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Conversion efficiency of spin power to charge power in a normal metal with spin-orbit coupling

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ABSTRACT

We theoretically investigate the conversion efficiency of spin power to charge power in a normal metal with spin-orbit coupling based on the Green's function method. The normal metal is connected with three leads. A spin current injected in one lead can induce a charge current between another two leads. We find that the conversion efficiency of spin power to charge power is roughly proportional to t_{SO}^4 when the spin-orbit coupling t_{SO} is weak, suggesting that the efficiency is limited. Moreover, an increase of temperature may reduce the efficiency. The results may be useful in determining the overall efficiency of a thermoelectric setup based on the longitudinal spin Seebeck effect.

1. Introduction

Recently, there has been an intensive interest to develop high-efficiency thermoelectric materials for potential applications, e.g., electric power generation from waste heat and thermal management in electronics [1–4]. The conversion efficiency of heat to power is normally measured by the dimensionless figure of merit ZT, which is defined as $ZT = S^2\sigma T/\lambda$. Here S is the thermopower (or charge Seebeck coefficient), σ is the electrical conductivity, λ is the thermal conductivity, and T is the temperature. From this definition, one can see that improving the performance of thermoelectric materials requires the simultaneous optimization of three mutually counter-indicated properties, namely, S, σ, and λ, rendering the improvement not easy. Over the past decades, only modest improvements have been made by ways like nanostructuring to reduce the phonon conductivity [5–7], or band engineering to optimize electronic properties [8,9].

Very recently, a novel approach based on the spin Seebeck effect (SSE) in magnetic materials has been proposed [10–14]. In this approach, electrical transport and heat transport occur in different regions of the system, thus providing the opportunity to optimize thermal properties and electronic properties of the system separately [14]. In the longitudinal configuration consisting of a ferromagnetic-insulator (FI) and a normal-metal (NM) [15,16], the SSE is in particular promising. In such a configuration, the power (or a voltage) generation can be viewed as a two-step process. First, a spin current is pumped to the NM by a temperature gradient between the FI and the NM. Then, the spin current is converted to a perpendicular charge current (or the voltage) via the inverse spin Hall effect (ISHE) [17]. Although many works have been devoted to the study of heat/spin transport properties in this configuration [18–24], to our knowledge the thermoelectric efficiency is less discussed [25–27].

In this paper, we consider the conversion efficiency of spin current to charge current in a normal metal with spin-orbit coupling, that is, the conversion efficiency of spin power (corresponding to the spin current) to charge power. This efficiency is relevant to the second process of the longitudinal SSE (LSSE), and may be useful in determining the overall efficiency of heat current to charge power. The efficiency is estimated based on a tight-binding model with spin-orbit coupling. We find that the efficiency for this system is on the order of 0.2×10^{-4} in the weak regime of spin-orbit coupling. The efficiency can be enhanced by improving the spin-orbit coupling; however, an increase of temperature may reduce the efficiency.

2. Model and method

We consider a two-dimensional system with three ideal metal leads, as illustrated in Fig. 1. The Hamiltonian of the system and

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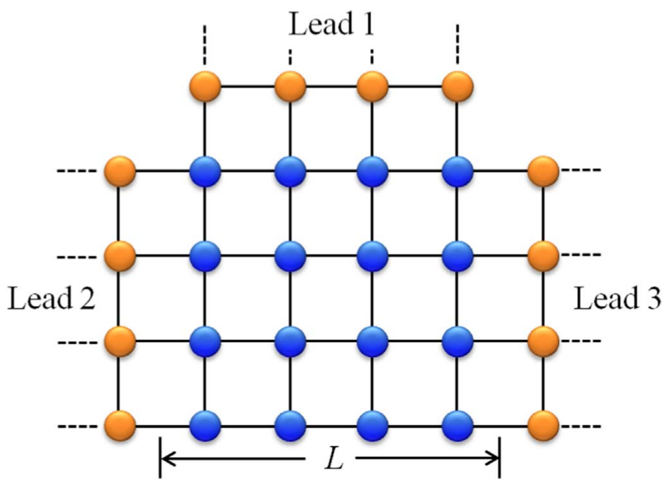

Fig. 1. Schematic of a three-terminal junction. The spin-orbit coupling only exists in the central region with a size of $L \times L$. A spin current is injected from lead 1 to induce a longitudinal charge current between leads 2 and 3.

the leads can be written as

$$H = -t\sum_{\langle ij\rangle\sigma} c_{i,\sigma}^{\dagger}c_{j,\sigma} + t_{SO}\sum_{i}\Big[\Big(c_{i,\uparrow}^{\dagger}c_{i+\delta_x,\downarrow} - c_{i,\downarrow}^{\dagger}c_{i+\delta_x,\uparrow}\Big) - i\Big(c_{i,\uparrow}^{\dagger}c_{i+\delta_y,\downarrow} + c_{i,\downarrow}^{\dagger}c_{i+\delta_y,\uparrow}\Big) + \text{H. c.}\Big], \tag{1}$$

where t (units of energy) denotes the nearest-neighbor hopping, and t_{SO} is the Rashba-type spin-orbit coupling. δ_x (δ_y) is the unit vector along the x (y) direction. Note that the spin-orbit coupling in the leads is chosen to zero. Although we have adopted a simple model here, we believe that the results below can also be extended to realistic models, where one may resort to first-principles calculations [28]. We expect that the results for realistic models may not change drastically.

At an FI/NM interface, a spin current carried by magnons can be injected to the NM. To mimic this effect, we adopt a metal lead (lead 1) and assume that a spin bias (spin accumulation) exists between this lead and the central region. Since there is no charge current across the FI/NM interface, we further assume the charge current from this lead is zero. Due to the spin accumulation at lead 1, a spin current is injected into the central system. Then it will induce a longitudinal charge current between leads 2 and 3. We shall consider the conversion efficiency of spin current to charge current in the following. To this end, we set the chemical potential at lead 1 to $\mu_{1\sigma} = \mu_F + \chi_\sigma \Delta\mu_{1s}/2(\chi_{\uparrow,\downarrow} = \pm 1)$, where μ_F is the chemical potential (Fermi energy) at equilibrium and $\Delta\mu_{1s}$ is a spin bias. Note that there is no charge bias at lead 1 ($\Delta\mu_1 = 0$). At leads 2 and 3, there is only charge bias, that is, $\mu_{2,3\sigma} = \mu_F + \Delta\mu_{2,3}$. The heat current, spin current, and charge current flowing *out* from lead i are, respectively,

$$\begin{aligned} I_{iq} &= \frac{1}{h}\int d\epsilon \sum_{\sigma,j\sigma'} (\epsilon - \mu_{i\sigma})[\mathcal{T}_{j\sigma',i\sigma}f_{i\sigma}(\epsilon) - \mathcal{T}_{i\sigma,j\sigma}f_{j\sigma'}(\epsilon)],\ I_{is} \\ &= \frac{1}{h}\int d\epsilon \sum_{\sigma,j\sigma'} \frac{\hbar}{2}\chi_\sigma[\mathcal{T}_{j\sigma',i\sigma}f_{i\sigma}(\epsilon) - \mathcal{T}_{i\sigma,j\sigma}f_{j\sigma'}(\epsilon)],\ I_{ic} \\ &= \frac{e}{h}\int d\epsilon \sum_{\sigma,j\sigma'} [\mathcal{T}_{j\sigma',i\sigma}f_{i\sigma}(\epsilon) - \mathcal{T}_{i\sigma,j\sigma}f_{j\sigma'}(\epsilon)]. \end{aligned} \tag{2}$$

Here $f_{i\sigma}(\epsilon) = [e^{(\epsilon-\mu_{i\sigma})/k_BT} + 1]^{-1}$ is the Fermi-Dirac distribution function with T being the temperature. The electron transmission can be calculated from the nonequilibrium Green's functions [29,30]; for example, $\mathcal{T}_{j\sigma',i\sigma} = \text{Tr}(\Gamma_{j\sigma'}G^r\Gamma_{i\sigma}G^a)$ is the probability for a spin-σ electron incident in lead i to be transmitted to lead j with spin-σ'. Here $G^{r,a}$ is the retarded (advanced) Green's function with the leads being taken into account through self-energies $\Sigma_{j\sigma}$, and $\Gamma_{j\sigma}$ is given by $\Gamma_{j\sigma} = i(\Sigma_{j\sigma} - \Sigma_{j\sigma}^{\dagger})$. The transmission satisfies the relations, $\mathcal{T}_{j\sigma',i\sigma} = \mathcal{T}_{i\bar\sigma,j\bar\sigma'}$ (time-reversal symmetry) and $\mathcal{T}_{2\sigma',1\sigma} = \mathcal{T}_{3\bar\sigma',1\bar\sigma}$ [31,32].

From Eq. (2) it follows that

$$I_{1s}\frac{\Delta\mu_{1s}}{\hbar} = -\sum_{i=1}^{3} I_{iq} - \sum_{i=2,3} I_{ic}\frac{\Delta\mu_i}{e}, \tag{3}$$

which indicates that the spin power ($P_s = I_{1s}\frac{\Delta\mu_{1s}}{\hbar}$) corresponding to spin current is partly converted to charge power ($P_c = -\sum_{i=2,3} I_{ic}\frac{\Delta\mu_i}{e}$), and is partly converted to heat flowing *into* the three leads. The conversion efficiency of spin power to charge power is then given by $\eta = P_c/P_s$. Note that in Eq. (3) we have assumed $I_{1c} = 0$, i.e.,

$$I_{1c} = \frac{e}{h}\int d\epsilon \sum_{\sigma\sigma',j\neq 1} [\mathcal{T}_{j\sigma',1\sigma}f_{1\sigma}(\epsilon) - \mathcal{T}_{1\sigma,j\sigma}f_{j\sigma'}(\epsilon)] = 0. \tag{4}$$

3. Results and discussion

We first consider the case of the low temperature limit ($k_BT \ll \mu_F$). In the linear regime (or low bias limit), Eq. (4) reduces to

$$I_{1c} = \frac{e}{h}\left\{\sum_{\sigma',j\neq 1}\left[\mathcal{T}_{j\sigma',1\uparrow}\frac{\Delta\mu_{1s}}{2} - \mathcal{T}_{j\sigma',1\downarrow}\frac{\Delta\mu_{1s}}{2}\right] - \sum_{\sigma'\sigma}\mathcal{T}_{1\sigma,2\sigma'}\Delta\mu_2 - \sum_{\sigma'\sigma}\mathcal{T}_{1\sigma,3\sigma'}\Delta\mu_3\right\} = 0, \tag{5}$$

from which we obtain $\Delta\mu_3 = -\Delta\mu_2$. If we consider leads 2 and 3 as two voltage probes (closed boundary conditions), there is no charge current between the central region and lead 2 (or 3). Then we have $I_{2c} = 0$, i.e.,

$$I_{2c} = \frac{e}{h}\sum_{\sigma',j}[\mathcal{T}_{j\sigma',2\sigma}\Delta\mu_2 - \mathcal{T}_{2\sigma,j\sigma'}\Delta\mu_{j\sigma'}] = 0, \tag{6}$$

from which we can obtain the ratio between $\Delta\mu_2 - \Delta\mu_3$ and the spin bias,

$$\frac{\Delta\mu_2 - \Delta\mu_3}{\Delta\mu_{1s}} = \frac{\sum_\sigma(\mathcal{T}_{2\sigma,1\uparrow} - \mathcal{T}_{2\sigma,1\downarrow})}{\mathcal{T}_{12} + 2\mathcal{T}_{32}}, \tag{7}$$

which measures the ability of the spin bias to induce the charge bias. Here we have used the abbreviation $\mathcal{T}_{ij} = \sum_{\sigma\sigma'}\mathcal{T}_{i\sigma,j\sigma'}$.

Fig. 2(a) shows the ratio $(\Delta\mu_2 - \Delta\mu_3)/\Delta\mu_{1s}$ as a function of the Fermi energy μ_F. The ratio is an odd function of the Fermi energy due to the particle-hole symmetry. That is, the carriers at $\mu_F > 0$ ($\mu_F < 0$) are electronlike (holelike), and these carriers make opposite contribution to the charge current. As the Fermi energy varies, the ratio oscillates drastically. This is largely due to the carrier reflection at the interface between the leads ($t_{SO} = 0$) and the central region with spin-orbit coupling, and also due to the precession of the electron spin [32]. Apart from the oscillation, we also note that the ratio increases slightly with increasing $|\mu_F|$. This is partially because the transmission $\mathcal{T}_{12} + 2\mathcal{T}_{32}$ [cf. Eq. (7)] drops as $|\mu_F|$ increases, as reflected in the inset of Fig. 2(a). The behavior of $\mathcal{T}_{12} + 2\mathcal{T}_{32}$ reflects the fact that around $\mu_F \sim 0$ there are more conducting channels. Further, as μ_F changes, the ratio takes several peak values, one of which is located at $\mu_F = 0.24t$, and in the following we will focus on properties at this Fermi energy.