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Thermospin diode effect based on a quantum dot system

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ABSTRACT

The rectification of spin current driven by a temperature difference in a simple model consisting of a quantum dot connected to two ferromagnetic leads has been studied using the rate equation technique. In addition to the dot level, the magnitude of thermospin current rectification depends on the temperature bias across the system, the asymmetry parameter and the Coulomb charging energy, where the last two parameters are necessary conditions for rectification to occur in the system. The thermospin current rectification becomes analytically simplified at the limitation condition of asymmetry. With an applied Zeeman magnetic field, an ideal 100% rectification of thermospin current can be obtained at specific dot energies, which can be controlled by an external gate voltage.

1. Introduction

The generation of spin-voltage induced by a temperature bias is called thermospin effect or spin Seebeck effect, and can be applied to fabrication of thermal-spin generators for driving spintronic devices. Uchida et al. observed a way to generate and amplify a net spin current without electric current using temperature gradient in a metallic magnet [1]. A recent experiment revealed that an electric voltage can be generated in a magnetic insulator due to the spin Seebeck effect [2]. Furthermore, the spin Seebeck effect has also been observed in ferromagnetic (FM) semiconductors [3] and half-metallic ferromagnets [4]. Theoretically, the spin Seebeck effect has been investigated in a quantum dot (QD) [5–9], a ferromagnet [10] and a Molecule Magnet junction [11]. It has been demonstrated that only spin current can be supplied with high efficiency of thermo-spin transformation in the junction of a QD with FM contacts [5].

The spin-current rectification (spin diode) effect has been investigated in the asymmetric system consisting of a QD [13,12,14,15] and a molecular wire [16] in contact with FM and nonmagnetic leads or two FM leads. The studies proposed the spin-current rectification characteristics when only a voltage bias is applied in the system.

In this study, we propose a simple system that not only has charge current rectification effect but can also function as a thermo-spin current rectifier (spin diode) with the application of a temperature bias across the system. The system is composed of a QD sandwiched between two FM leads. A schematic is shown in Fig. 1. The dot has a single electronic energy level which can be controlled by the gate voltage (GV). The electrons can be driven by either temperature bias (see Fig. 1(b)) or a voltage bias (see Fig. 1(c)) across the system.

2. Model

The Hamiltonian describing a QD connecting two metallic leads is given by

$$H = \sum_{\alpha;k,\sigma} (\varepsilon^{\alpha}_{k,\sigma} - \mu^{\alpha}) c^{\dagger\alpha}_{k,\sigma} c^{\alpha}_{k,\sigma} + \sum_{\alpha;k,\sigma} (\tau^{\alpha}_{\sigma} c^{\dagger\alpha}_{k,\sigma} d_{\sigma} + \text{h.c.}) + \sum_{\sigma} \varepsilon_{\sigma} \hat{n}_{\sigma} + U \hat{n}_{\uparrow} \hat{n}_{\downarrow}, \quad (1)$$

where $c^{\dagger}_{\alpha k,\sigma}$ is the creation operator for an electron in the $\alpha = L, R$ leads with spin $\sigma = \uparrow, \downarrow$ and spin-dependent energy $\varepsilon_{\alpha k,\sigma}$, $\hat{n}_{\sigma} = d^{\dagger}_{\sigma} d_{\sigma}$ is the number operator and $d^{\dagger}_{\sigma}$ is the creation operator for an electron in the dot with spin σ, ε_{σ} is the spin-dependent energy level in the dot, U is the Coulomb charging energy, $\tau_{\alpha,\sigma}$ is the coupling between the leads and the dots.

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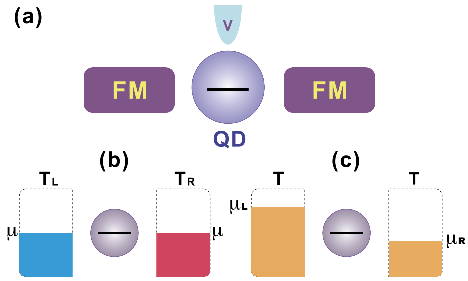

Fig. 1. (Color online.) (a) A schematic of a QD sandwiched between FM leads, where the energy level in the dot is controlled by the gate-voltage (GV). (b) A temperature difference δT is applied across the system where $|T_L - T_R| = \delta T$, while the chemical potentials in the leads are same $\mu_L = \mu_R = \mu$. (c) A bias voltage δV is applied in the system $\mu_L = \mu_R + \delta V$, while there is no temperature difference between the two leads.

The evolution of different states in the system can be described with the rate equation [1,5]

$$\partial_t P_i = \sum_j (\mathcal{W}_{j\to i} P_j - \mathcal{W}_{i\to j} P_i), \tag{2}$$

where P_i is the probability of an electron occupation state with $i = 0, \uparrow, \downarrow$ and $\updownarrow$ representing empty, spin-up, spin-down and double occupied states respectively. $\mathcal{W}_{j\to i} = \sum_\alpha \mathcal{W}^\alpha_{j\to i}$ $(\alpha = L, R)$ denotes the transition rate from state i to state j, specifically $\mathcal{W}^\alpha_{0\to\sigma} = \Gamma^\alpha_\sigma f_\alpha(\varepsilon_\sigma)$, $\mathcal{W}^\alpha_{\sigma\to\updownarrow} = \Gamma^\alpha_{\bar\sigma} f_\alpha(\varepsilon_{\bar\sigma} + U)$, $\mathcal{W}^\alpha_{\updownarrow\to\sigma} = \Gamma^\alpha_{\bar\sigma}[1 - f_\alpha(\varepsilon_{\bar\sigma} + U)]$, where $\bar\sigma$ denotes the opposite spin direction to σ. $f_\alpha(E) = [\exp(\frac{E-\mu_\alpha}{k_B T_\alpha}) + 1]^{-1}$ is the Fermi distribution function of the lead α with chemical potential μ_α and temperature T_α. The parameter Γ^α_σ denotes the spin dependence coming from the ferromagnetic band shift and characterizes the density of states and the coupling between lead α and the dot for an electron with spin σ. By solving the rate equation in steady-state, the probabilities P_i are obtained and we can find the charge current and energy current carried by the electrons with spin σ through the junction between the QD and lead α

$$I^\alpha_\sigma = P_0 \mathcal{W}^\alpha_{0\to\sigma} + P_{\bar\sigma} \mathcal{W}^\alpha_{\bar\sigma\to\updownarrow} - P_\sigma \mathcal{W}^\alpha_{\sigma\to 0} - P_\updownarrow \mathcal{W}^\alpha_{\updownarrow\to\bar\sigma}, \tag{3a}$$

$$I^\alpha_{Q\sigma} = (\varepsilon_\sigma) P_0 \mathcal{W}^\alpha_{0\to\sigma} + (\varepsilon_\sigma + U) P_{\bar\sigma} \mathcal{W}^\alpha_{\bar\sigma\to\updownarrow} - (\varepsilon_\sigma) P_\sigma \mathcal{W}^\alpha_{\sigma\to 0} - (\varepsilon_\sigma + U) P_\updownarrow \mathcal{W}^\alpha_{\updownarrow\to\bar\sigma}. \tag{3b}$$

The charge current consists of contributions from the propagation of all electrons in same direction, while the net spin current is composed of two charge currents with opposite spin polarizations and opposite propagation directions. Then the total charge current, spin current and energy current are obtained by $I_C = (I^L_\uparrow + I^L_\downarrow) - (I^R_\uparrow + I^R_\downarrow)$, $I_S = (I^L_\uparrow - I^L_\downarrow) - (I^R_\uparrow - I^R_\downarrow)$ and $I_Q = (I^L_{Q\uparrow} + I^L_{Q\downarrow}) - (I^R_{Q\uparrow} + I^R_{Q\downarrow})$ respectively.

For simplicity, we set the ratios $\gamma = \Gamma^R_\sigma/\Gamma^L_\sigma$ representing the asymmetric character and $\nu = \Gamma^\alpha_\downarrow/\Gamma^\alpha_\uparrow$ denoting the difference between the transfer rate of the different spins. With the temperature difference δT, the rectification of thermospin current is $R_S = (|I_{S+}| - |I_{S-}|)/\mathrm{Max}\{|I_{S+}|, |I_{S-}|\}$, where I_{S+} and I_{S-} are the spin currents with the forward temperature bias $T_L = T_R + \delta T$ and the reverse temperature bias $T_L + \delta T = T_R$.

Similarly, the rectification of charge current and energy current are $R_C = (|I_{C+}| - |I_{C-}|)/\mathrm{Max}\{|I_{C+}|, |I_{C-}|\}$ and $R_Q = (|I_{Q+}| - |I_{Q-}|)/\mathrm{Max}\{|I_{Q+}|, |I_{Q-}|\}$. It can be found that with temperature bias, the three different rectifications have the same expression as the Zeeman magnetic field approaches zero.

We should note that the conditions in which the rectification effect occurs in this system include the asymmetric junctions $\gamma = \Gamma^R_\sigma/\Gamma^L_\sigma \neq 1$ and the Coulomb charge energy $U \neq 0$. Once either condition cannot be satisfied, the rectification effect disappears in this system (i.e. $I_+/I_- = 1$, where I_+ and I_- denote the currents with forward and reverse bias).

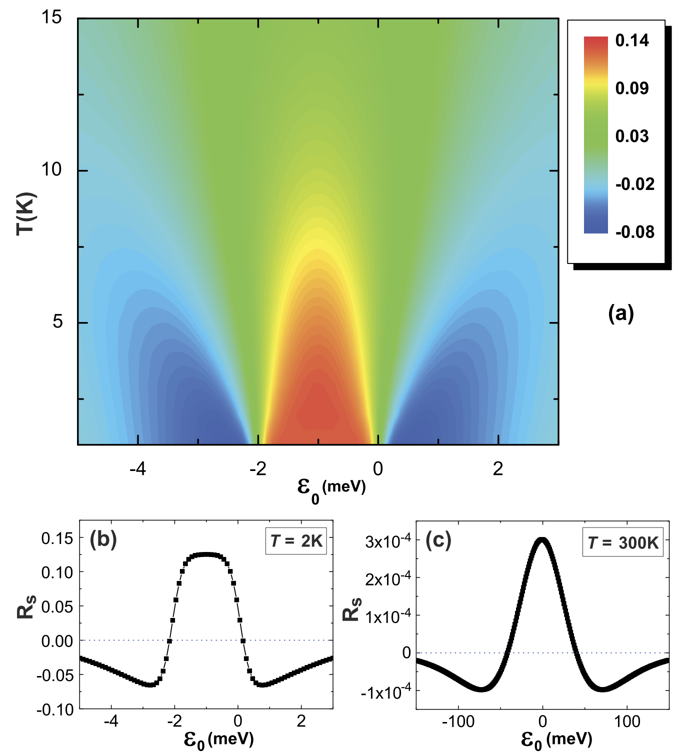

Fig. 2. (Color online.) (a) The rectification of thermospin current as a function of temperature and ε_0 without a Zeeman field. (b) and (c) show the R_s as a function of ε_0 at $T = 2$ K and $T = 300$ K respectively. The Coulomb charging energy is $U = 2$ meV, the temperature difference is $\delta T = 15$ K, the asymmetric parameter is $\gamma = 1/2$.

3. Results and discussion

At first, we investigate the relationship between rectification and dot energy at different temperatures. Fig. 2(a) shows the rectification of thermospin current as a function of dot energy ε_0 and temperature T without magnetic field B. In the plot, the rectification reaches its maximum value at $\varepsilon_0 = -U/2$ due to lack of Zeeman splitting on the dot energy. For comparison, we give the rectification vs ε_0 at $T = 2$ K and $T = 300$ K in Fig. 2(b) and (c) respectively. We find that the rectification generally has a larger magnitude at lower temperatures. In prior studies [17,18], reversal of thermal rectification has been found in a thermal transport quantum system. In this system, the region of ε_0 in which the reversal of thermospin current rectification presents is far from $\varepsilon_0 = -U/2$ (i.e. $|\varepsilon_0 + 1\text{ meV}| > 1.157$ meV at $T = 2$ K; $|\varepsilon_0 + 1\text{ meV}| > 40.885$ meV at $T = 300$ K). The critical value of ε_0 is independent of ν in the absence of a magnetic field on the system.

Fig. 3 depicts the rectification of thermospin current as a function of the asymmetric ratio γ at $T = 2$ K for different temperature bias δT without magnetic field. The value is chosen at the dot energy $\varepsilon_0 = -U/2$ corresponding to the peak value (see the inset of Fig. 3). It is evident that larger R_S corresponds to stronger asymmetry in the system. At the limitation condition of asymmetry ($\gamma \ll 1$), the value R_S can reach its maximum value $[1 - \exp(\frac{-\tau U}{(1+\tau)T})]/\{1 + \exp(-U/T) + 3\exp(\frac{-\tau U}{(1+\tau)T})[1 + \exp(\frac{(2+\tau)U}{(1+\tau)^2 T})]\}$, where $\tau = \delta T/T$. The expression shows that R_S can be induced and increased by enlarging temperature gradient at a certain environment temperature. Fig. 4 represents rectification of thermospin