Tunneling through ferromagnetic barriers on the surface of a topological insulator

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We study the transmission through single and double ferromagnetic barriers on the surface of a topological insulator. By adjusting the gate voltage and magnetization orientation, the ferromagnetic barrier can be tuned into various transmission regions, where the wavevector-dependent tunnelings are quite different. We find that the Klein tunneling can be manipulated or even be turned off. These special properties offer the possibility to control electron beams on the “topological metal”. Various novel devices, such as electronic collimation, wavevector filter, magnetic and electric switches, and wavevector-based spin valve, may be constructed based on our observed phenomena.

I. INTRODUCTION

Due to its unique electronic properties, the study about the graphene system has recently drawn great attentions. The charge carriers in single-layer graphene behave like “relativistic” chiral massless particles and possess a gapless linear energy spectrum. Effectively, in low energy regime, graphene can be viewed as a two-dimensional (2D) Dirac fermion system. For such Dirac-like quasiparticles, the transport properties are dramatically different from the conventional semiconductors. There is hope to utilize these peculiar transport characteristics to develop novel relativistic electronic devices.

Recently, another 2D Dirac fermion system has been confirmed experimentally. It is called topological metal (TM), i.e., the surface states of a strong topological insulator (STI). The strong topological insulator is a new state of matter protected by the time-reversal invariance. Though still with a bulk gap, it is distinguished from the normal insulator by the topological $Z_2$ invariance. This distinction results in the existence of the gapless electronic states on the sample surfaces. The surface state is the TM mentioned above, which can be effectively viewed as a 2D chiral Dirac fermion system. Due to the time-reversal symmetry and the topology of the bulk gap, the topological surface states are robust against disorder.

Because of the similar energy dispersions, the transport property of the TM is very similar to that of a graphene. However, there are important differences between the two systems. TM is a surface state of semiconductor alloy, e.g., Bi$_{1-x}$Sb$_x$ or Bi$_2$Se$_3$, thus more stable than a fragile thin graphene sheet. Furthermore, the spin of the Dirac fermion of a TM is the real spin, while for graphene it is the pseudo spin. Hence, the magnetic or spin control of the electronic transport on a TM can be much more effective than that on a graphene. In this work, we study the transport properties with ferromagnetic barriers on top of a topological surface. As shown in Fig.1, for a ferromagnetic barrier, a ferromagnetic insulator is put on the top of the topological insulator to induce an exchange field via the magnetic proximity effect. Meanwhile, a metal gate on the top of the insulator is used to control the electrostatic potential. We find that by adjusting the magnetization orientation in the ferromagnetic insulator and the gate voltage, the ferromagnetic barrier can be tuned into various transmission regions. The behaviors of the transmission probability, as a function of the incident angle of the electron, in different regions are rather different. An interesting issue is about the Klein tunneling. It is well known that, for Dirac fermion, merely with electrostatic potential one cannot block the electron transport, and the normal incidence is at least partially transmitted. But for the ferromagnetic barrier, because the induced exchange field, not only could the angle of Klein tunneling be controlled, but also the Klein tunneling could even be blocked.
carefully analyze the transmission probabilities in various regions, for both single and double barriers. Based on these analyses, we propose that electron beam collimation, wavevector filtering, magnetic and electric switch, wavevector-based in-plane spin valve could be realized in such structures. These transport phenomena are quite different from the case with ferromagnetic barrier on graphene\textsuperscript{15,16,17,18}.

This paper is organized as follows. In Sec. II, we introduce the model and formalisms. In Sec. III, we discuss the analytical and numerical results of the transport properties of single and double ferromagnetic barriers. And we then show how to construct novel electronic devices based on the phenomena obtained in our theory. Finally, a brief summary is given in Sec. IV.

II. MODEL AND FORMALISM

The Dirac fermion of the topological surface can be described as:

\[ H = \hbar v_f \mathbf{k} \cdot \sigma + \mathbf{M} \cdot \sigma \]  

(1)

where \( \mathbf{M} = M(\sin \theta_m \cos \phi_m, \sin \theta_m \sin \phi_m, \cos \theta_m) \) is the effective exchange field induced via magnetic proximity effect. In this work, we only consider the in-plane exchange field. The main consequence of the z component of the exchange field is to open an energy gap and its effects have been investigated in a recent theoretical study\textsuperscript{19}. If the Fermi level of the whole system is inside the gap, the transport of the barrier is completely blocked. No tunneling is permitted. Otherwise, the effect is just a change of the position of the Fermi surface. So for simplicity and without loss of generality, we merely consider an in-plane exchange field. The sketch of the barrier structure is shown in Fig.1.

Take the single barrier structure for example, the whole system consists of three different regions and the interfaces between these regions are labeled by \( l_i \). With the above Hamiltonian, the eigenfunctions for region \( \alpha \) are

\[ \phi^{(1)}_\alpha(x, y) = e^{ik_\alpha x}x + k_{\alpha y} y \left( \frac{1}{S_\alpha e^{i\theta_\alpha}} \right) \]  

(2)

\[ \phi^{(2)}_\alpha(x, y) = e^{ik_\alpha x}x + k_{\alpha y} y \left( \frac{1}{S_\alpha e^{i(\pi - \theta_\alpha)}} \right) \]  

(3)

where \( S_\alpha = \epsilon - V_\alpha, e^{i\theta_\alpha} = (k_{\alpha x} + ik_{\alpha y})/|k_{\alpha x}| \), and \( k_{\alpha x} = -M \cos \phi_{\alpha} \pm \sqrt{(\epsilon - V_\alpha)^2 - (k_{\alpha y}^2 + M \sin \phi_{\alpha})^2} \). \( V_\alpha \) is the potential of this region, \( \epsilon \) is the energy of the incident electron. Due to the translation invariant along the y-axis, the momentum \( k_y \) is conserved, i.e., \( k_{\alpha y} = k_y \).

In order to solve the transport problem, we use the standard transfer matrix method\textsuperscript{20}. By matching the wave functions at the interface \( l_1 = 0 \), we get the transfer matrix

\[ T_{l_1} = T^{(0)}_{21} = \frac{1}{2S_2 \cos \theta_2} \]  

(4)

\[ \cdot \left( \begin{array}{cc} S_2e^{-i\theta_2} + S_1 e^{i\theta_1} & S_2e^{-i\theta_2} - S_1 e^{i\theta_1} \\ S_2e^{i\theta_2} - S_1 e^{-i\theta_1} & S_2e^{i\theta_2} + S_1 e^{-i\theta_1} \end{array} \right) \]

The transfer matrix at the interface \( l_2 = a \) can be represented as

\[ T_{l_2} = \left( \begin{array}{cc} e^{-ik_\alpha x}a & 0 \\ 0 & e^{ik_\alpha x}a \end{array} \right) \cdot T^{(0)}_{32} \]  

(5)

where \( T^{(0)}_{32} \) is the same as \( T^{(0)}_{21} \) except the region index. Finally, we will get the total transfer matrix for the single barrier

\[ T_s = T_{l_1}T_{l_2} \]  

(6)

With the transfer matrix, the reflection and translation coefficients can be got through following equation

\[ \left( \begin{array}{c} t \\ 0 \end{array} \right) = T_s \cdot \left( \begin{array}{c} 1 \\ r \end{array} \right) \]  

(7)

\( T = |t|^2 \) is just the transmission probability we want.

Double barrier structure could be treated in similar way. The only difference is that we have four interfaces here.

\[ T_d = T_{l_1}T_{l_2}T_{l_3}T_{l_4} \]  

(8)

With the transmission probability, in the linear transport regime and for low temperature, we can get the conductance density (the conductance per unit length along the interface) of the barrier structure\textsuperscript{23}

\[ g = g_0 \int_{-\pi/2}^{\pi/2} d\theta_{in} T(\epsilon_f, \theta_{in}) \cos \theta_{in} \]  

(9)

Here, \( g_0 = \frac{e^2}{4\pi k_BT} \), \( \epsilon_f \) is the Fermi energy of the system, \( \theta_{in} \) is the incident angle of the electron and \( T(\epsilon_f, \theta_{in}) \) is the transmission probability through the barrier.

III. RESULT AND DISCUSSION

A. Single barrier

For a single barrier, an analytical expression of the transmission probability could be given.
where \( q_x = k_{2x} + M \cos \phi_m \). Formally, it is the same as the one for the graphene potential barrier except a shift of the Fermi surface due to the in-plane exchange field.

As mentioned above, for a ferromagnetic barrier, changing the gate voltage will alter the Fermi surface, the in-plane exchange field will also cause a shift. The key issue about the transport is that, during the tunneling, the energy and \( k_x \) of the incident electron are conserved. As shown in Fig. 2, in the incident region (Region 1 in Fig. 1), the range of \( k_y \) values \( |\epsilon - V_1| |k_y| \) is plotted. But not all the incident electrons are allowed to transmit, since the Fermi surface has been changed in the ferromagnetic barrier (Region 2 in Fig. 1). The \( k_y \) range of the ferromagnetic barrier is \( |\epsilon - V_2| > |k_y + M \sin \phi_m| \).

Therefore, the permitted incident angle of the electron is determined by the overlap of the \( k_y \) ranges of adjacent regions. It means that, through adjusting the gate voltage and the direction of the magnetization of the ferromagnetic barrier, we can tune the acceptable range of \( k_y \), and rather different transmissions will appear accordingly.

In the case of Fig. 3, \( V_2 \) is far from the energy of incident electron \( \epsilon \). So for any in-plane rotation angle \( \phi_m \), there are always \( |\epsilon - V_2| - M \sin \phi_m > |\epsilon - V_1| \) and \( -|\epsilon - V_1| > -|\epsilon - V_2| - M \sin \phi_m \). Hence, all the incident angles are allowed from the viewpoint of \( k_y \) conservation.

We can say that the ferromagnetic barrier is in the total transmission status now. As shown clearly, when we rotate the magnetization orientation, the angle of the Klein tunneling will be changed and new resonance peaks will appear.

Another intriguing case occurs when the gate voltage of the barrier \( V_2 \) is near the energy of the incident electron \( \epsilon \). In this situation, the relations, \( |\epsilon - V_1| > |\epsilon - V_2| - M \sin \phi_m \) and \( -|\epsilon - V_1| > -|\epsilon - V_2| - M \sin \phi_m \) are always hold for any angle \( \phi_m \). As shown in Fig. 4, we can get a transmission sector of incident angle in this partial transmission status. The width of the sector is determined by \( |\epsilon - V_2| \) and its position can be tuned through adjusting the magnetization orientation. It obviously can be used as a wavevector filter. Furthermore, as pointed in electron optics, this has immediate applicability in electron beam collimation and lensing. Better collimation effect could be achieved through a series of barriers.

When \( -M > |\epsilon - V_2| > |\epsilon - V_1| \), for some angle \( \phi_m \), the overlap between the \( k_y \) ranges of the two regions will be absent and the conductance becomes zero. This is
FIG. 5: (Color online) Up: The transmission probability of the single ferromagnetic barrier in the blockable status. $V_2 = 90\text{meV}$, $V_1 = 60\text{meV}$ and other parameters are the same as Fig. 3. Down: The corresponding conductance density in this case.

FIG. 6: (Color online) Up: The transmission probability of the single ferromagnetic barrier in the blockable status. $\phi_m = 0.5\pi$ and other parameters are the same as Fig. 5. Down: The corresponding conductance density in this case.

FIG. 7: (Color online) Up: The transmission probability of the double ferromagnetic barrier structure. $\phi_{m1(2)}$ is the in-plane rotation angle of ferromagnetic barrier 1(2), and $\phi_{m2} = 0.5\pi$. Both barriers are in the partial transmission status. $V_1 = V_3 = V_5 = 60\text{meV}$, $V_2 = V_4 = 90\text{meV}$, $\epsilon = 80\text{meV}$ and $l_2 - l_1 = l_3 - l_2 = l_4 - l_3 = 100\text{nm}$. Down: The corresponding conductance density in this case.

The blockade status, in which the transmission of the ferromagnetic barrier can be completely blocked. Since that both $V_2$ and $\phi_m$ could be used to tune the overlap, we can construct magnetic and electric on-off with the single ferromagnetic barrier structure. Fig. 5 gives the case of magnetic switch. With a definite $V_2$, there is a blocked sector of angle $\phi_m$, in which the transmission probability is zero for any incident electron. The conductance of the magnetic switch is shown as well. The alteration of electrostatic potential can also completely block the transmission. This is quite different from a normal tunneling barrier for Dirac fermions. It is known, due to the Klein paradox, merely with electrostatic potential one can not block the transport of 2D Dirac fermions. However, with a ferromagnetic barrier the condition is different. For a definite angle $\phi_m$, if $|M \sin \phi_m| > |\epsilon - V_1|$, there must be a critical gate voltage $V_{2c}$ that $-M \sin \phi_m - |\epsilon - V_{2c}| = |\epsilon - V_1|$. Compared with $V_{2c}$, when $|\epsilon - V_2|$ decreases, the $k_y$ ranges of the two regions separate out and the transport is turned off (See in Fig. 6). It is just an electric switch which the on/off state of the current is controlled by the gate voltage. Interestingly, when increasing $V_2$, the current will be turned on (See in Fig. 6). This unique property, i.e. the voltage window for the open status, is not possible with a normal semiconductor barrier. Clearly, this transport phenomenon could be used to distinguish TM from the normal semiconductor and the graphene systems. It means that transport measurement is also a very useful tool to experimentally confirm the existence of the TM.

B. Double barrier

For the double barrier structure, we also could understand the transport properties through the conservation of the $k_y$ and the energy. As mentioned above, depending on the voltage and magnetization, single ferromagnetic
The angle of the first barrier \( \phi \) could also be tested in transport experiments as a distinction between the TM and normal semiconductors. The transport behavior of the double barrier system is more complex than that of the single one, since that the two barriers can be tuned into different transport situations.

Here, we investigate two interesting examples. One is the case that two ferromagnetic barriers are both in the partial transmission status. In this case, both barriers have their own transmission sector of the incident angle of the electron. Only when the two transmission sectors overlap, the double barrier structure becomes conducting. Hence, as shown in Fig. 7, the direction of magnetization of the second barrier is fixed \( \phi_{m2} = \pi/2 \). Only if the angle of the first barrier \( \phi_{m1} \) is tuned in parallel, the transmission of the double barrier structure is nonzero. The corresponding conductance is also given in Fig. 7. Essentially, in this situation the double barrier system becomes a special wavevector-dependent in-plane spin valve system, for which the parallel configuration is the only conducting state. The blockade of the transmission is mainly because the mismatch of the wavevectors, while for normal spin valve the primary reason is the different spin dependent potentials. Therefore, for a normal spin valve, the conductance will vary continuously with the angle between the magnetizations. But, as shown in Fig. 7, for the in-plane spin valve on TM the change of the conductance is rather sharp and the and the conductance of the non-parallel configuration is exactly zero. These special transport properties of the double barrier structure on TM could also be tested in transport experiments as a distinction between the TM and normal semiconductors.

For a single barrier, it is hard to directly observe the partial transmission region through the conductance. This is because that the change of position of the transmission sector will not induce an obvious change in the conductance. But in the double barrier system this can be done.

As a comparison (See in Fig. 8), we also calculate the case that both barriers are in the total transmission status. In this situation, the angle dependent transmission probability is much more complicated.

IV. SUMMARY

In conclusion, we have investigate the transport properties of the ferromagnetic barriers on the surface of a topological insulator. The single and double barrier structures have been carefully considered. We show that the gate voltage and the magnetization could be used to manipulate the Fermi surface of the barrier. Due to the conservation of energy and \( k_y \) of an incident electron during the transport process, adjusting the Fermi surface will tune the single ferromagnetic barrier into three different transmission statuses: total transmission, partial transmission, and the transmission blockade. In the total transmission case, all the incident angles are allowed. The angle of the Klein tunneling and position of the resonance vary with the direction of the magnetization, and meanwhile new resonance peaks appear. In the partial transmission situation, only the incident angles in a transmission sector are allowed. The position and width of the transmission sector can be adjusted through the gate voltage and the magnetization. Therefore, the electron collimation and wavevector filter could be realized based on this phenomenon. With proper gate voltage and magnetization, one can even separate the Fermi surfaces, reaching the blockade status. In this case, no transport can occur, even the Klein tunneling. We propose that both magnetic and electric switches, based on the single ferromagnetic barrier on topological surface, could be realized in this situation. We also study the transport of the double barrier structure. In this system, we can construct a special wavevector-dependent spin valve when both barriers are in the partial transmission status. The spin valve is conducting only if the magnetization of the two barriers are parallel. We emphasize that these unique transport properties of TM could be used to distinguish TM from the normal semiconductors and the graphene systems. Hence, the observations of these transport properties provide confirmation of the existence of TM.

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