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Electronic structure and transport on the surface of topological insulator attached to an electromagnetic superlattice

Haiyan Wang [a], Xiongwen Chen [a,b], Xiaoying Zhou [a], Lebo Zhang [a], Guanghui Zhou [a,c,*]

[a] Department of Physics and Key Laboratory for Low-Dimensional Quantum Structures and Manipulation (Ministry of Education), Hunan Normal University, Changsha 410081, China

[b] Department of Physics and Electronic Information Science, Huaihua University, Huaihua 418008, China

[c] International Center for Materials Physics, Chinese Academy of Sciences, Shenyang 110015, China

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ABSTRACT

We study the electronic structure and transport for Dirac electron on the surface of a three-dimensional (3D) topological insulator attached to an electromagnetic superlattice. It is found that, by means of the transfer-matrix method, the number of electronic tunneling channels for magnetic barriers in antiparallel alignment is larger than that in parallel alignment, which stems to the energy band structures. Interestingly, a remarkable semiconducting transport behavior appears in this system with a strong magnetic barrier due to low energy band nearly paralleling to the Fermi level. Consequently, there is only small incident angle transport in the higher energy region when the system is modulated mainly by the higher electric barriers. We further find that the spatial distribution of the spin polarization oscillates periodically in the incoming region, but it is almost in-plane with a fixed direction in the transmitting region. The results may provide a further understanding of the nature of 3D TI surface states, and may be useful in the design of topological insulator-based electronic devices such as collimating electron beam.

1. Introduction

Topological insulator (TI) [1] has been gaining increased theoretical and experimental attentions due to its novel properties and potential applications [2]. A TI is characterized by a fully insulating gap in the bulk and gapless helical edge or surface states on the boundary [3–9]. In a three-dimensional (3D) TI, it has been verified [10–15] that the surface states with an odd number of Dirac cones are robust against disorder scattering and many-body interaction. Owing to the strong spin–orbit interaction the direction of electron spin is locked perpendicularly to its momentum, and these surface states are protected by the time-reversal symmetry [16–18].

Interestingly, the properties of surface states can be manipulated electrically or/and magnetically [19–26]. For example, the sensitive dependence of conductance on ferromagnets or a gate voltage has been demonstrated [25,26]. Mondal et al. [27] have also obtained an interesting way to realize magnetic switching on 3D TI surface with the exchange field produced by a single ferromagnetic strip. Recently, Zhang et al. [28] have investigated the band and transport features of Dirac electrons on the surface of a 3D TI with a uniform magnetic superlattice, respectively. They have found that the Dirac point is shifted by the magnetic superlattice in parallel (P) configuration while unshifted in anti-parallel (AP) configuration, and a full transmission gap in both P and AP alignments has been presented for the system. Further, a sliding [29] or spiral [30] magnetic superlattice on the surface of a 3D TI has also been considered, respectively. The energy spectrum of these superlattice systems have only two Dirac points but many semi-Dirac points [29,30]. On the other hand, the effects of ferromagnets onto a conventional two-dimensional electron gas (2DEG) have been studied extensively [31]. Moreover, periodic magnetic and electric fields applied to a carbon monolayer (graphene) have also been studied recently [32], where a gap between the valence and conduction band is introduced. However, periodic vector and scale potentials on the surface of a 3D TI have not been mentioned. This system may also be realized by depositing ferromagnetic insulating (FI) and Schottky metal (SM) stripes on the surface of a TI crystal, and may present some different transport behavior from that for graphene [32].

In this paper, by means of the transfer-matrix method, we present a theoretical investigation on the transport property for Dirac electrons on the (1 1 1) surface of a Bi_2Se_3 crystal, modulated by an electromagnetic superlattice, i.e., alternative magnetic barriers inserted in electric barriers. It is found that the number of

* Corresponding author at: Department of Physics and Key Laboratory for Low-Dimensional Quantum Structures and Manipulation (Ministry of Education), Hunan Normal University, Changsha 410081, China.
E-mail address: ghzhou@hunnu.edu.cn (G. Zhou).

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transmission channels for magnetic barriers with AP configuration is larger than that for P configuration. Interestingly, for both P and AP configurations a remarkable semiconducting transport behavior appears when the magnetic barrier is strong enough. In the case of high electric barrier the transport for large incident angle is fully blocked in the high energy regime. Moreover, the distribution of the electron spin polarization shows a spatial-dependent distribution in the incoming region of the system, but in the transmitting region its direction is always the same as the incident direction. These phenomena are somewhat different from those for conventional 2DEG [31] and graphene [32] due to the spin–moment locking of electrons on TI surface, and may be used in designing TI-based nanodevices such as collimating electron beam [23,26].

The rest of the paper is organized as follows. In Section 2, we describe the model and present the general formalism with transfer-matrix method to evaluate the dispersion, transmission probability and conductance for the system. In Section 3, the results of typical numerical examples with physical explanations for the system are given. Finally, Section 4 summarize the work.

2. Model and method

As shown in Fig. 1, the system proposed in this work is the surface of a 3D TI in (x,y) plane modulated by an attached electromagnetic superlattice, i.e., magnetic barriers with electric barriers between them. This system can be realized [31] by alternatively depositing FI and SM stripes on the surface of a 3D TI to produce local fields. The Hamiltonian around Dirac point for the system can be described by [26]

$$H = v_F \boldsymbol{\sigma}\cdot[\mathbf{p}+e\mathbf{A}(x)]+V(x), \tag{1}$$

where the Zeeman term has been neglected and $\hbar=c=1$ is adopted, v_F is the Fermi velocity, $\mathbf{p}$ the in-plane momentum

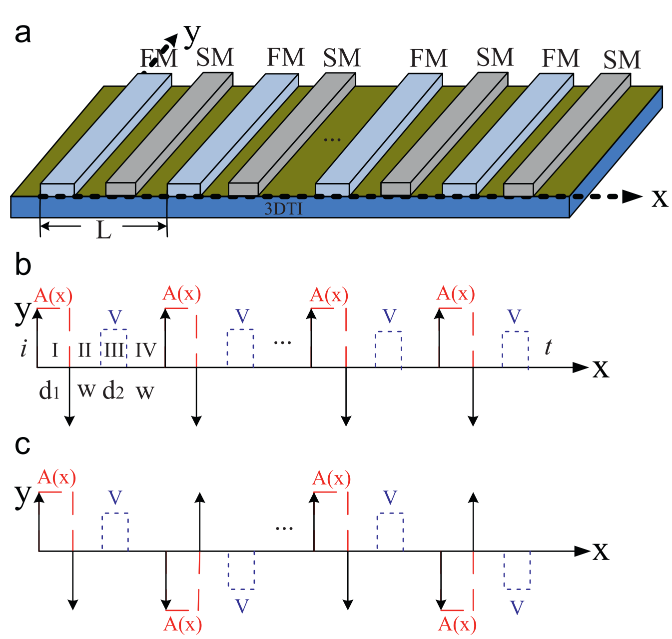

Fig. 1. (a) Schematic view of the considered surface of a 3D TI modulated by a periodic magnetic alternated with electric barrier, where the length of a unit is L. (b) Simplified profiles of the magnetic field $B(x)$ (spikelike black solid line), the corresponding vector potential $A(x)$ (squared red dashed line) and electric barrier (squared blue dotted line) for P alignment case, where the width of magnetic and electric barrier are, respectively, d_1 and d_2, the space between any two barriers is w. (c) The same as in (b) for AP alignment case. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

operator, e the electron's charge, $\boldsymbol{\sigma}=(\sigma_x,\sigma_y)$ the Pauli matrices, $\mathbf{A}(x)$ the FI-induced vector potential, and $V(x)$ the SM-induced scalar potential.

In particular, we assume that the FI-induced local magnetic field is

$$B_z(x) = B_0[\delta(x)-\delta(x-d_1)]+\lambda B_0[\delta(x-L)-\delta(x-L-d_1)]$$

with corresponding vector potential

$$A_y(x) = B_0 d_1[\Theta(x)\Theta(d_1-x)+\lambda\Theta(x-L)\Theta(L+d_1-x)]$$

under the Landau gauge, and the electric potential profile is

$$V(x) = V_0[\Theta(x-d_1-w)\Theta(d_1+w+d_2-x) + \lambda\Theta(x-L-d_1-w)\Theta(L+d_1+w+d_2-x)].$$

Here $\Theta(\cdot)$ is the step-function and $\delta(\cdot)$ the δ-function, $\lambda=1/-1$ for P/AP alignment of the magnetization configuration, d_1 is the width of a magnetic barrier, d_2 the width of an electric barrier, and w the distance between any two barriers. Consequently, $A_y(x)$ is replaced by a constant value $m=B_0d_1$ in the magnetic barrier regions with magnetization aligned to the $\pm y$-axis or zero otherwise. The periodic modulation length is $L=d_1+d_2+2w$ for P alignment and $2L$ for AP alignment. Therefore, the system of N units is modulated by a vector (magnetic) potential $A_y(x)=A_y(x+nL)$ and a scalar (electric) potential $V(x)=V(x+nL)$.

In the Hamiltonian, all the physical quantities can be expressed in the dimensionless units by introducing magnetic length $l_B=\sqrt{\hbar/eB_0}$. Then the magnetic field $B_z(x)\rightarrow B_z(x)B_0$, coordinate $\mathbf{r}\rightarrow\mathbf{r}l_B$, wavevector $\mathbf{k}\rightarrow\mathbf{k}/l_B$, vector potential $A_y(x)\rightarrow A_y(x)B_0l_B$, scalar potential $V(x)\rightarrow V(x)V_0$ and energy $E\rightarrow EE_0$. Thus Hamiltonian (1) can be rewritten as

$$H=\begin{pmatrix} V(x) & k_x-i(k_y+A_y(x)) \\ k_x+i(k_y-A_y(x)) & V(x)\end{pmatrix}, \tag{2}$$

with which the equation $H\psi(x,y)=E\psi(x,y)$ can employ the form of wavefunction

$$\psi(x,y)=\begin{pmatrix}\psi_I(x,y)\\ \psi_{II}(x,y)\end{pmatrix}. \tag{3}$$

Because that the system described by the above Hamiltonian is translational invariant along the y direction, the wave function for Dirac electrons can be expressed as $\psi(x,y)=e^{ik_yy}\phi(x)$, where k_y is the wavevector along the interface and $\phi(x)$ the spin function. In the regions without modulation potential, the x- and y-direction wave vectors are $k_1=E\cos\alpha$ and $q_1=E\sin\alpha$ with incident angle α. In the magnetic and electric barrier modulated regions for the case of P alignment, the wavevectors are $k_2=\sqrt{E^2-(k_y+A_y)^2}=E\cos\beta$ and $q_2=k_y+A_y=E\sin\beta$, $k_3=\sqrt{(E-V_0)^2-k_y^2}=(E-V_0)\cos\gamma$ and $q_3=(E-V_0)\sin\gamma$ with refraction angles β and γ, respectively. Correspondingly, for AP configuration $k_2'=\sqrt{E^2-(k_y-A_y)^2}=E\cos\beta'$, $q_2'=k_y-A_y=E\sin\beta'$, $k_3'=\sqrt{(E+V_0)^2-k_y^2}=(E+V_0)\cos\gamma'$, $q_3'=(E+V_0)\sin\gamma'$ with refraction angles β' and γ' in opposite magnetic and electric barriers, respectively. Therefore, in the regions of incoming (i), transmitting (t), unlimited (II, IV), magnetic barrier (I) and electric barrier (III) (see Fig. 1(b)), the wave function can be uniformly expressed as

$$\phi(x)=a_Xe^{ik_jx}\begin{pmatrix}1\\ e^{i\varphi}\end{pmatrix}+b_Xe^{-ik_jx}\begin{pmatrix}1\\ -e^{-i\varphi}\end{pmatrix}, \tag{4}$$

where a_X and b_X ($X=i$, I, II, III, $\ldots$,t) are the coefficients of waves with wave vector k_j ($j=1,2,3$) and refraction angle $\varphi=(\alpha,\beta,\gamma)$ in different regions. On the other hand, for AP alignment in magnetic and electric