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Topological insulator in junction with ferromagnets: Quantum Hall effects

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ABSTRACT

The ferromagnet–topological insulator–ferromagnet (FM–TI–FM) junction exhibits thermal and electrical quantum Hall effects. The generated Hall voltage and transverse temperature gradient can be controlled by the directions of magnetizations in the FM leads, which inspires the use of FM–TI–FM junctions as electrical and as heat switches in spintronic devices. Thermal and electrical Hall coefficients are calculated as functions of the magnetization directions in ferromagnets and the spin-relaxation time in TI. Both the Hall voltage and the transverse temperature gradient decrease but are not completely suppressed even at very short spin-relaxation times. The Hall coefficients turn out to be independent of the spin-relaxation time for symmetric configuration of FM leads.

The discovery and experimental realization of topological insulators (TI) opened a new and vividly developing field of theoretical and experimental investigations [1–4]. Two-dimensional TI belong to the class of quantum spin Hall systems [1,2] that are distinguished by the existence of chiral spin-polarized edge states. There are two chiral states with opposite spin-projections at each edge that propagate in the opposite directions. The existence of the edge states implies strong similarity between the properties of TI and of a quantum Hall system, although no external magnetic field is applied. Each spin-polarized edge state is subject to an effective magnetic field corresponding to a one magnetic flux quantum per electron (the condition for the lowest quantum Hall plateau), hence it contributes to the quantized Hall conductance of the sample. However, the signs of the effective magnetic fields are opposite for the edge states with opposite spin projections, which results in the exact cancellation of contributions from the two counter-propagating edge states to the total Hall conductance [2].

It has been suggested in the early papers on quantum spin Hall effect that the properties of spin-polarized edge states can be probed by injecting spin-polarized currents in TI [1,2]. In this paper we show that the quantum Hall electrical and thermal resistances can be revealed in the experimental measurements on a two-dimensional TI sandwiched between the two ferromagnets (FM) in a FM–TI–FM junction (see Fig. 1). The use of ferromagnets allows spin-selective contacting of the edge states in TI. In the ideal situation of completely polarized ferromagnets it is possible to contact a single chiral spin-polarized edge state. Thus one would measure quantized value of electrical Hall conductance $G_Q = dI_{\|}/dV_H = e^2/h$ proper to the lowest Landau level of the integer quantum Hall effect. Similarly, the longitudinal heat flow through TI will result in the appearance of a transverse temperature gradient, which is the essence of the *thermal* Hall effect. The corresponding thermal Hall coefficient is also quantized $K_Q = dQ_{\|}/dT_{\perp} = (\pi^2 k_B^2/3h)T$.

The coupling between the spin-polarized edge state of TI and FM lead depends on the angle between the magnetization of the lead and the direction of spin quantization axis in TI. The latter is determined by the crystallographic structure of TI [1–4]. Rotating the magnetization direction in FM leads, one can control the transverse voltage and the transverse thermal gradient induced in TI. It varies from a finite maximal value, when the orientation of magnetizations in FM is parallel to the spin-quantization axis in TI, to the complete suppression of transverse voltage and temperature gradient for the perpendicular orientation (see Fig. 2).

Topological insulators are often contaminated with magnetic impurities that introduce scattering between the chiral states at the edge. Nevertheless, as long as the localization length is larger than the system length [5], the edge states remain intact. The quasi-elastic spin-flip back-scattering by magnetic impurities, while reducing the transverse temperature gradient and the Hall voltage in general, *does not suppress* the thermal and electrical Hall effects in the FM–TI–FM structure completely (see Fig. 3). The Hall coefficients remain finite even in the formal limit of infinitely short

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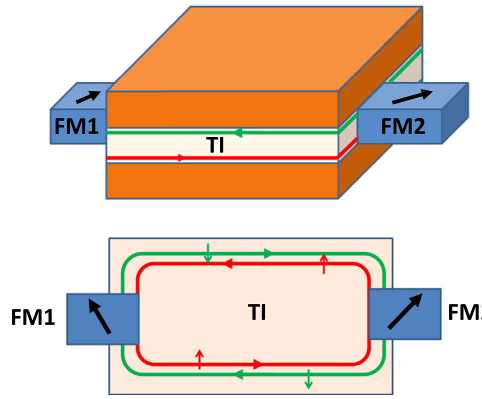

Fig. 1. Proposed experimental setup of FM–TI–FM junction. Spin-↑ and spin-↓ electrons have opposite chirality at the edge states.

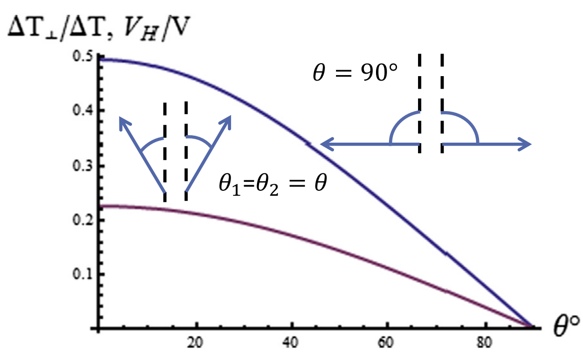

Fig. 2. Ratio of the transverse to longitudinal temperature gradient $\Delta T_\perp/\Delta T$, which is equal to the ratio of the Hall voltage to longitudinal voltage V_H/V, as a function of the angle θ between the magnetizations of ferromagnets and the spin-quantization axis in TI for symmetric contacts. The polarizations of contacts are $p=1$ (upper curve) and $p=0.5$ (lower curve). The spin-scattering time $\tau=10$. The total dimensionless conductances of the contacts $g_1 = g_2 = 1$. Insets show the magnetization directions in ferromagnets (arrows) and the direction of the spin quantization axis in TI (dashed line) for the general symmetric configuration and the case of perpendicular orientation, equivalent to the absence of FM leads.

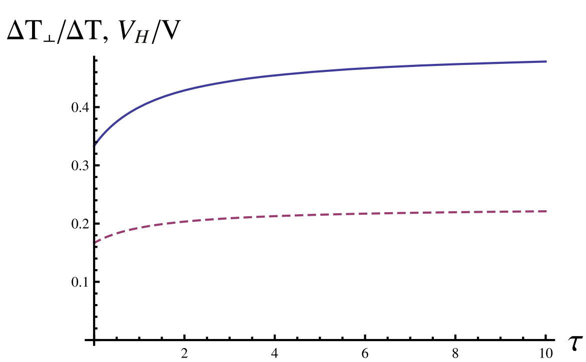

Fig. 3. Ratio of the temperature gradients and voltages $\Delta T_\perp/\Delta T = V_H/V$ as a function of the relaxation time τ for the parallel orientation of magnetizations $\theta=0$ and for the equal polarizations of ferromagnets $p=1$ (solid line) and $p=0.5$ (dashed line). The total dimensionless conductances of the contacts $g_1 = g_2 = 1$.

scattering time. The dimensionless electrical ($R_H = dV_H/dI_\parallel$) and thermal ($R_T = dT_\perp/dQ_\parallel$) Hall resistances are equal to each other,

$$R_H G_Q = R_T K_Q = \mathcal{F}, \qquad (1)$$

where the factor $\mathcal{F}$ depends on conductances, polarizations of ferromagnetic contacts, magnetization directions, and the spin-scattering time. Remarkably, in the case of identical ferromagnets with equal angle θ between the magnetization and spin-quantization axis of TI, the factor $\mathcal{F}$ turns out to be independent of the scattering time, its analytical expression reads

$$\mathcal{F}(g, p, \theta) = \frac{2p\cos\theta}{4 - g + gp^2\cos^2\theta}, \qquad (2)$$

where g denotes the total dimensionless conductance of each contact, and p denotes the polarization of FM (to be defined below). For completely polarized ferromagnets ($p=1$) with magnetizations parallel to the spin-quantization axis in TI ($\theta=0$), the Hall coefficients retain their quantized values. At the same time, the ratio of transverse and longitudinal voltages (V_H/V) as well as transverse and longitudinal temperature gradients ($\Delta T_\perp/\Delta T$) depends on the scattering time,

$$\frac{V_H}{V} = \frac{\Delta T_\perp}{\Delta T} = \frac{t_0 n_0 v_0 + 1}{3 + 2t_0 n_0 v_0}, \qquad (3)$$

where t_0 denotes the quasi-elastic spin-scattering time by magnetic impurities, n_0 is the linear concentration of electrons on the edge, and v_0 denotes the Fermi velocity in the edge state.

In the opposite case when electrons injected in the TI are completely unpolarized (FM polarization ($p=0$) or, equivalently, the magnetization of FM electrodes is perpendicular to the spin-quantization axis in the TI ($\theta = \pi/2$)) charge and thermal quantum Hall effects disappear in complete agreement with the situation in quantum spin Hall system [1,2]. In that case, the factor $\mathcal{F}$ in Eq. (2) equals to zero, indicating the vanishing Hall voltage and transverse temperature gradient.

The emergence of the temperature gradient transverse to the heat flow through TI is in fact identical to the thermal quantum Hall effect (Leduc–Righi effect) [6]. Consider a single chiral edge state in TI, which we denote as the spin-up state: let us suppose that the left contact has a higher temperature than the right one ($T_1 > T_2$) (see Fig. 4). In that case the hot electrons from the left contact propagate along the lower edge, and the cold electrons from the right contact propagate along the upper edge. In the absence of relaxation, the electrons on the edges are not in the equilibrium, however, as it will be shown below, one still can associate an effective temperature to the electron distribution. Thus, a temperature difference between the edges is created that is perpendicular to the heat flow. At the same time, there is a counter-propagating spin-down edge state in TI. For that state the Leduc–Righi effect has the opposite sign. If the reservoirs are spin-unpolarized, the temperature differences created by the spin-up and spin-down edge states compensate each other exactly resulting in zero net effect. Another situation is realized, if the reservoirs are ferromagnetic. In that case the contact conductances for spin-up and spin-down electrons differ, the compensation of contributions from spin-up and spin-down edge states does not take place any more, and a finite temperature difference between the edges is predicted. Analogously, the Hall voltage is generated by the potential difference between the ferromagnets.

In what follows we develop a general description of FM–TI–FM junction in terms of rate equations for distribution functions of the edge states. To this end let us consider the experimental setup shown schematically in Fig. 1. The contacts between ferromagnets

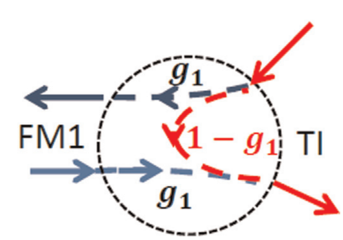

Fig. 4. Scheme of scattering in FM-TI contact for a single chiral spin-polarized edge state.