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Thermodynamic performance characteristics of a three-terminal quantum dot hybrid thermoelectric heat engine

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ABSTRACT

We propose a new model of the three-terminal quantum dot hybrid thermoelectric heat engine in which the electrons transfer between two electronic terminals at different temperatures and chemical potentials through two coupled single-level quantum dots. Based on master equation we derive the expressions for the output power and the efficiency. The working region of the hybrid heat engine is determined according to the first and second law of thermodynamics. The performance characteristic curves are plotted and the optimal performance parameters are obtained. Finally, the influence of the non-radiative effect on the optimal performance parameters is discussed in detail.

1. Introduction

Thermoelectric energy harvesters using nanostructured materials have recently attracted great interest because they can convert waste heat from the environment into practical electrical power [1–4]. In particular, a three-terminal structure used in these energy harvesters can separate paths of charge current and heat current. Therefore, thermal isolation and high conductivity can be simultaneously realized. Conversion efficiency of heat to electricity can be efficiently increased. A three-terminal quantum dot device is experimentally demonstrated and a separation of charge and heat flow is realized [5,6].

In 1993 Edwards et al. firstly proposed the theoretical model of the three-terminal quantum dot refrigerator which utilizes the discrete energy levels of quantum dots to customize the electronic Fermi–Dirac distribution, cooling a small reservoir to far below the ambient temperature [7,8]. Prance et al. presented experimentally measurements of a QDR designed to cool a $6\mu m^2$ electron gas, and significant electro-static interactions were observed in this device [9]. Jordan et al. proposed a three-terminal heat engine with resonant-tunneling dots/wells and obtained the maximum power and the corresponding efficiency [10,11]. Similarly, the three-terminal thermoelectric devices with ideal resonant-tunneling quantum dots have been studied [12–14]. Jiang et al. proposed a scheme of multilayer thermoelectric engine where one electric current is coupled to two temperature gradients in three-terminal geometry and demonstrated cooperative effect to effectively improve performance of the thermoelectric engine [15,16]. The thermoelectric properties of two capacitively coupled quantum dots in the Coulomb-blockade regime in a three-terminal thermoelectric heat engine or refrigerator have been analyzed [17,18]. Using a photon reservoir as the third terminal, Rutten et al. first proposed a nanosized quantum dot photoelectric device and analyzed its efficiency and power. They showed that the device can operates reversibly in thermodynamically strong coupling when nonradiative recombination processes are absent [19]. Cleuren et al. designed refrigeration processes powered by photons, i.e. cooling-by-heating (CBH), in which the bias voltage between two electronic terminals is kept zero [20]. We further proposed a hybrid driven photoelectric refrigerator when the bias voltage is nonzero [21] and a simple photoelectric refrigerator driven by photons when nonradiative recombination processes is considered [22]. Lately, a lot of

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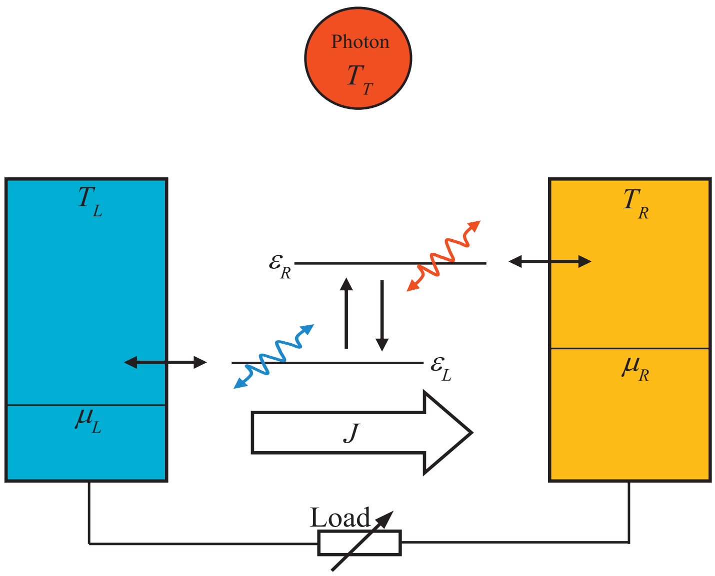

Fig. 1. The schematic diagram of three-terminal quantum dot hybrid thermoelectric heat engine. The dark arrows show the different allowed electron transitions. Transitions between the left and the right energy levels induced by thermal photons, and non-radiative processes are indicated by an upper curly red arrow and a lower curly blue arrow, respectively. The overall electron current through the heat engine is shown by the hollow arrow with "J". The left and right electronic terminals are connected by an external circuit with a load. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

other three-terminal thermoelectric devices have been studied and many novel results are obtained [23–29].

On the bases of the previous works, we propose a new model of the hybrid thermoelectric heat engine using quantum dots. The main focus in this paper is to analyze the thermodynamic performance characteristics and optimal performance parameters of the hybrid heat engine and to determine its working region. This paper is organized as follows. In Section 2, we briefly describe the model and basic physical theory. In Section 3, we determine the working region of the heat engine and study its performance characteristics. In Section 4, the influence of the non-radiative effect on the optimal performance parameters of the hybrid heat engine is discussed in detail. Finally, the important results of this paper are summarized in Section. 5.

2. Model and theory

A three-terminal quantum dot hybrid thermoelectric heat engine we consider is illustrated in Fig. 1. Two coupled single-level quantum dots with energy levels ε_L and ε_R ($\varepsilon_L < \varepsilon_R$) are connected with left (right) electronic terminal at temperature $T_L(T_R)$ and chemical potential $\mu_L(\mu_R)$, respectively. The single energy level $\varepsilon_L(\varepsilon_R)$ is near the Fermi level of the left (right) electronic terminal, and we define the energy level difference $\varepsilon_g = \varepsilon_R - \varepsilon_L$. The left (right) quantum dot with energy level $\varepsilon_L(\varepsilon_R)$ can only exchange electrons with the left (right) electronic terminal. The left and right terminals are connected by an external circuit with a load. We suppose that Coulomb interactions prevent two electrons from being present at the same time. Thus, the single energy level $\varepsilon_L(\varepsilon_R)$ can be occupied only by zero or one electron with respective probabilities p_i with $i \in \{0, L, R\}$. Electron transitions between the two energy levels ε_L and ε_R are induced by two possible mechanisms: the first is due to the incoming photons (the photon terminal with temperature kept at T_T) radiation at the resonant energy of $\varepsilon_g = h\nu$; the second is due to non-radiative processes at the same resonant transition. The relation among the temperatures of the three terminals satisfies $T_L < T_R < T_T$. Driven by thermal photons, electrons can be transmitted from the left terminal to the right terminal via the left and right quantum dot and come back to the left terminal through the external circuit, forming a net circulation of electrons.

The dynamics of the left and right quantum dots is described using master equation formulation for driven open systems [19,20]. The evolution of the probabilities p_0, p_L, and p_R to find no electron or one electron in energy level ε_L or ε_R, respectively, with time is given by

$$\begin{bmatrix} \dot{p}_0 \\ \dot{p}_L \\ \dot{p}_R \end{bmatrix} = \begin{bmatrix} -k_{L0} - k_{R0} & k_{0L} & k_{0R} \\ k_{L0} & -k_{0L} - k_{RL} & k_{LR} \\ k_{R0} & k_{RL} & -k_{0R} - k_{LR} \end{bmatrix} \begin{bmatrix} p_0 \\ p_L \\ p_R \end{bmatrix}. \tag{1}$$

At the steady state, i.e. $\dot{p}_0 = \dot{p}_L = \dot{p}_R = 0$, and the probabilities meet $p_0 + p_L + p_R = 1$. The occupation probabilities of each state are derived as

$$p_0 = \frac{k_{0L}k_{0R} + k_{RL}k_{0R} + k_{0L}k_{LR}}{\Omega}, \tag{2a}$$