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Optical control of spin-dependent thermal transport in a quantum ring

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ABSTRACT

We report on calculation of spin-dependent thermal transport through a quantum ring with the Rashba spin-orbit interaction. The quantum ring is connected to two electron reservoirs with different temperatures. Tuning the Rashba coupling constant, degenerate energy states are formed leading to a suppression of the heat and thermoelectric currents. In addition, the quantum ring is coupled to a photon cavity with a single photon mode and linearly polarized photon field. In a resonance regime, when the photon energy is approximately equal to the energy spacing between two lowest degenerate states of the ring, the polarized photon field can significantly control the heat and thermoelectric currents in the system. The roles of the number of photon initially in the cavity, and electron–photon coupling strength on spin-dependent heat and thermoelectric currents are presented.

The advances in nanoscale system have largely raised the development in thermoelectric materials that can convert thermal energy into the electrical energy [1]. The most interesting quantum properties are reduced dimensionality [2–4] and quantized energy levels [5] that lead to increase the thermal efficiency of nanoscale systems. First, Hicks and Dreslhaus in 1993 suggested to use low dimensional structure for enhancement of the thermal efficiency via creasing figure of merit. They showed that the figure of merit increases as the dimensionality of the system decreases [6]. What's more, the thermal transport behavior of nanoscale materials can be controlled by tuning the gate voltage [7]. This may open a new window to study the efficient thermoelectric materials. Consequently, the results such as the Mott formula and Wiedemann–Freanz law may not hold in nanodevices due to the quantum phenomena [8].

Thermal transport is currently an active field concerned with investigation the spin-dependent of heat and thermoelectric transport in a nanoscale materials [4,9]. It has been demonstrated that the spin accumulation strongly suppresses the thermoelectric efficiency, and a pure spin thermopower can be obtained in the presence of the magnetic field [10]. Furthermore, the spin conductance and the spin Seebeck coefficient have been calculated in a quantum dot system and shown that both spin conductance and Seebeck coefficient are increased by the increase of magnetic field and polarization of leads, resulting in enhancement of spin figure of merit [11].

On the other hand, the influences of photon field on thermal transport have been considered. It has been shown that the interplay between photon and thermally induced electron populations results in a switch of the current sign [12]. In the linear response regime, using a Keldysh nonequilibrium Green function technique, thermal transport is studied in a nanoscale system coupled a lead. By applying a photon field to one of the leads, heat flows mostly from the dark to the bright lead and almost irrespective of the direction of the thermal gradient. They attribute this effect to photon-induced opening of additional transport channels below the Fermi energy. The photon field can change both the magnitude and the sign of the electrical bias voltage induced by a temperature gradient [13]. In our previous work, we show the influences of a quantized photon field on thermoelectric current in a quantum wire. We found that the thermoelectric current is inverted for the off-resonant photon field due to participation of photon replica states in the transport. Furthermore, a reduction in the current is recorded for the resonant photon field, a direct consequence of the Rabi-splitting [14,15].

In the present paper, we investigate the thermal transport in a quantum ring including the Coulomb interaction and electron–photon interactions. Taking into a account a Rashba spin-orbit coupling in the ring system, the spin-dependent heat and thermoelectric currents are studied using the generalized non-Markovian master equation. We show the influences of the Rashba spin-orbit

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coupling and the photon field on both the heat and thermoelectric currents.

The paper is organized as follows: In Sec. 1, we present the model describing a quantum ring coupled to a photon cavity. Section 2 shows the numerical results and discussion. Concluding remarks are addressed in Sec. 3.

1. Theory

We assume a quantum ring coupled to a photon field and connected to two electron reservoirs where the photon cavity is much larger than the quantum ring. Below, we present the Hamiltonian of the ring system and the formalism that describes the time evolution of the electrons in the system.

1.1. Hamiltonian of the system

The present quantum system can defined by the following Hamiltonian

$$\hat{H}_S = \int d^2r\, \hat{\mathbf{\Psi}}^{\dagger}(\mathbf{r}) \left[\left(\frac{\hat{\mathbf{p}}^2}{2m^*} + V_r(\mathbf{r}) \right) + H_Z + \hat{H}_R(\mathbf{r}) \right] \hat{\mathbf{\Psi}}(\mathbf{r}) + \hat{H}_{ee} + \hbar\omega_{\gamma} \hat{a}^{\dagger}\hat{a}. \quad (1)$$

Herein, the total momentum operator of the central system coupled to the cavity is

$$\hat{\mathbf{p}}(\mathbf{r}) = \frac{\hbar}{i}\nabla + \frac{e}{c}\left[\hat{\mathbf{A}}(\mathbf{r}) + \hat{\mathbf{A}}\gamma(\mathbf{r})\right], \quad (2)$$

where the magnetic vector potential is $\hat{\mathbf{A}}(\mathbf{r}) = -By\hat{x}$ with $\mathbf{B} = B\hat{\mathbf{z}}$, and the photon vector potential is $\hat{\mathbf{A}}\gamma(\mathbf{r})$ which is defined in terms of the photon creation ($\hat{a}^{\dagger}$) and annihilation ($\hat{a}$) operators as

$$\hat{\mathbf{A}}_{\gamma} = A(\mathbf{e}\hat{a} + \mathbf{e}^*\hat{a}^{\dagger}), \quad (3)$$

with $\mathbf{e} = \mathbf{e}_x$ for the x-polarized and $\mathbf{e} = \mathbf{e}_y$ the y-polarized of the photon field [16]. The ring potential is defined by $V_r(\mathbf{r})$ which will be defined later.

The Zeeman Hamiltonian defined in the second term of Eq. (1) gives the interaction of electron spin with the external magnetic field which is introduced by $H_Z = \frac{1}{2}(\mu_B g_S B \sigma_z)$ with μ_B the Bohr magneto and g_S is the electron spin g-factor.

In addition, the Rashba-spin orbit coupling defined in the third terms of Eq. (1) describes the interaction between the spin and the orbital motion of the electron

$$\hat{H}_R(\mathbf{r}) = \frac{\alpha}{\hbar}\left(\sigma_x \hat{p}_y(\mathbf{r}) - \sigma_y \hat{p}_x(\mathbf{r})\right) \quad (4)$$

with α the Rashba spin orbit (RSO) coupling constant that can be tuned by electric field, and σ_x and σ_y are the Pauli matrices. The Coulomb interaction presented in the central system is defined by $\hat{H}_{ee}$ [17,18] and the free photon Hamiltonian is $\hbar\omega_{\gamma}\hat{a}^{\dagger}\hat{a}$ in the cavity with $\hbar\omega_{\gamma}$ the photon energy.

The components of the spinor vector is $\hat{\mathbf{\Psi}}(\mathbf{r}) = \begin{pmatrix} \hat{\Psi}(\uparrow, \mathbf{r}) \\ \hat{\Psi}(\downarrow, \mathbf{r}) \end{pmatrix}$ and $\hat{\mathbf{\Psi}}^{\dagger}(\mathbf{r}) = \begin{pmatrix} \hat{\Psi}^{\dagger}(\uparrow, \mathbf{r}), & \hat{\Psi}^{\dagger}(\downarrow, \mathbf{r}) \end{pmatrix}$, where $\hat{\Psi}(x) = \sum_a \psi_a^S(x)\hat{C}_a$ is the field operator with $x \equiv (\mathbf{r}, \sigma)$, $\sigma \in \{\uparrow, \downarrow\}$ and the annihilation operator, $\hat{C}_a$, for the single-electron state (SES) $\psi_a^S(x)$ in the quantum ring system.

The time-convolutionless generalized master equation (TCL-GME) is utilized to investigate the transport properties of the system. The TCL-GME is local in time and satisfies the positivity for the many-body state occupation in the reduced density operator (RDO). Before the central system is coupled to the leads, the total density matrix is the product of the density matrices of the system and the leads $\hat{\rho}_T$. The RDO of the system after the coupling is defined as

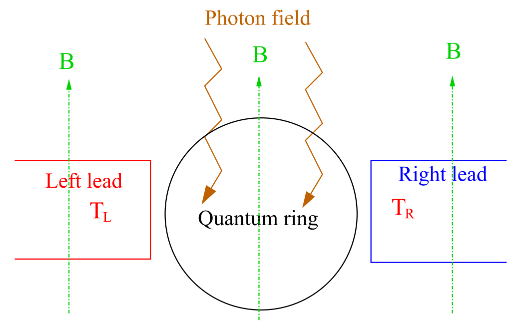

Fig. 1. (Color online.) schematic diagram shows the quantum ring (black color) connected to the leads where the temperature of the left lead (T_L) (red color) is higher than the temperature of the right lead (T_R) (blue color). The green arrows indicate the external magnetic fields and the brown zigzag display the photon field in the cavity.

$$\hat{\rho}_S(t) = \mathrm{Tr}_l(\hat{\rho}_T) \quad (5)$$

where $l \in \{L, R\}$ refers to the left (L) and the right (R), respectively. In our calculations 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 heat current is the ratio of the transferred heat over time. The heat current (I^H) in terms of the reduced density operator can be introduced as

$$\mathrm{I}_l^H = c_l \mathrm{Tr}_l\Big[\frac{d}{dt}\hat{\rho}_{S,l}(t)(\hat{H}_S - \mu\hat{N}_{\mathrm{e}})\Big] = \sum_{\alpha\beta}(\hat{\alpha}|\dot{\hat{\rho}}_{S,l}|\hat{\beta})(E_{\alpha} - \mu\hat{N}_{\mathrm{e}})\delta_{\alpha\beta} \quad (6)$$

where $c_L = 1$ and $c_R = -1$, $\hat{\rho}_{S,l}$ is the reduced density operator in terms of the l lead, $\mu = \mu_{\mathrm{L}} = \mu_{\mathrm{R}}$, and $\hat{N}_{\mathrm{e}}$ is the electron number operator.

Furthermore, the thermoelectric current (I^{TH}) can be defined as

$$\mathrm{I}_l^{\mathrm{TH}} = c_l \mathrm{Tr}\big[\dot{\hat{\rho}}_{S,l}\hat{Q}\,\big] \quad (7)$$

with the charge operator is $\hat{Q} = e\int d^2r \hat{\mathbf{\Psi}}^{\dagger}(\mathbf{r})\hat{\mathbf{\Psi}}(\mathbf{r})$.

1.2. Quantum ring system

The quantum ring connected to the electron reservoirs or leads with different temperatures is schematically displayed in Fig. 1, where the temperature of the left (right) lead is labeled as T_L (T_R), respectively. The total system is exposed to an external magnetic field B (green arrows) and the ring system is coupled to a photon field (brown zigzag arrows).

The potential of the quantum ring can be defined by

$$V_r(\mathbf{r}) = \sum_{i=1}^{6} V_i \exp\left[-(\gamma_{xi}(x - x_{0i}))^2 - (\gamma_{yi}\, y)^2\right] + \frac{1}{2}m^*\Omega_0^2 y^2, \quad (8)$$

where V_i, γ_{xi}, and γ_{yi} are constants shown in Table 1. $x_{03} = \epsilon$ is a small numerical symmetry breaking parameter and $|\epsilon| = 10^{-5}$ nm is enough for numerical stability. The characteristic energy of the electron confinement in the ring is defined by the second term of Eq. (8) with energy $\hbar\Omega_0$ [19].