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Model of a total momentum filtered energy selective electron heat pump affected by heat leakage and its performance characteristics

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ABSTRACT

A total momentum filtered energy selective electron (ESE) heat pump model with heat leakage is established in this paper. The analytical expressions of heating load and coefficient of performance (COP) for both the total momentum filtered (k_r-filtered) ESE heat pump and the conventionally filtered (k_x-filtered) ESE heat pump in which the electrons are transmitted according to the momentum in the direction of transport only are derived, respectively. The optimal performance of the k_r-filtered ESE heat pump is analyzed by using the theory of finite time thermodynamics (FTT). The optimal regions of COP and heating load for the k_r-filtered heat pump are obtained. By comparing the performance of the k_r-filtered device with that of the k_x-filtered device, it is found that the heating load performance and the COP versus heating load characteristic curves of the k_r-filtered heat pump are totally different from those of the k_x-filtered device; and the maximum COP and maximum heating load of the k_r-filtered device are generally higher than those of the k_x-filtered device. The influences of heat leakage, resonance width, hot reservoir temperature and chemical potential on the performance of the total momentum filtered ESE heat pump are further analyzed by numerical calculations. The obtained results can provide some theoretical guidelines for the design of practical electron systems such as solid-state thermionic heat pump devices.

1. Introduction

In the past few years, due to their importance in the fabrication of nanosize devices which help to utilize energy resources in the microscopic scale, the study of electron engine system has attracted considerable attentions. Many new types of micro electronic energy conversion systems have been proposed [1–7] and the constructing of practical electron refrigerator has also been reported [8–10]. The model of a quantum electron heat engine or refrigerator was first presented by Humphrey et al. [11] as a reversible quantum Brownian heat engine for electrons. The theoretical electron engine model was later termed as energy selective electron (ESE) heat engine or refrigerator since an energy filter is utilized in the device to selectively transmit electrons between the two electron reservoirs [12]. Energy selectivity is a particular characteristic of the ESE engine systems. Following the pioneer work of ESE engine systems [11,12], detailed performance analysis and optimization for ESE heat engine [13], refrigerator [14–16] and heat pump [17] have been carried out by some authors and many significant conclusions have been obtained.

Recently, the finite time thermodynamic (FTT) theory, which is widely used in the performance analysis and optimization of conventional [18–33] and quantum [34–41] energy conversion systems, has also been used to study the performances of microscopic energy conversion systems, such as Brownian motors [42–47] and quantum dot engines [48–50]. The major tasks in FTT are to optimize the performance of energy conversion systems and to analyze the transport losses between the reservoirs on the optimal performance of the systems. In the ESE engine systems, the typical transport loss is the heat leakage between the two electron reservoirs due to the propagation of phonons, which has significant influence on the performance of the device. So far, the FTT theory has also been utilized to study the performance of ESE engine systems [12–17], and the performance bounds of these systems have been obtained.

In practice, the thermionic refrigerator is a typical kind of ESE engine in which an energy barrier, which may be the work function of the emitter in vacuum devices, or a wide bandgap material in solid-state heterostructure devices, is taken as the energy filter to selectively transmit high energy electrons ballistically between two

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Nomenclature

E	energy level of electrons (J)
e	charge of an electron (C)
f	Fermi distribution of electrons
h	reduced Plank constant (Js)
k_B	Boltzmann constant (J/K)
k_f	coefficient of heat leakage (W/K)
k_r	total momentum filtered device
k_x	conventional device which filters electrons according to the momentum in the direction of transport only
m^*	effective mass of electron (kg)
$\dot{N}$	electron flux
$\dot{Q}$	rate of heat transfer (W)
T	temperature (K)
V_0	bias voltage (V)
v	elocity of electrons
w	width parameter of transmission function (J^{-2})

Greek symbols

β	COP
ΔE	resonance width (J)
θ	polar angle
μ	chemical potential (J)
ξ	transmission probability
ϕ	included angle
π	heating load (W)

Superscripts

opt	double maximum value
$+, -$	increased ($+$) and lost ($-$) amounts of heat

Subscripts

C	cold electron reservoir
H	hot electron reservoir
L	heat leakage
r	k_r-filtered device
x	k_x-filtered device
0	reversible operation condition

electron reservoirs. Studies on the ESE systems have shown that the energy spectrum of the transmitted electrons has significant influence on the performance of thermionic devices [12]. The performance of solid-state [51–54] and nanometer gap vacuum thermionic refrigerators [51,55,56] can be optimized in these systems. Besides thermionic devices, the performance of solid-state thermoelectric devices [51–53], thermoelectric nanomaterials [57,58] and hot carrier solar cell [59] can also be increased by optimizing the electron energy spectrum.

In thermionic systems, an energy barrier is used to transmit or block the electrons between the electron reservoirs. O'Dwyer et al. [53] and Humphrey et al. [54] had shown that in conventional k_x-filtered thermionic devices, the electrons are transmitted according to the electron momentum in the direction of transport only, and the momentum in the other two dimensions can take any value; while in k_r-filtered thermionic devices, the transport of electrons is determined by their total momentum in all three dimensions rather than their momentum in direction of transport. It was shown that the performance of the total momentum filtered device is generally superior to that of the conventionally filtered device [53]. Theoretically, in the ESE engine systems, the mechanism of filtering electrons according to their total momentum can also be utilized to transmit electrons between the reservoirs.

This paper will take a further step to include the non-ideal effect of heat leakage and apply the total momentum filtering mechanism in an ESE heat pump. Based on Refs. [16,17,53,54], a total momentum filtered ESE heat pump model with linear heat leakage is established. Especially, the energy filter in the newly established ESE heat pump model transmits electrons according to their total momentum in all three dimensions rather than their momentum in the direction of transport only. The device can be termed as a k_r-filtered ESE heat pump. Analytical expressions of some important performance parameters, such as heating load and coefficient of performance (COP) for both k_r-filtered and k_x-filtered ESE heat pumps are derived. The optimum performance of the ESE heat pump is analyzed by using the FTT theory. The performance of the k_r-filtered ESE heat pump is compared with that of the k_x-filtered device. Moreover, the influences of heat leakage, hot reservoir temperature, hot reservoir chemical potential and resonance width on the performance of the device are discussed.

2. Model of a total momentum filtered ESE heat pump with heat leakage

The total momentum filtered ESE heat pump is composed of two infinitely large electron reservoirs and an energy filter, as shown in Fig. 1. The temperatures of the two reservoirs are T_C and T_H, and the chemical potentials are μ_C and μ_H. The two electron reservoirs are thermally insulated from each other and interact only via the energy filter which transmits electrons according to their total momentum in all three dimensions rather than the momentum in direction of transport only. In the figure, E is the central energy level of the resonance, ΔE is the resonance width of the energy filter, and eV_0 is a bias voltage that is applied to the hot reservoir.

It was shown in Refs. [11,12] that when the energy of the filter is suited to $E_0 = (T_H\mu_C - T_C\mu_H)/(T_H - T_C)$ at which the Fermi distributions in the reservoirs have the same value, the electron system will operate reversibly and its efficiency (COP) can attain the Carnot value. E_0 is the reversible operation energy point for the ESE heat engine, refrigerator and heat pump. Moreover, for the energy of the

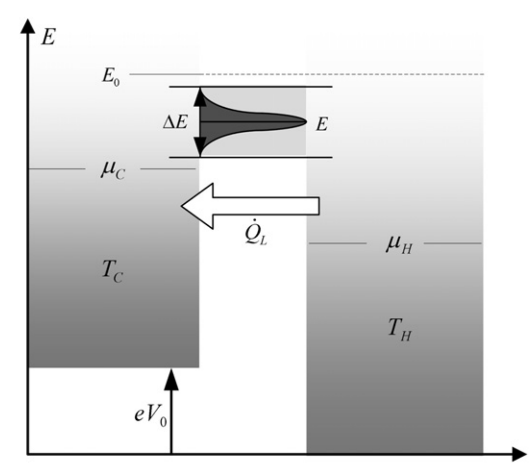

Fig. 1. Schematic diagram of a total momentum filtered ESE heat pump with heat leakage.