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Effects of photon field on heat transport through a quantum wire attached to leads

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We theoretically investigate photo-thermoelectric transport through a quantum wire in a photon cavity coupled to electron reservoirs with different temperatures. Our approach, based on a quantum master equation, allows us to investigate the influence of a quantized photon field on the heat current and thermoelectric transport in the system. We find that the heat current through the quantum wire is influenced by the photon field resulting in a negative heat current in certain cases. The characteristics of the transport are studied by tuning the ratio, $\hbar\omega_\gamma/k_B\Delta T$, between the photon energy, $\hbar\omega_\gamma$, and the thermal energy, $k_B\Delta T$. The thermoelectric transport is enhanced by the cavity photons when $k_B\Delta T > \hbar\omega_\gamma$. By contrast, if $k_B\Delta T < \hbar\omega_\gamma$, the photon field is dominant and a suppression in the thermoelectric transport can be found in the case when the cavity-photon field is close to a resonance with the two lowest one-electron states in the system. Our approach points to a new technique to amplify thermoelectric current in nano-devices.

1. Introduction

The wide research field of thermoelectric transport in nanoscale devices is very active nowadays due to their expected high efficiency comparing to bulk materials. The efficiency of thermoelectric materials is measured by the figure of merit, the ratio of the electrical conductance to the thermal conductance [1]. In bulk materials, the figure of merit is restricted by classical relationships such as the Wiedmann–Franz law and the Motto relation in which the electrical conductance is directly proportional to the thermal conductance. The violation of the Wiedmann–Franz law in the range of the nano-scale has caused nanostructures to be considered as good thermoelectric devices [2]. These relations may not hold in nanostructures due to quantum phenomena such as quantum interference [3], Coulomb blockade [4], and energy quantization [5].

It has been shown that the thermoelectric efficiency in nanodevices is increased [6] and plateaus in the thermoelectric current due to Coulomb blockade can be formed [4] in the presence of the Coulomb interaction. In addition, the thermal properties of a double quantum dot molecular junction have been studied and shown that the Fano effect can improve the thermoelectric efficiency [7]. Thermoelectric effects in an Aharonov–Bohm interferometer with embedded quantum dots has been demonstrated [8], where the effects of a geometrical phase on the thermopower in the absence of an interdot Coulomb interaction is shown. On other hand, the photon–phonon interaction also influences thermoelectric transport in quantum systems. Soleimani [9] has shown that the photon–phonon interaction can enhance the thermoelectric effect in molecular devices, with increasing oscillations of the thermopower in the presence of the electron–photon interaction.

A temperature gradient can also generate thermo-spin transport. The thermo-spin effect opens up a new possibility for fabricating spintronic devices. It has been shown that the thermo-spin effect in nanodevices is conceptually different from the traditional one in bulk material using magnetic semiconductors [10]. With the investigation of the thermo-spin effect, intensive study has been carried out on the thermal properties in quantum dots with a Rashba-spin orbit interaction [11].

Another interesting aspect is the use of light to control thermoelectric transport in quantum systems. The thermoelectric effect in a quantum dot in the presence of microwave field has been studied using Keldysh nonequilibrium linear-response approach. It was found that the microwave field can produce heat flow in the QD system by a formation of additional transport channels below

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the Fermi energy [12]. Furthermore, the thermoelectric transport properties of topological insulator have been investigated under the application of off-resonant light. It is shown that by applying a circularly polarized light, the band gap is tuned and results in enhanced thermoelectric transport. Moreover, an exchange of the conduction and valence bands of the symmetric and antisymmetric surface states is seen by tuning the light polarization [13].

The thermo-spin transport has been theoretically studied with the application of circularly polarized light in two regimes: Low and high temperature. At high temperature, the transport of the spin-down electron plays a dominant role in driving the thermoelectric effect. Alternatively, at low temperature, the polarized light induces an antiresonant transport of spin-up electron through the device, leading to an important contribution of the spin-up electrons to the thermoelectric effect [14].

The influences of light on the thermoelectric effect in quantum systems is still in its infancy. Especially, if the light is quantized such as photons in a cavity. In this study, we present theoretical investigation of thermoelectric transport through a quantum wire coupled to a quantized photon cavity. We study two different regimes: Low and high thermal energy comparing to the photon energy. In the high thermal energy regime ($\hbar\omega_\gamma < k_B\Delta T$), the temperature gradient is dominant, and the thermoelectric transport is enhanced. But in the low thermal energy regime ($\hbar\omega_\gamma > k_B\Delta T$), a reduction in the thermoelectric transport is found for the system close to a Rabi resonance.

The outline of the paper is as follows. We show the model system and discuss the quantum master equation in Sec. 2. Numerical results are discussed for the model in Sec. 3. Finally, conclusions are drawn in Sec. 4.

2. Theory

In this section, we introduce the Hamiltonian of the system and the formalism that defines the properties of the electron transport. We assume a quantum wire (QW) connected to two electron reservoirs (leads) and exposed to a quantized cavity photon field. The QW is coupled to a lead with high temperature on the left side and another lead with lower temperature no the right side. The hot (h) and cold (c) leads each obey a Fermi–Dirac contribution

$$f_{h/c} = \left[1 + \exp\left((E - \mu_{h/c})/(k_B T_{h/c})\right)\right]^{-1}, \tag{1}$$

where $\mu_h(T_h)$ and $\mu_c(T_c)$ are the chemical potential (temperature) of the hot and cold leads, respectively. We consider the voltage difference $eV_{\rm bias} = \mu_h - \mu_c$ to be applied symmetrically across the device such that the electrochemical potential of the hot and the cold leads is equal.

One can calculate the heat current (HC) that is the rate at which heat is transferred over time. In our system the heat current in our system can be expressed as

$$\begin{aligned} \mathrm{HC} &= \mathrm{Tr}\left[\dot{\hat{\rho}}_S(t)(\hat{H}_S - \mu\hat{N}_e)\right] \\ &= \sum_{\alpha\beta}(\hat{\alpha}|\dot{\hat{\rho}}_S|\hat{\beta})(E_\alpha - \mu\hat{N}_e)\delta_{\alpha\beta}, \end{aligned} \tag{2}$$

where $\hat{\rho}_S$ is the reduced density operator, $\hat{H}_S$ is the Hamiltonian of the electrons in the central system coupled to the photons in the cavity, $\hat{N}_e$ is the electron number operator, and $\mu = \mu_h = \mu_c$. But, the rate at which electrons are transferred over time by a temperature gradient is the thermoelectric current (TEC). The TEC through the QW connected to the leads and coupled to the photon cavity is defined as

$$\mathrm{TEC} =: \mathrm{Tr}[\dot{\hat{\rho}}_S^h(t)\hat{Q}] - \mathrm{Tr}[\dot{\hat{\rho}}_S^c(t)\hat{Q}]. \tag{3}$$

Herein, the first (second) term of Eq. (3) is the current from the hot (cold) reservoirs to the QW, respectively, and $\hat{Q} = e\hat{N}$ is the charge operator with the electron number operator $\hat{N}$. The negative sign between the first and second terms of Eq. (3) indicates the electron motion from the QW to the cold lead. The current carried by the electrons in the total system is calculated from the reduced density operator $\hat{\rho}_S^{h,c}$, describing the state of the electrons in the QW under the influence of the reservoirs [15].

In a steady state the left and right currents are of the same magnitude. We use a non-Markovian generalized master equation (GME) to describe the time-dependent electron motion in the system [15]. The time needed to reach the steady state depends on the chemical potentials in each reservoirs, the bias window, and their relation to the energy spectrum of the system [16]. In anticipation that the operation of an optoelectronic circuit can be sped up by not waiting for the exact steady state we integrate the GME to $t = 220$ ps, a point in time late in the transient regime when the system is approaching the steady state.

The QW is exposed to a uniform external perpendicular magnetic field and is in a quantized photon cavity with a single photon mode. Therefore, we write the vector potential in the following form

$$\mathbf{A}(\mathbf{r}) = \mathbf{A}_B(\mathbf{r}) + \mathbf{A}_\gamma(\mathbf{r}), \tag{4}$$

where $\mathbf{A}_B(\mathbf{r}) = -By\hat{\mathbf{x}}$ is the vector potential of the external magnetic field defined in the Landau gauge, and $\hat{\mathbf{A}}_\gamma$ is the vector potential of the photon field given by $\hat{\mathbf{A}}_\gamma(\mathbf{r}) = A(\hat{a} + \hat{a}^\dagger)\mathbf{e}$. Herein, the amplitude of the photon field is defined by A with the electron–photon coupling constant $g_\gamma = eAa_w\Omega_w/c$, and $\hat{a}(\hat{a}^\dagger)$ are annihilation(creation) operators of the photon in the cavity, respectively. The parameter that determines the photon polarization is $\mathbf{e}$ with either parallel polarized photon field $\mathbf{e} = \mathbf{e}_x$ or perpendicular polarized photon field $\mathbf{e} = \mathbf{e}_y$. The effective confinement frequency is $\Omega_w = \sqrt{\Omega_0^2 + \omega_c^2}$ with Ω_0 being electron confinement frequency due to the lateral parabolic potential and ω_c the cyclotron frequency due to the external magnetic field.

The QW is hard-wall confined in the x-direction and parabolically confined in the y-direction. The Hamiltonian of the QW coupled to a single photon mode in an external perpendicular magnetic field in the z-direction is

$$\begin{aligned} \hat{H}_S = &\int d^2r\, \hat{\psi}^\dagger(\mathbf{r})\left[\frac{1}{2m^*}\left(\frac{\hbar}{i}\nabla + \frac{e}{c}\mathbf{A}(\mathbf{r})\right)^2\right]\hat{\psi}(\mathbf{r}) \\ &+ \hat{H}_{ee} + \hbar\omega_\gamma\hat{a}^\dagger\hat{a}, \end{aligned} \tag{5}$$

where $\hat{\psi}$ is the electron field operator. The second term of Eq. (5) ($\hat{H}_{ee}$) represents the Coulomb electron–electron interaction in the quantum wire [17,18] and the last term is the quantized single-mode photon field, with photon energy $\hbar\omega_\gamma$. The electron–electron and the electron–photon interactions are taken into account stepwise using exact diagonalization techniques and truncations [19,15]. The time evolution of the system is described by a non-Markovian generalized master equation in order to study the non-equilibrium electron transport in the total system [20].

3. Results

In this section, we present results of our study of the thermoelectric transport. The system is a two-dimensional quantum wire in xy-plane with hard-wall confinement in the x-direction and parabolically confinement in the y-direction. The quantum wire is connected to two leads with different temperature and the same chemical potential. We assume the temperature of the left lead (T_h) is higher than that of the right lead (T_c). The electron confinement energy of the quantum wire is equal to that of the leads

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