2. Hamiltonian model

Let us first consider the tight-binding Hamiltonian in our model, a silicene-based N/TB/N/TB/N junction, as seen in Fig. 1a. In TB regions, it may be modeled as of the form [15]

$$h_{TB} = -t\sum_{\langle i,j\rangle\alpha} c^{\dagger}_{i\alpha}c_{j\alpha} + i\frac{\Delta_{so}}{3\sqrt{3}}\sum_{\langle\langle i,j\rangle\rangle\alpha\beta} \nu_{ij}c^{\dagger}_{i\alpha}\sigma^{z}_{\alpha\eta}c_{j\beta} - i\frac{2}{3}\Delta_R\sum_{\langle\langle i,j\rangle\rangle\alpha\beta}\gamma_i c^{\dagger}_{i\alpha}\left(\vec{\sigma}\times\hat{\xi}_{ij}\right)^{z}_{\alpha\beta}c_{j\beta} + \sum_{i\alpha}\gamma_i e\ell E_z c^{\dagger}_{i\alpha}c_{i\alpha} + \sum_{i\alpha\beta}\gamma_i M c^{\dagger}_{i\alpha}\sigma^{z}_{\alpha\beta}c_{i\beta} + i\frac{\Delta_{\Omega}}{3\sqrt{3}}\sum_{\langle\langle i,j\rangle\rangle\alpha\beta}\nu_{ij}c^{\dagger}_{i\alpha}c_{j\beta} + \sum_{i\alpha}Uc^{\dagger}_{i\alpha}c_{i\alpha}, \quad (1)$$

where $c^{\dagger}_{i\alpha}$ ($c_{j\beta}$) is creation (destruction) field operator at site i(j) for electron with spin polarization α (β) and $\langle i,j\rangle$ ($\langle\langle i,j\rangle\rangle$) run over all the nearest-neighbor (next-nearest neighbor) hoping sites. The first term represents graphene-like Hamiltonian with hoping energy $t = 1.6$ meV for silicene. The second term represents spin–orbit interaction effect in silicene with $\Delta_{so} = 3.9$ meV [34] where $\vec{\sigma} = \langle\sigma^x, \sigma^y, \sigma^z\rangle$ is vector of Pauli spin matrix acting on real-spin states. $\nu_{ij} = 1(-1)$ if the next-nearest-neighboring hoping is anti-clockwise (clockwise) respect to direction normal to silicene sheet. The third term represents Rashba spin orbit interaction with $\Delta_R = 0.7$ meV where $\gamma_i = 1(-1)$ for A-(B-) sublattice and $\hat{\xi}_{ij} = \vec{\xi}_{ij}/|\vec{\xi}_{ij}|$ with $\vec{\xi}_{ij}$ connecting two site i and j in the same sublattice. The fourth term represents interaction due to applying perpendicular electric field $\Delta_E = e\ell E_z$ where e,E_z and ℓ are bare electron charge, electric field and buckling parameter, respectively. The fifth term represents interaction induced by staggered exchange field with exchange energy $\Delta_M = M$ which may be realized by depositing magnetic insulators with exchange energy of M on top and bottom of silicene sheet with different exchange field directions [16,23]. The sixth term represents interaction induced by off-resonant circularly polarized light irradiated onto silicene sheet with vector potential $\vec{A} = \Lambda\langle\pm\sin\Omega t, \cos\Omega t, 0\rangle$, where Λ and Ω are the amplitude and frequency of light respectively. This is to get $\Delta_{\Omega} = \pm\hbar v_F^2 A^2/a^2\Omega$ where $+(-)$ denotes right (left) circulation. $A = ea\Lambda/\hbar$, $a = 3.86$ Å and $v_F = 5.5\times10^5$ m/s are dimensionless amplitude [33], the lattice constant and the Fermi velocity [34], respectively. The last term represents chemical potential applied by gate voltage with electric potential $-U/e$. In the low energy limit, the effect of Rashba term is usually neglected. Therefore, low energy effective Hamiltonian used to describe motion of quasiparticles, Dirac fermions, in TB-regions, related to tight-binding model in Eq. (1) may be given as

$$H_{TB} = \eta v_F\hat{p}_x\tau^x + v_F\hat{p}_y\tau^y + (\eta s\Delta_{so} + \eta\Delta_{\Omega} + s\Delta_M - \Delta_E)\tau^z + U, \quad (2)$$

where $\vec{\tau} = \langle\tau^x, \tau^y, \tau^z\rangle$ is vector of Pauli spin matrix acting on pseudo (or lattice)-spin states, $s = +(-)$ stands for electron with real-spin $\uparrow(\downarrow)$, $\eta = +(-)$ stands for electron in $k-(k'-)$ valley, and $\hat{p}_{x(y)} = -i\hbar\partial_{x(y)}$ is the momentum operator. In N-regions, there are no electric, exchange fields and circularly polarized light applied into silicene sheet. By taking $\Delta_{\Omega} = \Delta_M = \Delta_E = \mu = 0$ into Eq. (2), thus we get low energy effective Hamiltonian in NM-regions of the form

$$H_N = \eta v_F\hat{p}_x\tau^x + v_F\hat{p}_y\tau^y + \eta s\Delta_{so}\tau^z. \quad (3)$$

It is seen that from Eqs. (2) and (3), in N-region the band dispersion is not spin-valley dependent

$$E_{\eta s} = \pm\sqrt{v_F^2p_x^2 + v_F^2p_y^2 + \Delta_{so}^2}, \quad (4)$$

where $\pm$ denotes conduction (valence) band. In TB-regions, it is spin-valley dependent

$$E_{\eta s} = \pm\sqrt{v_F^2p_x^2 + v_F^2p_y^2 + (\eta s\Delta_{so} + \eta\Delta_{\Omega} + s\Delta_M - \Delta_E)^2} + U. \quad (5)$$

The energy gap and Dirac mass in N-regions are $E_{gap,\eta s} = 2\Delta_{so}$ and $m_{\eta s} = \eta s\Delta_{so}/v_F^2$, respectively. Energy gap and Dirac mass in TB-regions are $E_{gap,\eta s} = 2|\eta s\Delta_{so} + \eta\Delta_{\Omega} + s\Delta_M - \Delta_E|$ and $m_{\eta s} = (\eta s\Delta_{so} + \eta\Delta_{\Omega} + s\Delta_M - \Delta_E)/v_F^2$, respectively. Plot of band structure in each region is shown in Fig. 1b.

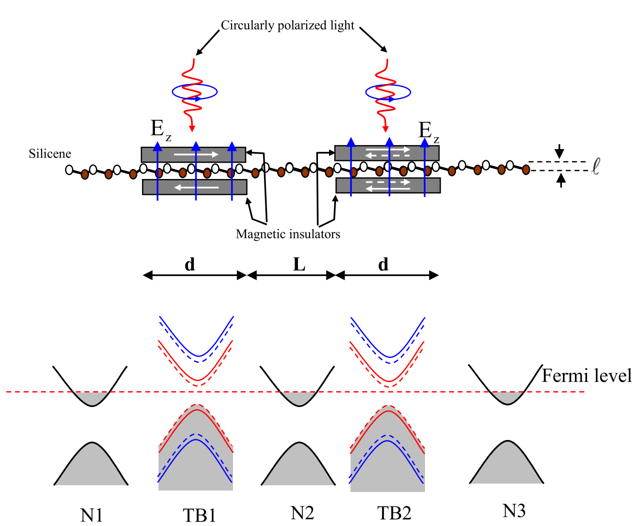

Fig. 1. Schematic illustration of a silicene-based N/TB/N/TB/N junction where N and TB are normal silicene and topological-phase-transition barriers, respectively (a). Electronic band structure in each region where the Fermi energy in the barriers lies inside band gap to cause topological phase transition (b). In the barriers, proximity-induced exchange energies in A and B sublattices, electric field and irradiating circularly polarized light are applied. Staggered magnetizations in TB-regions can be set to be P-junction and AP-junction.

3. Topological phase transitions in TB-regions

As mentioned in the first section, the topological phase transition is required in the TB-regions. The Fermi energy in TB-region must be inside the energy gap of the carriers, using the condition of $E = U$. The Fermi energy of electron only in N-regions lies above the gap leading to that all electron species can propagate through NM-regions and there is no topological phase in N-regions. Hence, TB-regions are considered as topological barriers in which phase transitions can be tunable by external forces. Let us start with