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A scheme for a topological insulator field effect transistor

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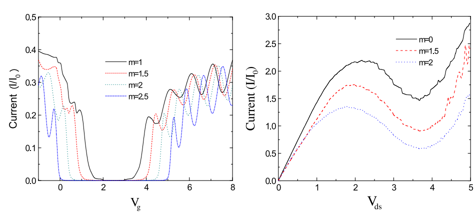
HIGHLIGHTS

- A topological insulator based Field effect transistor is proposed.
- It displays a switching effect with high on/off current ratio.
- It displays a negative differential conductance with a good peak to valley ratio.

GRAPHICAL ABSTRACT

We investigate the transfer characteristics and output characteristics of the topological insulator field effect transistor with a ferromagnetic topological insulator channel, using the transfer matrix method and Landauer formula.



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ABSTRACT

We propose a scheme for a topological insulator field effect transistor. The idea is based on the gate voltage control of the Dirac fermions in a ferromagnetic topological insulator channel with perpendicular magnetization connecting to two metallic topological insulator leads. Our theoretical analysis shows that the proposed device displays a switching effect with high on/off current ratio and a negative differential conductance with a good peak to valley ratio.

Introduction

Due to its electrical properties, topological insulator is a potential material to develop nanodevices such as field effect transistors [1]. Like in graphene, due to linear energy dispersion the surface electrons of the topological insulator behave as massless Dirac fermions with transport properties different from those of the charge carriers in conventional metallic or semiconductor systems. In graphene, the low energy charge carriers are described by massless Dirac equation where Fermi velocity plays the role of light velocity. Due to the peculiar linear band structure, graphene based systems exhibit many interesting phenomena such as half-integer quantum Hall effect [2], minimum conductivity [2] and special Andreev reflection [3]. These are novel phenomena that have not been observed in the conventional counterpart systems. Due to the linear energy spectra the normally incident electrons can pass through a potential barrier via Klein tunneling without reflection [4]. This is a significant drawback for use of graphene and topological insulator as field effect transistors since the Klein tunneling leads to an appreciable off current and thus a poor on/off current ratio [5]. One way to overcome this problem is gap generation in the linear energy spectrum. In graphene case, several schemes such as use of graphene on SiC [6], applying electric field on bilayer graphene [7] and use of graphene nanoribbons have been proposed to open an energy gap in linear energy

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dispersion [8,9].

One important difference between transport properties of the Dirac fermions in graphene-based- and topological insulator based- ferromagnetic barrier junctions arises from the fact that, unlike in graphene, the transport of the Dirac fermions on the surface of the topological insulator sensitively depends on the direction of the magnetization [10]. The magnetization with a direction parallel to the surface of the topological insulator will shift the position of the electrons' Fermi surface while the perpendicular magnetization induces an energy gap in linear energy spectra of the topological insulator surface states [11,12]. Yokoyama et al. investigated charge transport in ferromagnet/ferromagnet junction on a topological insulator [13]. They found that, unlike in conventional spin valve, the conductance across the junction depends sensitively on the directions of the magnetizations of the two ferromagnets. Wang et al. experimentally studied the transport properties of the nanosheets of a Bi_2Te_3 topological insulator [14]. They observed that the 20 nm thick nanosheets of topological insulator shows giant and linear magnetoresistance as high as 600% at room temperature. They also observed a magnetic field induced gap at low temperature. Yang et al. investigated magnetoresistance through a topological insulator based ferromagnet/superconductor/ferromagnet junction [15]. They showed that both the positive and negative magnetoresistance can be created in the cases of both retro and specular Andreev reflections. In contrast, in a graphene based junction the negative magnetoresistance can be observed only in the case of specular Andreev reflection. Zhang et al. investigated the conductance and magnetoresistance in a ferromagnet/normal/ferromagnet junction formed on the surface of topological insulator with a gate voltage exerted on the normal region [16]. They found that the conductance and magnetoresistance can be controlled by tuning the applied gate voltage. In this paper, we investigate the transport properties of the topological insulator based ferromagnetic tunnel junction with perpendicular magnetization, using solution of the Dirac equation and transfer matrix method. We find that, this system can be used as a field effect transistor with a high on–off current ratio.

In addition, recently the negative differential conductance was predicted to occur by a ferromagnetic barrier on the surface of topological insulator with the magnetization direction parallel to the surface [17]. It has been explained as a consequence of the Fermi surface shift due to magnetization. Here, we show that in the case of perpendicular magnetization, the negative differential conductance may occur and is explained differently. In the perpendicular magnetization case, the magnetically induced gap causes negative differential conductance with a good peak to valley current ratio.

Theoretical model

Fig. 1 shows the model device, schematically. A ferromagnetic insulator strip, such as EuO, of width d is deposited on the surface (x–y plane) of the topological insulator to induce the ferromagnetic ordering in region $0<x<d$ via the proximity effect. The left and right nonmagnetic topological insulator leads are connected to gold contacts which will be the source and drain. A metallic gate which is on top of the ferromagnetic strip leads to the formation of a potential barrier in the ferromagnetic channel under it and modulates the current flowing through the device from source to drain. A metallic back gate controls the Fermi energy, or in other words, the charge carrier density.

The motion of an electron in the present system can be described by the Hamiltonian [18,19]

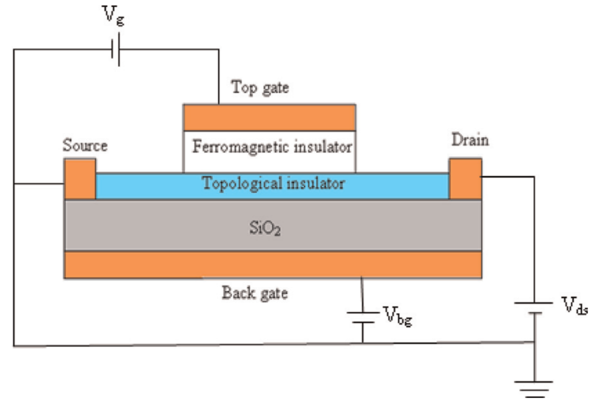

Fig. 1. Schematic sketch of the considered field effect transistor.

$$H = v_F\vec{P}.\,\vec{\sigma} + \vec{m}.\,\vec{\sigma} + V(x) \tag{1}$$

where $\vec{P}$ is the in-plane momentum operator, $\vec{\sigma}$ is the vector of Pauli matrices, v_F is the Fermi velocity, $\vec{m} = m\,\hat{z}$ is the magnetization induced via proximity effect. The effective potential across the system is given as

$$V(x) = \begin{cases} 0 & \text{for } x<0 \\ V_g - V_{ds}x & \text{for } 0<x<d, \\ -V_{ds} & \text{for } x>d \end{cases} \tag{2}$$

where V_{ds} is the applied drain–source voltage and V_g is the applied gate voltage. We divide the ferromagnetic barrier region to many strips with identical width such that in any strip j with the coordinate x_j the effective potential can be approximated as a constant $V_g - V_{ds}x_j/d$. In the left region $x<0$ and the right region $x>d$ the wave functions are given by

$$\psi_{x<0} = \begin{pmatrix}1\\ e^{i\theta_1}\end{pmatrix}e^{ik_1x} + r\begin{pmatrix}1\\ -e^{-i\theta_1}\end{pmatrix}e^{-ik_1x},$$
$$\psi_{x>d} = t\begin{pmatrix}1\\ e^{i\theta_2}\end{pmatrix}e^{ik_2x}, \tag{3}$$

where $k_1 = E\cos\theta_1$ and $k_2 = (E+V_{ds})\cos\theta_2$ are, respectively, the x-component of the wave vector of an electron with energy E. The wave function in jth strip of the ferromagnetic region can be expressed as

$$\psi_j = a_j\begin{pmatrix}1\\ A_je^{i\theta_j}\end{pmatrix}e^{ik_jx} + b_j\begin{pmatrix}1\\ -A_je^{-i\theta_j}\end{pmatrix}e^{-ik_jx}, \tag{4}$$

where $A_j = \frac{E - V_g + V_{ds}x_j/d - m}{\sqrt{(E - V_g + V_{ds}x_j/d)^2 - m^2}}$ and $k_j = \sqrt{(E - V_g + V_{ds}x_j/d)^2 - m^2}$. Using the conservation of y-components of the wave vectors which is held due to translational invariance of the system in y-direction, the angles θ_2 and θ_j can be expressed in terms of incident angle θ_1 as

$$\theta_2 = \arcsin\left(\frac{E\sin\theta_1}{E+V_{ds}}\right),$$

$\theta_j = \arcsin\left(E\sin\theta_1/E - V_g + V_{ds}x_j/d\right)$. Applying the continuity of the wave functions at the boundaries and by using the transfer matrix method, the transmission probability $T(E, V_{ds}, \theta_1) = \frac{\cos\theta_2}{\cos\theta_1}|t|^2$ can be obtained. By considering the matrix form of the relation between the coefficients of the left going and right going electron wave functions in adjacent regions throughout the system, one obtain the matrix equation relating the coefficients from source and drain with $M = \prod_j M_j^{-1}(x_j)M_{j+1}(x_j)$. Here $M_j(x_j)$ is the relating