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Parametric selection criteria of thermal electron-tunneling amplifiers operating at optimum states

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ABSTRACT

A new model of the thermal amplifier consisting of three electronic reservoirs connected by two energy filters and an electronic conductor with negligible resistance is proposed. The thermal amplifier may have two different connective methods and can be regarded as the equivalent system composed of an energy selective electron (ESE) heat engine and an ESE heat pump. With the help of the theory of the ESE devices operating between two electronic reservoirs, the coefficient of performance and rate of heat-pumping of the thermal amplifier are directly derived. The effects of the center energy levels and the half width (or the half width at the half maximum) of two energy filters on the performance of the thermal amplifier are discussed. The maximum coefficient of performance and rate of heat-pumping are calculated. The optimally operating regions of the thermal amplifier are determined. Moreover, the optimum performance characteristics of the thermal amplifier with two configurations of energy filters are compared.

1. Introduction

The studies of thermoelectric devices [1–4] have attracted huge interest due to their potential advantages over other energy converters, including lack of moving parts, no noise, possible miniaturization, and few pollutions to the environment. However, bulk thermoelectric materials generally suffer from the disadvantage of very low thermoelectric conversion efficiency, which limits the practical uses of thermoelectric devices [5–7]. The nanoscale thermoelectric materials have a higher value of the figure of merit ZT [8–11] compared to bulk thermoelectric materials because the nanoscale thermoelectric materials can efficiently reduce the heat conductivity of materials [12–14] and increase the Seebeck coefficient [15,16] and electrical conductivity of materials [17–19]. Recent developments in nanotechnology make it possible to produce high performance micro/nano-scale thermoelectric materials [14,20–24] with practical nanostructures such as nanowires [14,25], nanoribbons [26,27], and nanotubes [28] and offer solutions to the problem of low efficiencies of thermoelectric devices.

Thermoelectric devices can be used as power generators [29–32], refrigerators [33–36], or heat pumps [37–40] via the transport of electrons. The energy selective electron (ESE) devices are a class of recently developing thermoelectric devices [41–45], which operate under a temperature and a chemical potential gradient. When high-energy electrons flow from the hot reservoir to the cold reservoir against chemical potential gradient, the device works as a power generator [41,44,46]. In contrary, when high-energy electrons are driven from the cold reservoir to the hot reservoir along chemical potential gradient, it may work as a refrigerator [45,47] or a heat pump [38]. In order to reduce the irreversible losses and enhance the thermoelectric conversion efficiency, energy selection mechanisms [48–50] are needed to specify the probability for the electrons transmitted between the cold and the hot reservoirs.

In order to make one ESE device operate continuously, it is important to maintain a steady electronic current in the device. In traditional ESE refrigerators or heat pumps, this is usually realized by applying an external voltage between the cold and the hot reservoirs [38,51,52]. In the present paper, we propose a new model of the ESE devices, in which the electronic current is driven by a hot electronic reservoir instead of an external bias. The proposed model mainly consists of three electronic reservoirs at different temperatures and two energy filters. The heat flow is amplified by harvesting thermal energy from the cold reservoir, so that such a device may be referred to as a thermal ESE amplifier, which may be equivalent to a coupling system [53] consisting of an ESE heat pump [38] driven by an ESE heat engine [54]. Based on the proposed model and the theory of ESE heat engines and heat pumps, the coefficient of performance and rate of heat-pumping of the thermal amplifier are derived and the performance characteristics of the device are revealed. Moreover, the influence of the

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Nomenclature

f_i	Fermi-Dirac function
f_l	Fermi integral
g_n	parameters defined in Eq. (14)
h	Planck constant, J s^{-1}
k_B	Boltzmann constant, J K^{-1}
q	net heat flux, J s^{-1}
q_M	rate of heat-pumping, J s^{-1}
$q_{M,m}$	rate of heat-pumping at maximum COP, J s^{-1}
$\dot{S}$	overall entropy production rate, J K^{-1} s^{-1}
T	temperature, K

Greek symbols

δ	half width (or half width at high maximum) of energy filter, eV
ε^0	reversible energy level, eV
ε	center energy level of energy filter, eV
η	efficiency
φ	COP of heat pump
ψ	COP of amplifier
ψ_m	COP at maximum rate of heat-pumping
μ	chemical potential, eV

Subscript

C	reservoir *C*
H	reservoir *H*
i	H, M, C
j	H, C
l	1, 2
M	reservoir M
max	maximum
n	1, 2, …, 6
r	reversible

Abbreviations

COP	coefficient of performance
ESE	energy selective electron

different transmission functions of energy filters on the performances of the device is investigated and the configuration of the device is optimally designed.

2. Model description

The thermal amplifier considered here consists of three electronic reservoirs connected by two energy filters and an electronic conductor with negligible resistance, as shown in Fig. 1, where the temperatures T_i $(i = H, M, C)$ and chemical potentials μ_i of three electronic reservoirs satisfy the following relations: $T_H > T_M > T_C$ and $\mu_H = \mu_C \equiv \mu_0$, and two energy filters with tunable resonant levels ε_C and ε_H can be realized by quantum dots [54–56] or superlattices [57] weakly coupled to two electronic reservoirs. This model is similar to that adopted in Ref. [58]. However, energy filters may have different configurations. Two energy filters are first assumed to be rectangular and their half width is equal to δ. Such a thermal amplifier may have two different connective methods, where one is that electrons flow from the high-temperature reservoir to the low-temperature reservoir, as shown in Fig. 1(a), and the other is that electrons flow from the low-temperature reservoir to the high-temperature reservoir, as shown in Fig. 1(b). In order to maintain the continuity of electronic currents, the conductor with negligible resistance is used to connect two electronic reservoirs *H* and *C* so that the two electronic reservoirs have a same chemical potential μ_0. Although the directions of electronic currents are dif-

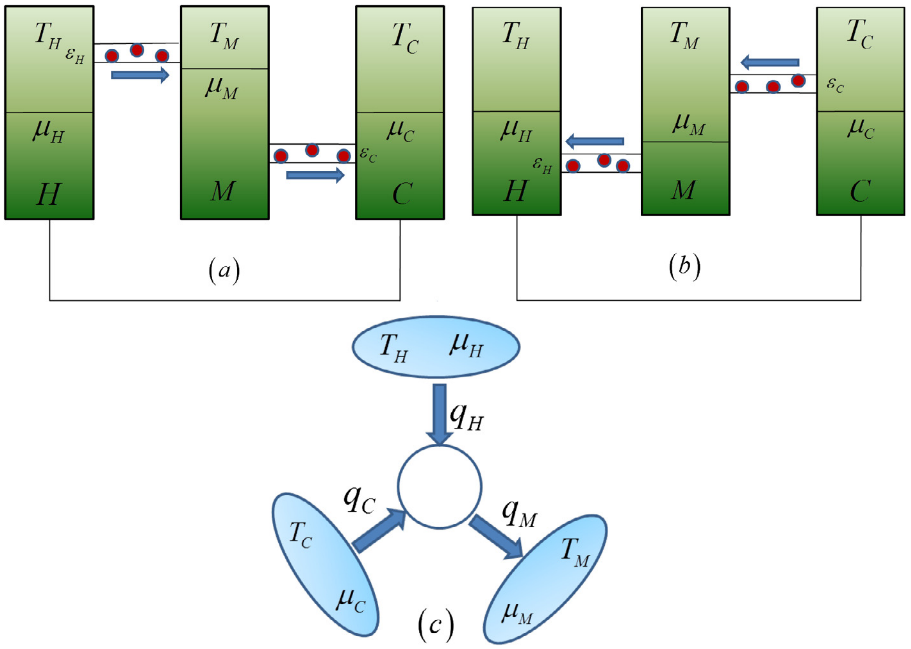

Fig. 1. The schematic diagrams of a thermal amplifier. (a) Electrons flow from the high-temperature reservoir to the low-temperature reservoir. (b) Electrons flow from the low-temperature reservoir to the high-temperature reservoir. (c) The directions of heat flows.