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Spin transport in normal metal/insulator/topological insulator coupled to ferromagnetic insulator structures

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In this study, we investigate the spin transport in normal metal (NM)/insulator (I)/topological insulator (TI) coupled to ferromagnetic insulator (FI) structures. In particular, we focus on the barrier thickness dependence of the spin transport inside the bulk gap of the TI with FI. The TI with FI is described by two-dimensional (2D) Dirac Hamiltonian. The energy profile of the insulator is assumed to be a square with barrier height V and thickness d along the transport-direction. This structure behaves as a tunnel device for 2D Dirac electrons. The calculation is performed for the spin conductance with changing the barrier thickness and the components of magnetization of FI layer. It is found that the spin conductance decreases with increasing the barrier thickness. Also, the spin conductance is strongly dependent on the polar angle θ , which is defined as the angle between the axis normal to the FI and the magnetization of FI layer. These results indicate that the structures are promising candidates for novel tunneling magnetoresistance devices. © 2014 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4852119>]

I. INTRODUCTION

Recently, topological insulators (TIs) have been widely investigated because of their new unique properties that they have fully gapped bulk states and gapless edge or surface states.^{1–6} The topological order inevitably leads to the consequence that there exist the gapless edge states in the two-dimensional (2D) TIs or the gapless surface states in the three-dimensional (3D) TIs. These gapless states are robust against the disorder scattering and electron-electron interactions due to the protection by the time reversal symmetry and the topology of the bulk gap. Also, an electron's spin is locked to its momentum in these gapless edge and surface states.^{4,7} Therefore, the electron with the spin locked to its momentum in TIs is expected to be useful for spintronic applications.^{8–14}

Some of main purposes in the spintronics are to make spin transistors and/or magnetoresistive devices by utilizing the electron spin.^{15–19} The generation of spin current is very important in order to make spin transistors and/or magnetoresistive devices. Since the electron in the gapless edge and surface states in TIs behaves like a massless Dirac fermion with the spin locked to its momentum, TIs are not only useful for simple spin current generators but also expected to show the exotic spin generation and/or transport.

In this paper, we investigate the spin transport in normal metal (NM)/insulator (I)/TI coupled to ferromagnetic insulator (FI) structures as shown in Fig. 1. The calculation is performed for the barrier thickness d , the polar angle θ , and the azimuthal angle φ dependences of the spin conductance inside the bulk gap of the TI with FI.

II. THEORY AND RESULTS

The coordinate axes are chosen as shown in Fig. 1. We also designate the left TI layer coupled to FI ($x \leq 0$), the insulator (barrier) ($0 \leq x \leq d$), and the normal metal ($x \geq d$) as the region 1, 2, 3, respectively. The electrons in the surface states in region 1 are described by the 2D Dirac Hamiltonian. The 2D Dirac Hamiltonian is supplemented by exchange coupling to the magnetic moment $\mathbf{m}$ of the adjacent FI because of the interaction between the TI and FI layers. The 2D Dirac Hamiltonian modified by the magnetization is written in the following way:⁵

$$H = \begin{pmatrix} m_z & k'_x - ik'_y \\ k'_x + ik'_y & -m_z \end{pmatrix}, \quad (1)$$

where $k'_x (=k_{1x} + m_x = k_F \cos \Psi)$ and $k'_y (=k_{1y} + m_y = k_F \sin \Psi)$ are renormalized wave numbers, in which k_F is the Fermi wave vector on surface of the TI layer and Ψ is the azimuthal angle for 2D electron momentum, k_{1x} and k_{1y} are x and y -components of the electron momentum in the

FIG. 1. A schematic illustration of a model of NM/insulator (I)/TI with FI structures. Electrons transmit through the potential barrier with height V of width d along x .

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region 1, respectively. Then, $(m_x, m_y, m_z) = (m \sin \theta \cos \varphi, m \sin \theta \sin \varphi, m \cos \theta)$ are the components of magnetization vector $\mathbf{m}$ of the FI material as shown in Fig. 1.

Throughout this paper, we use the units in which $\hbar = v_F = 1$, where $\hbar$ is the Planck constant divided by 2π , and v_F is the Fermi velocity of TI in region 1. The exact energy eigenvalues of Eq. (1) are given by $E = \pm \sqrt{m_z^2 + k_x'^2 + k_y'^2}$. The magnetization of the FI layer affects the surface electrons on TIs as an exchange field. Without the effect of the z -component of magnetization, 2D Dirac electrons behave like massless fermions, however, with the effect of the z -component of magnetization, 2D Dirac electrons become massive and the band gap opens by $\Delta E = 2|m_z|$ as shown in Figs. 2(a) and 2(b). Moreover, the $x(y)$ -component of the magnetization translates the crystal momentum $k_x(k_y)$ by $m_x(m_y)$, respectively, as shown in Figs. 2(c) and 2(d). In this way, the energy dispersion of TIs can be tuned by the magnetization of FIs. The energy profile of the insulator (barrier) is assumed to be a square with height V and thickness d along x -direction. Then, the barrier is described by the function $V(x) = V(\Theta(x) - \Theta(x-d))$, where $\Theta(x)$ is the step function. In region 3, we treat the conduction band of NM as a 2D free electron gas. In the following calculation, the 2D Dirac electron is assumed to transmit ballistically across the insulator (barrier) region. Also, we assume that the characteristic of the Dirac electron is preserved in the

proximity of the edge of normal metal. Therefore, we consider that electrons in the proximity of the edge of normal metal can be described by 2D Dirac electrons.

We can obtain the wave functions $\Phi^i(x)$ ($i = 1, 2, 3$) in the regions 1, 2, 3 by solving the each Dirac equation as follows:

$$\begin{aligned} \Phi^{(1)}(x) &= \sqrt{\frac{E - m_z}{2E}} e^{ik_{1x}x} \begin{pmatrix} \frac{k_{1x} + m_x - i(k_{1y} + m_y)}{E - m_z} \\ 1 \end{pmatrix} \\ &\quad + r \sqrt{\frac{E - m_z}{2E}} e^{-ik_{1x}x} \begin{pmatrix} \frac{-k_{1x} - m_x - i(k_{1y} + m_y)}{E - m_z} \\ 1 \end{pmatrix}, \\ \Phi^{(2)}(x) &= A e^{ik_{2x}x} \begin{pmatrix} \frac{e^{-i\chi^{(2)}}}{\sqrt{2}} \\ 1 \end{pmatrix} + B e^{-ik_{2x}x} \begin{pmatrix} \frac{e^{i\chi^{(2)}}}{\sqrt{2}} \\ 1 \end{pmatrix}, \\ \chi^{(2)} &= \tan^{-1} \frac{k_{1y}}{k_{2x}}, \quad \Phi^{(3)}(x) = \frac{t}{\sqrt{2}} e^{ik_{3x}x} \begin{pmatrix} e^{-i\chi^{(3)}} \\ 1 \end{pmatrix}, \\ \chi^{(3)} &= \tan^{-1} \frac{k_{1y}}{k_{3x}}, \end{aligned}$$

where k_{ix} is the x -component of the electron momentum in each region i ($i = 1, 2, 3$). k_{1y} is used throughout all the regions as the y -component of the electron momentum since the y -component of the electron momentum is conserved. Here, r and t are the reflection coefficient and the transmission coefficient of 2D Dirac electrons, respectively. The bias voltage V_B is applied between the TI layer and the NM layer in order to inject 2D Dirac electrons from TI layer into the insulator (barrier). According to the energy conservation law, the electron's energy satisfies $E = \sqrt{m_z^2 + k_x'^2 + k_y'^2} = -\sqrt{k_{2x}^2 + k_{1y}^2} + V = \sqrt{k_{3x}^2 + k_{1y}^2} - V_B$. The x -component of the spin of 2D Dirac electron in the region 3 is estimated in the following way:

$$\langle \Phi^{(3)} | \hat{S}_x | \Phi^{(3)} \rangle = \frac{1}{2} |t|^2 \cos \chi^{(3)} = \frac{1}{2} |t|^2 \frac{k_{3x}}{\sqrt{k_{3x}^2 + k_{1y}^2}}, \quad (2)$$

where $\hat{S}_x$ is the x -component of the spin operator. Hence, finally, the spin conductance σ_s is estimated by averaging over Ψ angle

$$\sigma_s = \frac{e}{4\pi} \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} |t|^2 \frac{k_{3x}}{\sqrt{k_{3x}^2 + k_{1y}^2}} d\Psi, \quad (3)$$

where e is the elementary charge.

Figure 3 shows the barrier thickness d and the polar angle θ dependences of the spin conductance of 2D Dirac electrons under the bias voltage V_B . We set the barrier height V , the bias voltage V_B , and the magnitude of the magnetization m to be $2.0E_F$, $2.5E_F$, and $0.9E_F$, respectively, where E_F is the Fermi energy of TI layer. From Fig. 3, we have found that the spin conductance decreases with increasing the barrier thickness.

FIG. 2. A schematic illustration of the energy dispersion of TIs (a) in the case of $m_z = 0$, $(m_x = m_y = 0)$, (b) in the case of $m_z \neq 0$, $(m_x = m_y = 0)$, (c) in the case of $m_z = 0$, $m_x > 0$ ($m_y = 0$), and (d) in the case of $m_z \neq 0$, $m_x > 0$ ($m_y = 0$).

FIG. 3. The barrier thickness d and the polar angle θ dependences of the spin conductance. The spin conductance is in units of $e/4\pi$. φ is set to be zero.

Also, the spin conductance is strongly dependent on the polar angle θ and has the maximum value for each barrier thickness at a polar angle of 90° . Moreover, it is symmetric about 90° . As shown in Figs. 2(a) and 2(b), the energy dispersion of the TI is affected by the z -component of the magnetization, which is determined by the polar angle, of the FI. The polar angle of 90° corresponds to the gap closing of the energy dispersion of the TI. Also, the magnitude of m_z is symmetric about 90° . Therefore, the spin conductance shows the maximum value at a polar angle of 90° and becomes symmetric about 90° .

Figure 4 shows the barrier thickness d and the azimuthal angle φ dependences of the spin conductance of 2D Dirac electrons under the bias voltage V_B . It is found that the spin conductance decreases with increasing the barrier thickness and has the minimum value for each barrier thickness at an azimuthal angle of 90° . Moreover, it is symmetric about 90° . In this calculation, we set the polar angle to be 90° . As a result, the magnetization vector $\mathbf{m}$ is in-plane. As shown in Figs. 2(c) and 2(d), the x and y -components of the magnetization shift the Fermi surface by m_x and m_y , respectively. The shift of the Fermi surface to the y -direction is largest at an azimuthal angle of 90° . This results in the reduction of x -component of the electron momentum. Also, m_y is symmetric about an azimuthal angle of 90° . Therefore, the spin conductance shows the minimum value at an azimuthal angle of 90° and becomes symmetric.

FIG. 4. The barrier thickness d and the azimuthal angle φ dependences of the spin conductance (in units of $e/4\pi$). θ is set to be 90° .

FIG. 5. The barrier thickness d and the magnitude of the magnetization m of FI layer dependences of the spin conductance (in units of $e/4\pi$). θ and φ are set to be zero.

Finally, we show the barrier thickness d and the magnitude of the magnetization m of FI layer dependences of the spin conductance in Fig. 5. It is found that the spin conductance has the maximum value at a magnetization of 0. We notice that it is similar to the half-plane of Fig. 3. However, we also notice the difference between Figs. 3 and 5. Although the variation of the magnetization in Fig. 5 does not affect the position of the Fermi surface, the variation of the magnetization in Fig. 3 strongly affects its position. As a result, the x -component of electron momentum is enhanced in the case of Fig. 3. Therefore, the maximum value of the spin conductance becomes larger than that of the spin conductance in the case of Fig. 5 though the spin conductance has the maximum value at $m_z = 0$ in both cases.

We have investigated the spin transport in NM/I/TI coupled to FI structures. The calculated results indicate that the structures are promising candidates for novel tunneling magnetoresistance devices by changing the barrier thickness, the polar angle, and the azimuthal angle.

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