Solid State Communications 188 (2014) 45–48

Contents lists available at ScienceDirect

Solid State Communications

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

Transport in a quantum spin Hall bar: Effect of in-plane magnetic field

Fang Cheng [a,b,*], L.Z. Lin [b], D. Zhang [b]

[a] Department of Physics and Electronic Science, Changsha University of Science and Technology, Changsha 410004, China
[b] SKLSM, Institute of Semiconductors, Chinese Academy of Sciences, P.O. Box 912, Beijing 100083, China

ARTICLE INFO

Article history:
Received 30 May 2013
Received in revised form
18 September 2013
Accepted 25 February 2014
by S. Tarucha
Available online 6 March 2014

Keywords:
A. Topological insulator
D. Electronic states
D. In-plane magnetic field
D. Quantum transport

ABSTRACT

We demonstrate theoretically that edge transport in quantum spin Hall bar can be controlled by in-plane magnetic fields. The in-plane magnetic field couples the opposite spin orientation helical edge states at the opposite edges, and induces the gaps in the energy spectrum. The hybridized electron wave functions $\psi_\uparrow(x,k_y)$ of the edge states can be destroyed with increasing the in-plane magnetic fields. When the Fermi surface is located within this energy gap induced by the in-plane magnetic field, one can expect that the conductance of the edge states becomes e^2/h. By tuning the magnetic field and Fermi energy, the edge channels can be transited from opaque to transparent. This switching behavior offers us an efficient way to control the topological edge state transport.

1. Introduction

Topological insulators (TIs), a strong spin–orbit coupling system, exhibit rich and fascinating physics, which have been investigated intensively both theoretically and experimentally [1–4]. The two-dimensional (2D) TIs have been realized in HgTe quantum wells (QWs) and InAs/GaSb QWs [5,6] by tuning the thickness of the QWs or electric field [7–11]. HgTe is a narrow gap semiconductor with very strong spin–orbit interaction (SOI) [12]. Strong SOI inverts the band structure of HgTe, leading to a topological insulating phase. In this phase, HgTe possesses an insulating in the bulk with a gap separating the valence and conduction bands but with gapless helical edge states that are topologically protected by the time-reversal symmetry [13,14]. The existence of the helical edge states in 2D TIs was proved by recent experiments [15,16]. The helical feature and suppressed backscattering render edge states an attractive platform for high mobility charge- and spin-transport devices.

Since the topological edge states in 2D TI are protected by time-reversal symmetry and robust against to backscattering, control of the edge states, e.g., switch on/off, is a challenging issue from the viewpoint of basic physics and potential device application. Recently, there have been a few proposals to control the edge state transport using a quantum point contact [17–20]. These electrical means can control the transport, magnetic properties and even quantum phase transition, and provide us an efficient way to control spin transport [11,20–22]. It is natural to ask if there is any other method to control the edge state transport?

In this letter, we study the effect of in-plane magnetic field on the transport property of a quantum spin Hall (QSH) bar. The magnetic field can lead to a large Zeeman term because of the large g factor of HgTe material. The Zeeman term couples spin-up and spin-down electron and holes, and induces the gaps in the energy spectrum. Electrons with the opposite spin orientation at the opposite edges couple together due to in-plane magnetic fields. And the density distributions of hybridized electron wave functions $\psi_\uparrow(x,k_y)$ become more localized in the center of the QSH bar, indicating destroy of the edge state. When the Fermi surface is located within this energy gap induced by the in-plane magnetic field, one can expect that there is only an edge state and the conductance of the edge states becomes one-half of the conductance quantum $2e^2/h$. The in-plane magnetic field can control the coupling between the edge states at opposite edges and between the topological edge state and the bulk state. Tuning the in-plane magnetic field, one can switch-on/off the edge channel in the finite width QSH bar system when the Fermi energy is the gap. This feature provides us an efficient means to control the edge state transport in QSH bars.

2. Theoretical model

The total Hamiltonian for the system in the presence of an external in-plane magnetic field is

$$H = H_0 + H_Z, \tag{1}$$

* Corresponding author at: Department of Physics and Electronic Science, Changsha University of Science and Technology, Changsha 410004, China. Tel.: +86 15807314598.
E-mail address: chengfangg@gmail.com (F. Cheng).

http://dx.doi.org/10.1016/j.ssc.2014.02.028
0038-1098

where the first term is the single-particle Hamiltonian of electron in HgTe QWs and the second term H_Z is the Zeeman effect. The electron transport in the quasi-one-dimensional (Q1D) QSH bar is along the longitudinal y-direction. The four-band single-particle Hamiltonian H reads as

$$H=\begin{pmatrix} \epsilon_k+M(\mathbf{k}) & Ak_- & g_e\mu_B B & 0 \\ Ak_+ & \epsilon_k-M(\mathbf{k}) & 0 & g_h\mu_B B \\ g_e\mu_B B & 0 & \epsilon_k+M(\mathbf{k}) & -Ak_+ \\ 0 & g_h\mu_B B & -Ak_- & \epsilon_k-M(\mathbf{k}) \end{pmatrix}, \quad (2)$$

where $\mathbf{k}=(k_x,k_y)$ is the in-plane momentum of electrons, $\epsilon_k=C+V(x,y)-D(k_x^2+k_y^2)$ with $V(x,y)$ being the confinement potential, $M(\mathbf{k})=M-B(k_x^2+k_y^2)$, $k_\pm=k_x\pm ik_y$, A, B, C, D, and M are the parameters describing the band structure of the HgTe/CdTe QW. $g_{e/h}$ denotes electron or hole g factor, respectively. μ_B is the Bohr magneton. B is the external transversal x-direction magnetic field.

The transport property of a Q1D QSH bar can be obtained by discretizing the Q1D system into a series of in-plane stripes along the transport direction. Assuming a hard-wall in-plane confining potential, the traveling-wave-like or evanescent-wave-like eigenstates of the Schrödinger equation $H\psi=E\psi$ in a given region λ can be written as the form

$$\psi_\lambda(x,y)=\exp(ik_y^\lambda y)\sum_n \chi_n^\lambda \varphi_n(x), \quad (3)$$

where

$$\varphi_n(x)=\sqrt{\frac{2}{W}}\sin\frac{n\pi x}{W}$$

in which W is the width of the lead, and the subband index $n=1,2,\ldots N$ with N being the number of the basis function which is chosen to ensure the convergence of the energies of the low subbands near the Dirac point. $\{\chi_n^\lambda\}$ $(\lambda=L,R)$ are the expanded coefficients. The longitudinal wave vector k_y^λ and the eigenvector χ_n^λ $(n=1,2,3,\ldots)$ are determined from the generalized eigenvalue problem [20]. Assuming an electron injected from a given energy with wave vector k_l^L in the left lead, the wave functions in the left lead and the right lead can be written as

$$\psi_L=e^{ik_l^L y}\sum_n \chi_{l,n}^L\varphi_n(x)+\sum_{mn} r_m\chi_{m,n}^L e^{-ik_m^L y}\varphi_n(x),$$

$$\psi_R=\sum_{mn} t_m\chi_{m,n}^R e^{ik_m^R y}\varphi_n(x). \quad (4)$$

By using scattering matrix theory, we can calculate the coefficients r_m, t_m in the left and right leads. Thus we can obtain the total conductance from the Landauer–Büttiker formula

$$G=G_0\sum_{m,n}^{RM}\frac{\upsilon_m^R}{\upsilon_n^L}|t_m|^2, \quad (5)$$

where $G_0=e^2/h$ is the conductance unit, RM denotes the summation over all right-moving modes in the left and right leads, t_m is the transmission coefficient where the electron incidents from the subband n in the left lead to be scattered into the subband m in the right lead, and $\upsilon_m^\lambda=\langle\hat{\upsilon}_m^\lambda\rangle=\langle\partial H/\partial k_y\rangle$ are the group velocity of the electron in the subband m in the leads along the QSH bar, i.e., the y-axis direction.

3. Numerical results and discussions

In the case of a QSH bar in the absence of in-plane magnetic field, the finite size effect induces the overlap of the wave functions of the edge states localized at the opposite edges, and can open a minigap in the energy spectrum of the edge states at $k_y=0$ (see Fig. 1(a)). The in-plane magnetic field couples the edge states at the opposite edges (see Eq. (1)), and induces a mass term for massless Dirac electrons in the edge states. Therefore the gaps in the energy spectrum increase with increasing the magnetic fields.

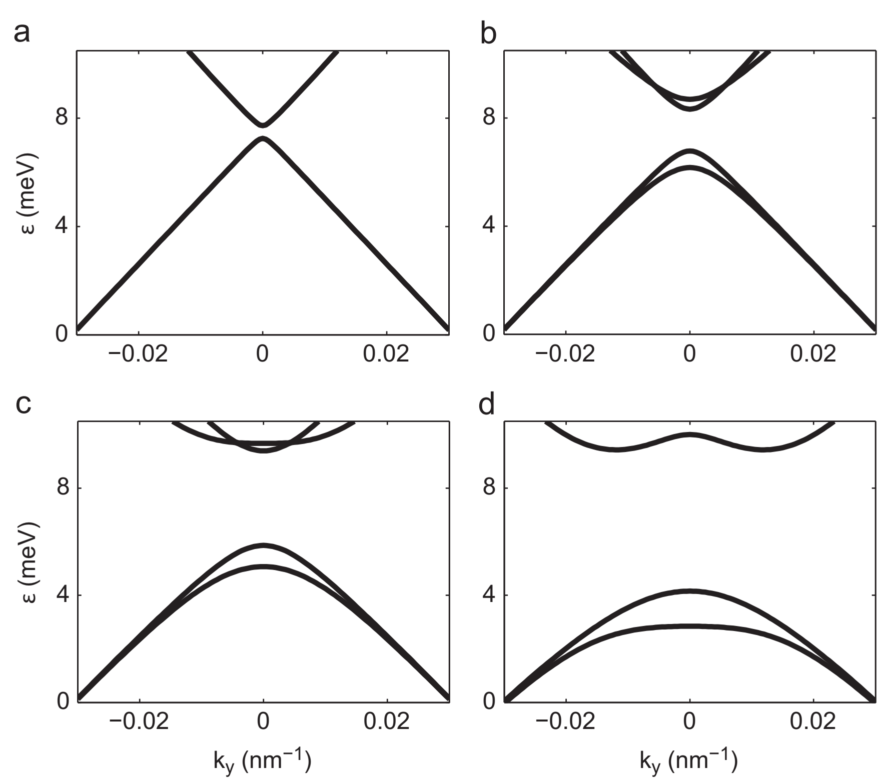

Fig. 1. The energy spectra with width $W=200$ nm under different in-plane magnetic fields (a) $B=0$, (b) $B=0.5$ T (c) $B=1$ T, and (d) $B=2$ T. The parameters used in the calculation are $A=364.5$ meV, $B=-686$ meV nm^2, $C=0$, $D=-512$ meV nm^2, $M=-10$ meV.