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Spin injection from topological insulator into metal leads

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ABSTRACT

We study theoretically helical edge and surface states of 2D and 3D topological insulators (TI) tunnel-coupled to metal leads and show that their transport properties are strongly affected by contacts as the latter play a role of a heat bath and induce damping and relaxation of electrons in the helical states of TI. A simple structure that produces a pure spin current in the external circuit is proposed. The current and the spin current delivered to the external circuit depend on the relation between characteristic lengths: decay length due to tunneling, contact length and, in case of 3D TI, mean free path and spin relaxation length caused by momentum scattering. If the decay length due to tunneling is the smallest one, then the electric and spin currents are of order of the conductance quantum in 2D TI, and of order of the conductance quantum multiplied by the ratio of the contact width to the Fermi wavelength in 3D TI. A role of electron–electron interaction is discussed in case of 2D TI, and it is shown that in contrast to the conventional Luttinger liquid picture the interaction can be treated perturbatively. The presence of interaction results in suppression of density of states at the Fermi level and hence in decrease of the electric and spin currents.

Spin properties of edge and surface states of topological insulators (TI) are of great interest both for fundamental physics and for potential applications in spintronics [1]. The spin of electrons is strongly coupled to their momentum giving an idea of generating spin polarized currents in TI [2–4]. However, it would be interesting and of practical importance to generate not only spin polarized currents but pure spin currents as well. The general idea for generating pure spin current was suggested in Ref. [5]: a Y-shaped two-dimensional conductor forming a three-terminal junction with intrinsic spin–orbit interaction was proposed, where one of the terminals is a voltage probe which draws no electric current, but the polarizations of incoming and outcoming electrons are opposite to each other, causing a pure spin current. However, the particular realization of this system does not relate to a TI. An example of a multiterminal system involving the edge state of TI, in which a pure spin current in the external circuit may occur, is given in Ref. [6]. However, the decoherence and damping induced by contacts were out of consideration, while we find that damping and relaxation induced by coupling to a metal contact are very important. The systems for generating a pure spin current suggested in Refs. [5,6] were mesoscopic and ballistic. It is interesting to study a possibility to produce a pure spin current also in a 3D TI where the spin current can be larger as it is proportional to geometrical dimensions of the sample. In the helical surface state of 3D TI the physics is more complicated because a finite angle impurity scattering is not prohibited by momentum-spin locking and strongly affects transport properties.

Since edge state of 2D TI is a 1D electron state an electron–electron interaction can play a significant role in electron transport [7,8]. It is known that 1D systems are usually described by the Luttinger liquid picture rather than the Fermi liquid picture, and even a weak interaction dramatically affects electron transport. In particular, it results in a power-law suppression of density of states at the Fermi level. However, an edge state with a long tunnel contact is not a true 1D system since it is coupled to a lead of a higher dimension, and it is interesting how electron–electron interaction will affect transport properties of an edge state with tunnel contacts.

In this paper we study an edge state in a 2D TI and a surface state in a 3D TI coupled to metal leads by tunnel contacts, and we calculate charge and spin currents in the external circuit. We take into account the decoherence induced by the contacts and show that it determines the electric and spin currents in the TI with contacts. In the case of 3D TI we also take into account a spin relaxation due to scattering on the impurities in the TI. We find that the currents strongly depend on relations between the characteristic lengths: the decay length due to tunneling, the length of the contact and the mean free path. In the case of 2D TI we discuss the role of electron–electron interaction, and in contrast to [4] we take into account the finite decay length while considering

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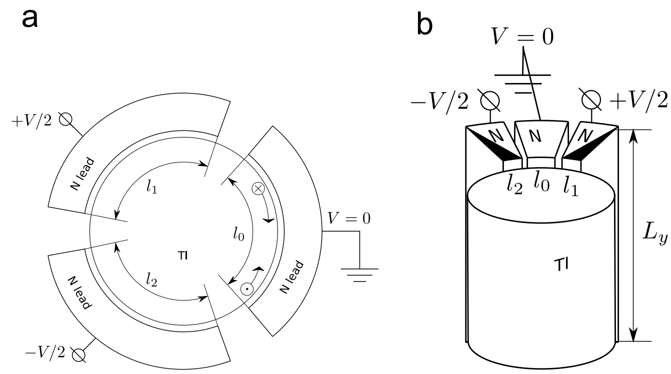

Fig. 1. (a) Helical edge state of 2D TI coupled to the leads and (b) helical surface state of 3D TI coupled to the leads.

interaction.

Below we set e, $\hbar$ and k_B to unity, restoring dimensional units in final expressions when necessary.

We consider a TI with a conducting helical state coupled by tunnel contacts to bulky leads made of normal metal (Fig. 1). The effects we study can be observed in various realizations but we consider the simplest three-terminal version when one of the leads is grounded, and the voltage V is symmetrically applied to the two other leads. In this paper we examine a 2D TI with a helical edge state (Fig. 1a) and a 3D TI cylinder with a conducting surface state (Fig. 1b). We denote the length of the tunnel contact to the grounded lead by l_0, while l_1 and l_2 stand for the lengths of the contacts to the leads with potentials $V_\pm = \pm V/2$.

The total Hamiltonian reads

$$\hat{H} = \hat{H}_{TI} + \sum_{i=1,2,3} \hat{H}_{lead,i} + \hat{H}_{tun,i}. \tag{1}$$

Here $\hat{H}_{lead,i}$ is the Hamiltonian of the ith lead, $\hat{H}_{TI}$ is the Hamiltonian of the conducting state in TI. For the edge state [9–11]

$$\hat{H}_{TI}^{(edge)} = \int dx \hat{\Psi}^{\dagger}(x)\left(-i\sigma_z v\partial_x - \varepsilon_F\right)\hat{\Psi}(x), \tag{2}$$

where v is the velocity of the excitations, $\hat{\Psi}$ is a two-component spinor and $\boldsymbol{\sigma}$ are the Pauli matrices. We do not take into account an impurity scattering in the 2D case, since the spin-momentum locking prohibits such a scattering. For the surface state the Hamiltonian reads in the simplest case [11,10]

$$\hat{H}_{TI}^{(s)} = \int d^2\mathbf{r}\, \hat{\Psi}^{\dagger}(\mathbf{r})\left[\left(-iv_F\partial_{\mathbf{r}} \times \mathbf{e}_z\cdot\boldsymbol{\sigma}\right) - \varepsilon_F + V_{imp}(\mathbf{r})\right]\hat{\Psi}(\mathbf{r}), \tag{3}$$

where $\mathbf{e}_z$ is a unit vector normal to the surface, V_{imp} is a random potential of impurities, and we assume that it is delta-correlated $\overline{V(\mathbf{r})V(\mathbf{r}')} = u_0\delta(\mathbf{r}-\mathbf{r}')$.

The tunnel Hamiltonian $\hat{H}_{tun}$ reads

$$\hat{H}_{tun} = \int d^3\mathbf{R}d^D\mathbf{r}\, \hat{\psi}^{\dagger}(\mathbf{R})\mathcal{T}(\mathbf{R}-\mathbf{r})\hat{\Psi}(\mathbf{r}) + H.c. \tag{4}$$

where dimension $D=1$ for the edge state and $D=2$ for the surface state; $\hat{\psi}(\mathbf{R})$ is the field operator in a lead, the matrix element $\mathcal{T}(\mathbf{R}-\mathbf{r})$ describes tunneling between the lead and TI. We assume a site-to-site tunneling $\mathcal{T}(\mathbf{R}-\mathbf{r}) = td^{(3-D)/2}\delta(\mathbf{R}_\parallel - \mathbf{r})\delta(\mathbf{R}_\perp)$, where t is real and does not depend on $\mathbf{r}$, and $\delta(\mathbf{R}_\perp)$ selects an average value of a function at a distance d of the order of inter-atomic scale near the surface. Here $\mathbf{R}_\parallel$ stands for the component(s) along the contact, and $\mathbf{R}_\perp$ stands for component(s) normal to the contact.

First, we focus on the helical edge state coupled by tunnel contacts to the leads (Fig. 1a) and consider the case of non-interacting electrons. We start from the Hamiltonian (1), (2), and (4), and then derive equations for Keldysh matrices [12]

$$\check{G} = \begin{pmatrix} G^R & G^K \\ 0 & G^A \end{pmatrix}, \quad \check{\Sigma}_t = \begin{pmatrix} \Sigma^R & \Sigma^K \\ 0 & \Sigma^A \end{pmatrix},$$

where $G^{R,K,A}$ are Green functions of the edge state, Σ_t is a self-energy describing tunneling from a lead to the edge state. Deriving an expression for a self-energy we follow Kopnin and Melnikov [13]. For details one can also refer to Ref. [14], where the self-energy was derived for helical states tunnel-coupled to a superconductor. Finally, we obtain $\Sigma_t(x,x') = \Sigma\delta(x-x')$, where

$$\check{\Sigma} = i\Gamma\begin{pmatrix} -1 & -2\tanh\dfrac{\varepsilon}{2T} \\ 0 & 1 \end{pmatrix}. \tag{5}$$

Here we introduce the tunneling rate $\Gamma \simeq \pi\nu_3 d^3 t^2 \sim t^2/\varepsilon_F$, $\nu_3 = mp_F/(2\pi^2\hbar^3)$ is the 3D density of states.

The Dyson equation for the Green functions $\check{G}$ reads

$$\left(\varepsilon + \varepsilon_F + i\sigma_z v\partial_x - \check{\Sigma}\right)\check{G}(x,x') = \delta(x-x') \tag{6}$$

The left-right subtracted Dyson equation for $G^K(x,x)$ can be reduced to a kinetic equation for distribution function f by ansatz $G^K = (G^R - G^A)(1-2f)$

$$\sigma_z v\partial_x f = -\gamma(x)(f - f_i), \tag{7}$$

where $\gamma = 2\Gamma/v$ is the inverse decay length due to tunneling, $f_i = f_0(\varepsilon - V_i)$ is the equilibrium distribution function in the ith lead.

Solving (6) for retarded and advanced components we obtain

$$G^R(x,x) - G^A(x,x) = -\frac{i}{v}\frac{\sinh\gamma l/2}{\cosh\gamma l/2 - \cos(k_F L + \varepsilon L/v)}, \tag{8}$$

where $l = l_0 + l_1 + l_2$ and L is the circumference of the edge state. The solution of (7) can be represented as a sum of equilibrium and non-equilibrium terms $f = f_0 + \delta f$. Non-equilibrium term at the region $0 < x < l_0$ coupled to the grounded lead reads

$$\delta f = \frac{\delta f_2 + \left[\delta f_1 - \delta f_2\right]e^{-\gamma\sigma_z l_2} - \delta f_1 e^{-\gamma\sigma_z(l_1+l_2)}}{(1 - e^{-\gamma\sigma_z l})e^{\gamma\sigma_z x}}, \tag{9}$$

where $\delta f_i = f_0(\varepsilon - V_i) - f_0(\varepsilon)$. The charge current flowing through the edge state is related to the non-equilibrium part of the Keldysh Green function G^K_{ne} by $I_e = (i/2)ev\,\mathrm{Tr}\,\sigma_z G^K_{ne}$. Spin current reads $J_s = v\rho$, where ρ is a linear density of electrons related to the Keldysh Green function by equation $\rho = -(i/2)\,\mathrm{Tr}\,G^K_{ne}$.

The spin current flowing through the grounded lead can be calculated as the difference of the spin currents in the edge state of TI at the end points of the contact $J_s = J_s(x=0) - J_s(x=l_0)$. Its derivative with respect to the applied voltage at low temperatures $T \ll \hbar v/L$ reads

$$\frac{dJ_s}{dV} = \frac{2G_0}{e}\sinh\frac{\gamma l_0}{2}\sinh\frac{\gamma l_1}{2}\sinh\frac{\gamma l_2}{2} \times\left[\frac{1}{\cosh\frac{\gamma l}{2} - \cos\left(k_F L + \frac{eVL}{2\hbar v}\right)} + \frac{1}{\cosh\frac{\gamma l}{2} - \cos\left(k_F L - \frac{eVL}{2\hbar v}\right)}\right], \tag{10}$$

where $G_0 = e^2/h$ is the conductance quantum. Here and below a spin current is measured in units of $\hbar/2$. In the limit of high temperatures $T > \hbar v/L$ the oscillations are washed out, and the term in the square brackets should be substituted by $2/(\sinh\gamma l/2)$

The electric current flowing through the grounded lead $I = I_e(x=0) - I_e(x=l_0)$ in case of symmetrical geometry $l_1 = l_2$, is determined by the conductance