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Thermospin effects in a quantum dot connected to normal leads

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ABSTRACT

We study thermospin effects through a quantum dot (QD) with a magnetic field attached to normal leads. In the stationary case, we obtain a tunable pure spin current and highly spin-polarized current. The spin Seebeck coefficient can be as large as the charge counterpart and a pure spin Seebeck coefficient is found. In the presence of microwave (MW) fields, the spin and charge current can be controlled by the amplitude of MW fields. Due to the photon-assisted tunneling, the behavior of current spin polarization *SP* becomes complicated and we can find a large *SP* in a larger range of the QD level V_g. At zero V_g, we can modulate both amplitude and direction of the spin current by the phase ϕ of MW fields. More peaks and valleys appear in the Seebeck coefficient owing to more sub-channels opened by the photons. Like the current, the spin Seebeck coefficient can be also tuned by ϕ.

1. Introduction

Generating a spin-polarized current and a pure spin current are two important topics in spintronics [1]. Conventionally, spintronic devices are driven by an external electric bias. Recently, the spin Seebeck effect (SSE), where the spin current or spin accumulation is driven by a temperature gradient across the sample, has been observed [2–8]. The SSE can be applied directly to the construction of thermal spin generators for driving spintronic devices, thereby opening the door to thermo-spintronics [9–11]. However, the spin Seebeck coefficient in these bulk samples is so weak that it may be overwhelmed by the accompanied charge Seebeck coefficient of several orders larger. Recognizing this problem, recent efforts have been shifted toward nanostructured materials. Thermally driven spin-polarized currents through a graphene or silicene-based device have been reported in Refs. [12–16]. Many works have proved that quantum dot (QD) tunnel junctions (based on the tunneling from ferromagnetic contacts) are good candidates for obtaining a large spin Seebeck coefficient and spin current [17–19]. The transport properties of the QDs strongly depend on the kind of the leads so that metallic and ferromagnetic leads affect the SSE in strongly different manner. Despite a large amount of theoretical investigations on the SSE in QD devices, the SSE has seldom been addressed in normal/QD/normal junctions [20].

Recently, investigation of the influence of the time-dependent fields on the thermoelectric transport has generated a great deal of theoretical and experimental interest [21–26]. On the experimental side, Zhang et al. [21] first explored the possibility of utilizing spin caloritronics in high-frequency applications. They reported an experimental discovery of a Seebeck rectification and frequency-dependent transport measurements at GHz frequency for magnetic tunnel junctions. On the theoretical side, Liu et al. [23] proposed a pure-spin-current generator based on a single level QD device under step-like magnetic field pulses. Chen et al. [25] reported theoretical analysis of thermal-spin and thermoelectric properties of noncollinear spin valves driven by a high-frequency ac voltage bias. When the time-dependent fields are different in different parts of the device, their phase and amplitude can strongly influence the transport. For example, a pumped current is generated by applying two periodic oscillating gate voltages with a phase lag. However, until now, the effect of the microwave (MW) field's phase and amplitude on the SSE has not yet been considered in normal/QD/normal junctions.

The work is organized as follows: In Section 2 we describe the Hamiltonian of the system and present the basic formulas for the thermally induced spin resolved current and spin-dependent Seebeck coefficient. We present the corresponding numerical results in Section 3, where we first focus on the stationary case in the absence of MW fields and then analyze the results with MW fields applied to both leads and the QD with different phase and amplitude, respectively. Final conclusions are given in Section 4.

2. Model and formulation

The system under consideration is a QD in an external magnetic field coupled to two normal leads with a temperature bias $\Delta T = T_L - T_R$, where T_α ($\alpha = L, R$) is the temperature in the α

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lead. We assume that external MW fields are applied to both normal leads and the QD, respectively. The system is described by the Hamiltonian:

$$H(t) = \sum_{\alpha,k,\sigma} \varepsilon_k(t) c^{+}_{\alpha,k,\sigma} c_{\alpha,k,\sigma} + \sum_{\sigma} \varepsilon_\sigma(t) d^{+}_{\sigma} d_\sigma + \sum_{\alpha,k,\sigma} \left[t_{\alpha,k} c^{+}_{\alpha,k,\sigma} d_\sigma + t^{*}_{\alpha,k} d^{+}_{\sigma} c_{\alpha,k,\sigma} \right], \tag{1}$$

where $c^{+}_{\alpha,k,\sigma}$ ($c_{\alpha,k,\sigma}$) and d^{+}_{σ} (d_σ) are creation (annihilation) operators with spin σ ($\sigma = \uparrow, \downarrow$ or ± 1) in the lead α and QD, respectively. $\varepsilon_k(t)$ has the form of $\varepsilon_k(t) = \varepsilon_k + \Delta(t)$, where ε_k is the time-independent single electron energy and $\Delta(t) = \Delta\cos(\omega t + \phi)$ is a time-dependent part from the MW fields. For simplicity, we assume that the MW fields have the same phase and amplitude in both leads. For the dot energy $\varepsilon_\sigma(t)$, $\varepsilon_\sigma(t) = V_g - \sigma h + \Delta_0 \cos(\omega t)$ with h being a Zeeman splitting of the dot level and V_g the bare dot level, which can be tuned by an external gate voltage. The amplitude Δ (Δ_0), phase ϕ, and frequency ω of the MW fields can be taken arbitrarily in this work.

Following the work of Jauho, Wingreen, and Meir [27], we obtain the time average spin-σ current from lead L as

$$I_\sigma = -\frac{2e}{h} \frac{\Gamma_L \Gamma_R}{\Gamma} \int d\varepsilon \, \mathrm{Im}\langle A_\sigma(\varepsilon, t)\rangle \left[f_L(\varepsilon) - f_R(\varepsilon) \right], \tag{2}$$

where $f_\alpha(\varepsilon) = 1/[1 + e^{(\varepsilon - \mu_\alpha)/k_B T_\alpha}]$ is the Fermi–Dirac distribution function of the α lead, μ_α denotes the chemical potential of the lead α, and k_B is Boltzmann's constant. $\Gamma_\alpha = 2\pi \sum_k |t_{\alpha,k}|^2 \delta(\varepsilon_k - \varepsilon)$ is the line-width function in the wide band approximation and $\Gamma = \Gamma_L + \Gamma_R$. $A_\sigma(\varepsilon, t)$ is given as $A_\sigma(\varepsilon, t) = \int dt_1 G^r_{00,\sigma}(t, t_1) \exp[i\varepsilon(t - t_1) - i\int_t^{t_1} dt_2 \Delta(t_2)]$ with $G^r_{00,\sigma}(t, t_1) = -i\theta(t - t_1)\langle\{d_\sigma(t), d^{+}_{\sigma}(t_1)\}\rangle$. We assume that external MW fields in both leads and the QD have the same frequency. This case under consideration is equivalent to that with only one independent parameter $\Delta' = \sqrt{(\Delta_0 - \Delta\cos\phi)^2 + \Delta^2 \sin^2\phi}$ [28]. By introducing $X = \Delta'/\hbar\omega$, we have

$$\mathrm{Im}\langle A_\sigma(\varepsilon, t)\rangle = -\frac{1}{2}\Gamma \sum_n \frac{J_n^2(X)}{(\varepsilon - n\hbar\omega - V_g + \sigma h)^2 + \frac{1}{4}\Gamma^2} \tag{3}$$

with J_n being the nth order Bessel function of the first kind. Substituting Eq. (3) into Eq. (2), we can evaluate the current

$$I_\sigma = \frac{e}{h} \int d\varepsilon T_\sigma \left[f_L(\varepsilon) - f_R(\varepsilon) \right]. \tag{4}$$

Here $T_\sigma = \Gamma_L \Gamma_R \sum_n \frac{J_n^2(X)}{(\varepsilon - n\hbar\omega - V_g + \sigma h)^2 + \frac{1}{4}\Gamma^2}$ is the time-averaged effective transmission coefficient of the spin-σ electrons. By using Eq. (4), we can define the current spin polarization $SP = \frac{|I_\uparrow| - |I_\downarrow|}{|I_\uparrow| + |I_\downarrow|} \times 100\%$.

Utilizing the linear response assumption, i.e., $T_L \approx T_R = T$, by setting the spin-σ current $I_\sigma = 0$ we calculate the spin-dependent Seebeck coefficient S_σ [25],

$$S_\sigma = -\frac{1}{eT} \frac{L_{1\sigma}}{L_{0\sigma}} \tag{5}$$

where $L_{n\sigma} = \frac{1}{\hbar} \int d\varepsilon (\varepsilon - \mu)^n T_\sigma [-\partial_\varepsilon f(\varepsilon)]$ and $f(\varepsilon) = 1/[1 + e^{(\varepsilon - \mu)/k_B T}]$ with μ the chemical potential. Thus, the charge and spin Seebeck coefficient S_c and S_s can be calculated as

$$S_c = \frac{1}{2}(S_\uparrow + S_\downarrow), \qquad S_s = S_\uparrow - S_\downarrow. \tag{6}$$

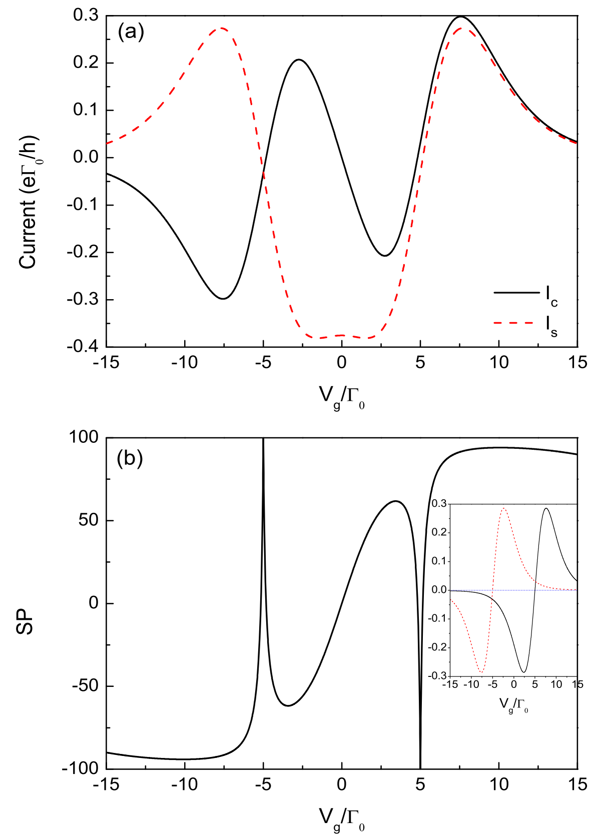

Fig. 1. I_c and I_s (a) and SP as a function of V_g. In the inset of Fig. 1b $I_\uparrow$ (dash line) and $I_\downarrow$ (solid line) versus V_g are plotted. Parameters: $k_B T_L = 2\Gamma_0$, $k_B T_R = \Gamma_0$ and $h = 5\Gamma_0$.

3. Results and discussions

We first discuss spin-dependent thermoelectric transport in the stationary case without MW fields, and then study in the presence of MW fields how the photon-assisted tunneling influences the thermally driven spin dependent current and Seebeck coefficient.

3.1. Thermoelectric transport in stationary case

We first study the current in the absence of MW fields, i.e., $\Delta = \Delta_0 = 0$. A temperature bias ΔT is applied between two leads, which drives a spin-σ current through the QD. Fig. 1a describes the spin current $I_s = I_\uparrow - I_\downarrow$ and charge current $I_c = I_\uparrow + I_\downarrow$ as a function of the QD level V_g. We have chosen $\Gamma_\alpha = \Gamma_0$ and all the energies are measured in Γ_0. We set the chemical potential μ_α to be zero. It is clearly shown that I_s is an even function of V_g, while I_c is an odd function of V_g. The amplitude and direction of I_s and I_c can be modulated by V_g. This special feature can be used to control the current spin polarization SP by using V_g. For example, when V_g is zero, we have zero I_c but large I_s, thus a spin current but no charge counterpart can be obtained. For $V_g = +(-)h$, we find $I_s = -(+)I_c$, so we get a 100% spin-polarized current (see Fig. 1b), whose flowing direction can be changed by adjusting V_g. In Fig. 1b SP versus V_g is plotted. SP is an odd function of V_g and vary with V_g. For $V_g < 0$ SP is negative except for $V_g \sim -h$, where a sharp positive peak exists and SP can reach 100% at $V_g = -h$. While for positive V_g SP is positive except for $V_g \sim h$, where a sharp negative peak appears and SP can achieve -100% at $V_g = h$. Thus a tunable spin-polarized current can be obtained in our simple normal/QD/normal junctions. We can understand the mechanism of such interesting features