Single-photon controlled thermospin transport in a resonant ring-cavity system

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Abstract

Cavity-coupled nanoelectric devices hold great promise for quantum technology based on coupling between electron-spins and photons. In this study, we approach the description of these effects through the modeling of a nanodevice using a quantum master equation. We assume a quantum ring is coupled to two external leads with different temperatures and embedded in a cavity with a single photon mode. Thermospin transport of the ring-cavity system is investigated by tuning the Rashba coupling constant and the electron-photon coupling strength. In the absence of the cavity, the temperature gradient of the leads causes a generation of a thermospin transport in the ring system. It is observed that the induced spin polarization has a maximum value at the critical value of the Rashba coupling constant corresponding to the Aharonov-Casher destructive interference, where the thermospin current is efficiently suppressed. Embedded in a photon cavity with the photon energy close to a resonance with the energy spacing between lowest states of the quantum ring, a Rabi splitting in the energy spectrum is observed. Furthermore, photon replica states are formed leading to a reduction in the thermospin current.

Keywords: Thermo-optic effects, Electronic transport in mesoscopic systems, Cavity quantum electrodynamics, Electro-optical effects

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1. Introduction

Thermoelectric properties have been so far investigated mainly in nanoscale systems to achieve high thermoelectric efficiency that would be useful for energy harvesting \cite{1, 2}. To obtain a high thermoelectric efficiency, thermoelectrically active materials are used. These materials should have high electrical conductivity and low thermal conductivity. High electrical conductivity can be obtained by increasing the carrier mobility or their concentration that can be influenced in quantum structures. Consequently, the figure of merit and Seebeck effect can be enhanced in nanodevices \cite{3, 4, 5}. Generally, there is a challenge in the conventional thermoelectric material because if the electrical conductivity is enhanced the thermal conductivity is increased as well. As a result, the Seebeck effect and the device efficiency are decreased.

An advantageous method relying on the Spin Seebeck effect has been used to decouple electrical conductivity from thermal conductivity. So the electrical and thermal conductivity can be separately controlled concurrently \cite{6, 7}. In 2008, Saitoh and et. al. discovered the spin Seebeck effect when heat is applied to a magnetized metal. In a magnetically active material electrons reconfigure themselves according to their spin. In this way, unlike in a conventional electron transport, this rearrangement does not create heat as a waste product. The spin Seebeck effect can lead the way to the growth of smaller, faster and more energy-efficient microchips as well as spintronics devices \cite{8, 9, 10}.

On the other hand, the influences of light on thermoelectric effects have been investigated and shown that the thermoelectric power can be enhanced by increasing the intensity of light \cite{11}. It was also found that a polarized light can induce a Fano-like resonance in the thermal conductance \cite{12}. Therefore, The thermopower and the figure of merit may be enhanced near a Fano-like resonance. In addition, the polarized light and the increase of magnetic polarization may lead to a better thermoelectric performance, especially, a significant increase of the spin thermal efficiency may be obtained.

Influenced by the aforementioned studies, we try to explore the influences of a quantized photon field on thermospin transport through a quantum ring including the Rashba spin-orbit coupling. We model a quantum ring system coupled to two leads with different temperatures. The ring system is embedded in a cavity with a linearly polarized photon field. In our previous publications, we have seen that both thermoelectric and heat currents can be controlled by a polarized photon field \cite{13, 14, 15, 16}. The aim of our study here is twofold. First, we induce a thermospin current through a multi-level quantum ring
and see the influences of the Rashba spin-orbit coupling on thermospin current using a quantum master equation. Second, we show how the spin-polarization and thermospin current can be controlled by a single photon in the cavity.

The paper is organized as follows: In Sec. 2, we present the model describing a quantum ring coupled to a photon cavity. Section 3 shows the numerical results and discussion. Concluding remarks are addressed in Sec. 4.

2. Model and Theory

In this section, we first present the Hamiltonian of the system, and subsequently apply the general master equation formalism to calculate the thermospin-polarized current.

2.1. Hamiltonian of the system

The Hamiltonian of a quantum ring system coupled to a cavity can be expressed as

\[ H = H_e + H_{e-\gamma} + H_\gamma, \]

(1)

where the Hamiltonian of the electronic part \( H_e \) and the electron-photon interaction \( H_{e-\gamma} \) together can be defined as

\[ \hat{H}_e + H_{e-\gamma} = \int d^2r \left[ \hat{A}^\dagger(r) \left( \frac{\hbar^2}{2m_e} + V_e(r) \right) + H_Z \right] + \hat{H}_R(r) \hat{\Psi}(r) \hat{H}_{ee}, \]

(2)

and the Hamiltonian of the free photon field in the cavity is

\[ H_\gamma = \hbar \omega_\gamma \hat{a}^\dagger \hat{a}. \]

(3)

Herein, \( \hat{\Psi}(r) \) is the spinor vector [15], and \( \hat{p}(r) \) is the momentum operator of the quantum ring system coupled to the photon cavity which can be written as

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

(4)

where the vector potential of the external perpendicular magnetic field is \( \hat{A}(r) = -B_y \hat{x} \) with \( B = B \hat{z} \), and the vector potential of the photons in the cavity is \( \hat{A}_\gamma(r) \) which can be introduced in terms of the photon creation (\( \hat{a}^\dagger \)) and annihilation (\( \hat{a} \)) operators as

\[ \hat{A}_\gamma = A(e \hat{a} + e^* \hat{a}^\dagger), \]

(5)

with \( e = e_x \) for the \( x \)-polarized and \( e = e_y \) for the \( y \)-polarized photon field [17]. The potential that forms the quantum ring is \( V_e(r) \) and \( H_Z \) is the Zeeman Hamiltonian [15]. The strength of the vector potential of the photons \( A \) is defined by the electron-photon coupling constant \( g_y = e \Omega_\omega a_w / c \), where \( \Omega_\omega = (\omega_x^2 + \Omega_0^2)^{1/2} \) is the effective characteristic frequency with \( \Omega_0 \) the frequency of the confined electron in the \( y \)-direction, \( \omega_x \) is the cyclotron frequency and \( a_w \) the effective magnetic length.

Furthermore, \( \hat{H}_R(r) \) is the Rashba-spin orbit interaction

\[ \hat{H}_R(r) = \frac{\alpha}{\hbar} (\sigma_x \hat{p}_y(r) - \sigma_y \hat{p}_x(r)), \]

(6)

with \( \alpha \) the Rashba spin-orbit (RSO) coupling constant that can be tuned by an external electric field, and \( \sigma_x \) and \( \sigma_y \) the Pauli matrices. The last term of Eq. (2) is \( \hat{H}_{ee} \) which accounts for the electron-electron interaction of the quantum ring system [17, 18]. The Hamiltonian presented in Eq. (1) is used to obtain the energy spectrum of the quantum ring-cavity system using a numerically exact diagonalization technique [19, 20].

2.2. Transport Formalism

To describe the transient electron transport through the quantum ring system, we use a time-convolution-less generalized master equation (TCL-GME) [21, 22, 23]. The TCL-GME is local in time and satisfies the positivity for the many-body state occupation described by the reduced density operator (RDO). The RDO of the system quantum ring system \( \hat{\rho}_S \), in terms of the total density matrix \( \hat{\rho}_T \), is defined as

\[ \hat{\rho}_S(t) = \text{Tr}_l [\hat{\rho}_T(t)], \]

(7)

where \( l \in \{ L, R \} \) indicates the two electron reservoirs, the left (L) and the right (R) leads, respectively.

In our study, we integrate the GME to the point in time \( t = 220 \) ps, late in the transient regime when the total system is approaching the steady state.

The RDO is utilized to calculate the spin-polarization and thermospin current. We define the spin polarization \( \hat{S}_i \) of the quantum ring system in \( i = x, y, z \) direction. Thus, the spin polarization operator is

\[ \hat{S}_i = \int d^2r \hat{n}^i(r), \]

(8)

with \( \hat{n}^i(r) \) the spin polarization density operator for the spin polarization \( \hat{S}_i \) [24]. In addition, the top local thermospin current (\( I^{th,i}_t \)) through the upper arm \( (y > 0) \) of the quantum ring system can be introduced as

\[ I^{th,i}_t(x) = \int_0^\infty dy \hat{j}^{th,i}_x(x, y, t), \]

(9)

and the bottom local thermospin polarization current (\( I^{th,i}_b \)) through the lower arm \( (y < 0) \) of the quantum ring system

\[ I^{th,i}_b(x) = \int_{-\infty}^0 dy \hat{j}^{th,i}_x(x, y, t), \]

(10)

where the spin polarization current density is

\[ \hat{j}^{th,i}(r, t) = \left( \hat{j}^{th,i}_x(r, t) \hat{j}^{th,i}_y(r, t) \right) = \text{Tr} \left[ \hat{\rho}_S(t) \hat{j}^{th,i}(r) \right], \]

(11)

calculated by the expectation value of the spin polarization current density operator [24].
Finally, the total local (TL) thermospin polarization current is obtained from the top and the bottom thermospin current polarization

\[ I_{tl}^{th,i}(t) = I_{t}^{th,i}(t) + I_{b}^{th,i}(t). \]  

(12)

The TL-thermospin current is related to non-vanishing spin-polarization sources, and the circular local (CL) thermospin polarization current is

\[ I_{cl}^{th,i}(t) = \frac{1}{2} \left[ I_{t}^{th,i}(t) - I_{b}^{th,i}(t) \right]. \]  

(13)

In the result section, we present the main results on the thermospin transport in the quantum ring system and the influence of the photon field on the quantum ring system.

3. Results

In this section the numerical results are shown for a ring-cavity system including the Rashba spin-orbit interaction and the electron-photon interaction. The quantum ring and the leads are made of a GaAs-based material with electron effective mass \( m^* = 0.067 m_e \) and the relative dielectric material \( \kappa = 12.4 \).

An external perpendicular magnetic field with strength \( B = 10^{-5} \text{T} \) is applied to the total system including the leads. We assume a very weak external magnetic field to avoid spin degeneracy, and have it weak enough to prevent creating a circular motion due to a Lorentz force in the quantum ring system. The main goal of the study here is to show the “real” circular local (CL) thermospin current due to the Rashba effect in the quantum ring system. Therefore we choose the low strength of the external magnetic field and tune the Rashba coupling constant. This assumed external magnetic field is out of the Aharonov-Bohm (AB) regime because the area of the ring structure is \( A = \pi a^2 \approx 2 \times 10^4 \text{nm}^2 \) leading to a magnetic field \( B_0 = \phi_0 / A \approx 0.2 \text{ T} \) corresponding to one flux quantum \( \phi_0 = h c / e \) [22, 25].

The ring system is parabolically confined in the \( y \)-direction with characteristic energy \( h \Omega_0 = 1 \text{ meV} \). It gives a broad quantum ring. However, the broad ring geometry together with the spin degree of freedom, and the spin-orbit interactions require a substantial computational effort. Transport properties linked to spin-orbit interactions can be clearly realized in a broad quantum ring.

It is assumed that the cavity initially contains one photon with linear polarization. It is also considered that the left and the right leads have the same chemical potential \( \mu_L = \mu_R = \mu \), but are at different temperatures, which induce a thermal transport in the quantum ring system.

3.1. Energy spectrum

The potential defining the quantum ring system and its energy spectrum are demonstrated here. Figure 1 shows the potential of the ring where the top arm is located in the positive \( y \)-axis and the bottom arm is in the negative \( y \)-axis. It should be mentioned that the electrons are mainly transferred through the ring system in the \( x \)-direction by the thermal bias.

The energy spectrum of the quantum ring system as a function of the photon energy is plotted in Fig. 2, where the electron-photon coupling strength is \( g_\gamma = 0.05 \text{ meV} \) and the photon is linearly polarized in the \( x \)-direction. The Rashba coupling constant is fixed at \( \alpha = 14.0 \text{ meV nm} \), which is a critical value of the Rashba coupling constant described later. The energy states around 0.885 meV and 1.112 meV are the one-electron ground state (GS) and the first-excited state (FES), respectively. The aforementioned states are double states due to the spin-orbit interaction including both spin-up and spin-down states. The energy of the second-excited state (SES) is monotonically increased with increasing photon energy. The energy value of the SES is 1.4 meV at photon energy \( h \omega_\gamma = 0.3 \text{ meV} \) and it is enhanced to 1.9 meV at \( h \omega_\gamma = 1.0 \text{ meV} \). In addition, the SES is in resonant with the first photon replica of the ground state (GS). The energy value of \( \gamma \text{GS} \) is 1.2 meV at \( h \omega_\gamma = 0.3 \text{ meV} \) and it becomes 1.49 meV at \( h \omega_\gamma = 1.0 \text{ meV} \). The resonant states, the SES and the \( \gamma \text{GS} \), form a Rabi-splitting (RS) in the energy spectrum. The strongest Rabi-effect is recorded at the photon energy \( \approx 0.55 \text{ meV} \) (black arrows).

We study the thermospin transport in the strong Rabi effect regime. Therefore, we fix the photon energy at \( h \omega_\gamma = 0.55 \text{ meV} \) in our calculations from now on, and investigate the properties of the thermospin transport of the system. The many-electron (ME) energy (a) and the Many-Body (MB) energy (b) for the photon dressed electron states of the quantum ring system versus the RSO-coupling are shown in Fig. 3. In the absence of the cavity (Fig. 3(a)), the energy of the one-electron states decreases with increasing RSO-coupling and crossings of the one-electron states are formed at \( \alpha \approx [10 - 15] \text{ meV nm} \). The crossing of the states corresponds to the Aharonov-Casher (AC) destructive phase interference in the quantum ring.

![Figure 1](image1.png)

**Figure 1**: (Color online) The potential \( V_r(r) \) defining the central ring system that will be coupled diametrically to the semi-infinite left and right leads in the \( x \)-direction.
For the three lowest energy states of the quantum ring system, the photon field does not play an important role in the transport. In our study, we focus on the three lowest degenerate energy states which are the terms of the GS at $E_{GS} \approx 0.88$ meV, FES at $E_{FES} \approx 1.112$ meV, and SES at $E_{SES} \approx 1.47$ meV, respectively.

The MB-energy spectrum of the quantum ring system in the presence of the cavity is shown in Fig. 3(b) where the photon energy is $\hbar \omega_0 = 0.55$ meV and electron-photon coupling strength $g_e = 0.05$ meV. Comparing to the ME-energy shown in Fig. 3(a), in addition to the degenerate states, the photon replica states are formed. The energy spacing between the photon replicas is approximately equal to the photon energy at low electron-photon coupling strength $g_e = 0.05$ meV. For instance, the $\gamma_{GS}$ is formed near the SES and the energy spacing between GS and SES is approximately equal to the photon energy $E_{SES} - E_{GS} \approx \hbar \omega_0 = 0.55$ meV. Under this condition, the quantum ring system is resonant with the photon field [15]. In addition, we should mention that the first subband energy of the semi-infinite leads is located at 1.0 meV (not shown). Therefore, the GS energy of the quantum ring system does not play an important role in the transport.

In addition, the range of RSO is $\alpha = [0 : 24]$ meV nm which is a reasonable and applicable range for GaAs materials. The parameter $\alpha$ depends on the electric field. An electric field can be generated in a heterostructure with two layers either by the intrinsic potential at the interface or as an external field. The Rashba parameter depends on that electric field, and thus it can be varied in the selected range here [24, 26].

Figure 3: (Color online) Many-Electron (ME) energy spectrum (a) and Many-Body (MB) energy spectrum (b) of the ring system versus the Rashba spin-orbit (RSO) coupling constant ($\alpha$). The green rectangles show the GS, FES and SES at $E_{GS} \approx 0.88$ meV, $E_{FES} \approx 1.112$ meV, and $E_{SES} \approx 1.47$ meV, respectively.

3.2. Transport properties in the absence of the cavity

In this section we investigate the transport properties of the quantum ring system without the photon field. To calculate the spin-polarization and the thermospin current for the three lowest energy states, the chemical potential of the leads is fixed at $\mu_L = \mu_R = 0.91, 1.112$ and $1.47$ meV for the GS, FES and SES calculations, respectively. The spin polarization, $S_z$ (a), $S_y$ (b) and $S_x$ (c), of the electrons versus the RSO-coupling constant is shown in Fig. 4 for the three lowest energy states of the quantum ring system without the photon field. The non-vanishing spin-polarization in the range of $\alpha = [10 - 15]$ meV nm corresponds to the location of degenerate energy states (crossing energy states) shown in Fig. 3(a) and the destructive AC interference. Furthermore, it appears that the spin-polarization in both $x$- and $z$-directions is much smaller than that of $y$-direction ($\sim 10$ times smaller) in the selected range of the Rashba coupling constant [1 15] meV nm. The reason is that the main transport and canonical momentum are along the $x$-direction, and thus the effective magnetic field of Rashba effect should be parallel to the $y$-direction. As a result, a higher spin-polarization in the $y$-direction ($S_y$) is induced in the system [22, 24].

We note that the spin-polarization of the GS (blue rectangles) are very small comparing to the FES and SES which is due to the position of the GS located below the first subband of the leads. In addition, the spin-polarization of the FES is higher than that of the SES.

Since the $S_y$ is dominant in the quantum ring system comparing to both the $S_x$ and $S_z$, we only focus on the...
especially in the ranges of the properties. Since the FES and SES are the most active states of the quantum ring system without the photon field, the Rashba effective magnetic field should be parallel to the Rashba polarization should increase with the transfer between the GS and the SES. We can thus say that the SES of the quantum ring system is resonant in the presence of the photon field. The temperature of the left (right) lead is fixed at $T_L = 0.41$ K ($T_R = 0.01$ K) implying a thermal energy $k_B T_L = 0.35$ meV ($k_B T_R = 0.00086$ meV), respectively. The magnetic field is $B = 10^{-5}$ T, and $\hbar \Omega_0 = 1.0$ meV.

Figure 4: (Color online) Spin polarization $S_x$ (a), $S_y$ (b) and $S_z$ (c) of the quantum ring system without the photon field versus the RSO-coupling constant. The temperature of the left (right) lead is fixed at $T_L = 0.41$ K ($T_R = 0.01$ K) implying a thermal energy $k_B T_L = 0.35$ meV ($k_B T_R = 0.00086$ meV), respectively. The magnetic field is $B = 10^{-5}$ T, and $\hbar \Omega_0 = 1.0$ meV.

3.3. Transport properties in the presence of the cavity

We now assume the quantum ring system is coupled to the photon field. The energy spectrum of the ring-cavity system was shown in Fig. 3(b) where the photon field is linearly polarized in the $x$-direction. The cavity forms photon replica states influencing the thermospin transport properties. Since the FES and SES are the most active state in transport, we focus only on the transport properties of these two states here. We fix the chemical potential of the leads at $\mu_L = \mu_R = 1.112$ meV for the FES and 1.47 meV for the SES calculations. The photon energy is fixed at 0.55 meV which is approximately equal to the energy spacing between the GS and the SES. We can thus say that the SES of the quantum ring system is resonant with the photon cavity while the FES is off-resonant. Figure 6 shows the $S_y$ spin polarization of the quantum ring system without (w/o ph) and with (w ph) photon field. We have mentioned, that in the absence of the photon, the Rashba effective magnetic field should be parallel to the $y$-direction and induce a spin polarization in the $y$-direction. In the presence of the photon field, a kinetic momentum in the $x$-direction is added to the electrons (see Eq. (4)), therefore, the $S_y$ spin polarization should increase with the $x$-polarized photon field. This can be clearly seen in the $S_y$ spin polarization of the FES, off-resonant regime. But in the on-resonant regime, the $S_y$ spin polarization of the SES is slightly decreased in the presence of the photon field which is a direct consequence of the Rabi effect. Similar effect has been observed for the thermoelectric current in a quantum wire [13].

Figure 7 indicates the TL-Thermospin current (a) and CL-Thermospin current (b) of the quantum ring system versus the RSO-coupling for both FES and SES. The photon field causes to decrease the CL-Thermospin current while the TL-Thermospin current is almost unchanged. The suppression of CL-Thermospin of the FES, off-resonant regime, is due to the enhancement of the spin-polarization shown in Fig. 6 especially in the ranges of the degenerate energy states ($\alpha = [10 - 15]$ meV nm).

It is interesting to see the resonant regime. The spin
polarization of the SES is decreased in the presence of the cavity as is shown in Fig. 6, the CL-Thermospin current of the SES is also decreased. In addition to the $S_y$ spin polarization that is used to explain the characteristics of the thermospin current, the photon replica states play an important role in the properties of the thermospin current. In the resonant regime, the $\gamma GS$ together with a SES form a Rabi-split pair (see Fig. 2) and contribute to the transport. As a result, the participation of the $\gamma GS$ to the transport decreases the CL-Thermospin current.

To further show the influences of the photon field on thermospin transport, we present Fig. 8 which shows the TL-Thermospin current (a) and CL-Thermospin current (b) of the SES (on-resonance regime) as a function of the RSO-coupling for different values of the electron-photon coupling strength $g_r$. Both the TL-Thermospin and CL-Thermospin currents are suppressed with increasing electron-photon coupling strength. This reduction in the TL- and CL-Thermospin currents is a direct consequence of the Rabi-splitting of the energy levels of the quantum ring system in which the energy spacing between the SES and $\gamma GS$ shown in Fig. 2 and Fig. 3(b) is increased at high electron-photon coupling strength [13]. Therefore, the TL- and CL-Thermospin currents decrease.

4. Conclusions

In summary, we have demonstrated properties of a thermospin transport through a quantum ring coupled to a photon cavity. In the absence of the photon field, thermospin current is induced at a low temperature gradient of the reservoirs that are connected to the quantum ring system. Tuning the Rashba spin-orbit coupling, degenerate energy states are formed. It is observed that spin-polarization is maximum at the point of degenerate energy states corresponding to the AC destructive interference. In the presence of the photon field, the thermospin transport can be controlled using a single photon mode in the cavity. Two regimes, off- and on-resonant regimes, are studied. In the resonant regime, when the photon energy is approximately equal to the two lowest energy state of the quantum ring system, photon replica states are formed...
and the spin polarization is sufficiently enhanced. Tuning the electron-photon coupling strength, the energy spacing between the states is increased leading to a suppression of the thermospin transport which is a direct consequence of the Rabi-splitting.

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