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Optimum energy conversion strategies of a nano-scaled three-terminal quantum dot thermoelectric device

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ABSTRACT

A model of the three-terminal nano-scaled energy conversion system as a heat engine based on two capacitively coupled quantum dots in the Coulomb-blockade regime is established within four quantum states that include the essential physical features. The dynamical properties of the model are calculated by master equation approach account for the quantitative behavior of such a system. Expressions for the power output and efficiency of the three-terminal quantum dot heat engine are derived. The characteristic curves between the power output and the efficiency are plotted. Moreover, the optimal values of main performance parameters are determined by the numerical calculation. The influence of dissipative tunnel processes on the optimal performance is discussed in detail. The results obtained here can provide some theoretical guidelines for the design and operation of practical three-terminal quantum dot heat engines.

1. Introduction

In recent years, investigations on the thermoelectric effects of nano-thermoelectric devices have attracted considerable interest due to their importance in developing miniaturized devices which help to utilize energy resources at the microscopic scale [1–5]. In particular, there is broad, current interest in developing high performance thermoelectric materials for the generation of electric power from heat sources such as waste heat. It was pointed out that structures of reduced dimension can give rise to an increased thermoelectric figure of merit ZT as compared to bulk structures made from the same materials [6,7] and that sharp spectral features can improve thermoelectric performances characterized by a high value of ZT in materials with a delta-like density of states [8]. Furthermore, it was reported that the Carnot efficiency can be reached for reversible electron transport between two reservoirs at different temperatures and chemical potentials by using a sharply tuned energy filter for which the electron density is the same in both reservoirs [9–11].

Quantum dots naturally provide these sharp spectral features. Hence, there are many investigations of the quantum dot thermoelectric devices because quantum dots can be applied to the high-potential solid-state energy conversion devices [12–15]. Hence, the study of nano-thermoelectric heat engines and refrigerators using the quantum dot system as the working substance embedded between two reservoirs at different temperatures and chemical potentials has attracted considerable interest [16–21]. In two-terminal nano-thermoelectric device, when both the gradients of temperature and chemical potential are applied to the device and the thermoelectric response as heat engines and refrigerators is investigated, it is found that the heat flow will be accompanied by the electron current. But, for the purpose of energy harvesting, it suffers from the fact that the different parts of the thermoelectric response must be at different temperatures which make thermal isolation difficult [22]. Hence, some theoretical works on the thermoelectric effects in three-terminal quantum dot devices have attracted considerable interest [23–33]. This is because that such a three-terminal thermoelectric device offers the advantage of spatially separating the hot and cold reservoirs and exhibits a crossed flow of heat and electric currents. This is useful for energy harvesting applications because such a three-terminal thermoelectric device can be driven by electronic sources [23–25], phonon sources [26–28], or photon sources [29–31]. The maximum power output and efficiency of a mesoscopic heat engine based on a hot chaotic cavity capacitively coupled to a cold cavity were investigated [24]. A resonant-tunneling quantum dot heat engine was researched. Such a heat engine converts a part of the heat into electrical current in a three-terminal geometry which permits one

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Nomenclature

T	temperature (K)
U	Coulomb interaction (J)
ZT	figure of merit
C	capacitance (F)
$\tilde{C}$	effective capacitance (F)
Ω	normalization factor
Γ	transition rate
p	occupation probability
I	charge currents (W)
Q	heat flow (W)
η_C	Carnot efficiency
η	efficiency
η_{max}	maximum efficiency
η_{mP}	efficiency at maximum power output
P	power output (W)
P_{max}	maximum power output (W)
$P_{m\eta}$	power output at maximum efficiency (W)
ΔV	voltage output (V)
ΔV_{open}	open circuit voltage (V)
ΔV_P	optimum voltage output at maximum power output (V)
ΔV_η	optimum voltage output at maximum efficiency (V)
k_B	Boltzmann's constant (J × K^{-1})
q	elementary charge (C)

Greek letters

μ	chemical potential (J)
ε	single energy level (J)
$\hbar$	reduced Planck constant (J × s)
λ	dissipation factor
γ	bare tunneling rate
Δ	difference
α	quantum dot

Subscripts

s	conductor dot
g	gate dot
n	electron occupation number
l	left side reservoir
r	right side reservoir
max	maximum
$m\eta$	maximum efficiency
mP	maximum power
opt	optimal

to separate current and heat flows. This provides an option to highly efficient solid-state energy harvesting [25]. Soon after, Sothmann et al. investigated a heat engine consisting of a single-level quantum dot coupled to two ferromagnetic metals and one ferromagnetic insulator held at different temperatures and demonstrated that in the tight-coupling limit the device can reach the Carnot efficiency [28]. Photon-driven heat engines or refrigerators were also studied [29–33]. Rutten et al. used the quantum dot structure to design a photoelectric device as a heat engine and studied the thermodynamic efficiency of the heat engine [29]. Ruokola et al. theoretically researched single-electron heat engines coupled to electromagnetic environments and predicted that high efficiencies are possible with the quantum dot system [30]. Only recently, a possibly realized hybrid microwave cavity heat engine consisting of two macroscopically separated quantum dot conductors coupled capacitively to the fundamental mode of a microwave cavity was proposed. Such a heat engine can reach the Carnot efficiency when the optimal conversion is achieved [31].

The thermoelectric properties of two capacitively coupled quantum dots in the Coulomb-blockade regime in a three-terminal nano-sized structure thermoelectric system were firstly analyzed by Sánchez et al. [23]. They showed that such a system can be used to transform a part of the heat flowing from a hot reservoir into electric current. Furthermore, they demonstrated that a three-terminal heat engine can act as an ideal thermal-to-electric energy converter that can reach the Carnot efficiency. But, these authors only considered the ideal situation and ignored many non-ideal factors. Thus, it is lack of practical guidance significance for actual engine devices. On the basis of the previous works, the main focus in this paper is to analyze the performance characteristics of a thermoelectric quantum dot heat engine, to discuss the influence of dissipative tunnel processes on the performance in detail, and to optimally design the main parameters of the heat engine.

This paper is organized as follows. In Section. 2, we briefly describe the model and basic physical theory of a three-terminal quantum dot thermoelectric heat engine. In Section. 3, we investigate the performance characteristics of the heat engine in different dissipative tunnel processes. The influence of dissipative tunnel processes on the optimal performance of the heat engine is discussed in Section. 4. Finally, the main results are summarized in Section. 5.

2. Model and theory

The model of a three-terminal quantum dot heat engine is illustrated in Fig. 1, where the system consists of three independent electron reservoirs and two quantum dots. The conductor dot s is coupled to two reservoirs via two tunnel contacts which permit particle and energy exchange between the left reservoir at temperature T_l and potential μ_l and the right reservoir at temperature T_r and potential μ_r. The gate dot g is coupled to a single gate reservoir with temperature T_g and potential μ_g. U is the long-range Coulomb interaction between the electrons of the conductor dot s and the

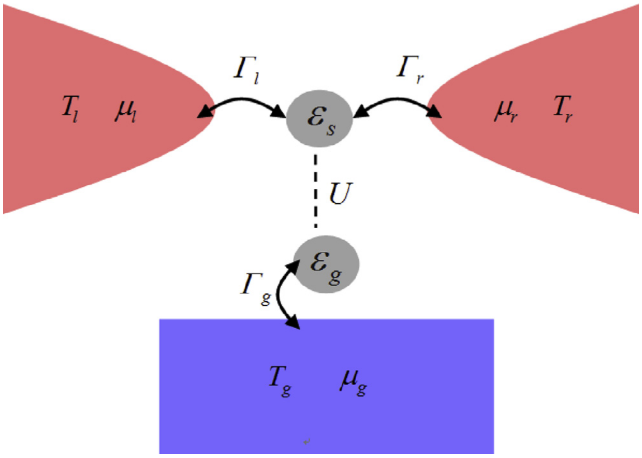

Fig. 1. The schematic diagram of a three-terminal quantum dot thermoelectric device.