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An electronic cooling device with multiple energy selective tunnels

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ABSTRACT

A new model of the electronic cooling device with multiple energy selective tunnels is proposed. By connecting four electron reservoirs, a cold reservoir, a hot reservoir, and two reservoirs with the ambient temperature, via four suitably tuned energy selective tunnels to form a closed circuit, a steady current of electrons is driven and cooling is achieved by continuously extracting high-energy electrons from, and simultaneously injecting low energy electrons into, the cold reservoir. The performances of the cooling device varying with the resonant levels and half widths of energy selective tunnels are explored, and the optimal configuration of the cooling device is established.

1. Introduction

Thermoelectric devices are currently of broad interest both for solid-state cooling and for converting heat into electric power [1,2]. However, devices composed of bulk thermoelectric materials generally suffer from the disadvantage of low conversion efficiencies that limit their practical applications. Recent advances in nanotechnology have enabled production of high performance micro/nano-scaled thermoelectric materials [3–6] that are characterized by a high value of figure of merit ZT [7], and that offer solutions to the problem of low efficiencies of thermoelectric devices. It was noted that structures with reduced dimensions and a high density of interfaces realized in nanostructured materials [8–10] give rise to an increased thermoelectric figure of merit. Additionally, the use of energy selection mechanisms [11–14] can effectively improve the performances of thermoelectric devices and obtain an increased efficiency. In particular, it was predicted that by introducing a precisely tuned energy selective tunnel between the hot and the cold electronic reservoirs, thermoelectric refrigerators and power generators can be reversibly operated with the efficiency close to the Carnot value [15–18].

Thermoelectric devices using the energy selectivity of electron transport in low-dimensional systems are often referred to as the ESE (energy selective electron) devices. The existing ESE devices generally consist of two reservoirs with different temperatures and chemical potentials linked by an energy selective tunnel. When the ESE device functions as a refrigerator, an external voltage is needed to drive the electron current in the device [19–22]. In the present paper, we propose a new model of the electronic cooling device consisting of four tunable energy selective tunnels used for selecting electrons in different energy ranges for transport. The proposed model shows two main advantages over the previous ESE cooling devices: (1) the device is driven by a hot electron reservoir and no external bias is needed; (2) cooling is achieved by simultaneously extracting high-energy electrons from and injecting low energy electrons into the cold reservoir; hence, the cooling power can be doubly enhanced without reducing the COP (coefficient of performance) of the system.

2. Model and theory

The cooling device considered here consists of four reservoirs, labeled as H, C, L, and R, with temperatures T_H, T_C, and $T_L = T_R \equiv T_0$ ($T_C < T_0 < T_H$), and chemical potentials μ_H, μ_C, μ_L, and μ_R, respectively. These are thermally insulated from each other and can only exchange electrons through four energy selective tunnels with tunable resonant levels ε_{LH}, ε_{HR}, ε_{RC}, and ε_{CL}. The schematic diagram of the device is shown in Fig. 1. The temperatures T_H, T_C, and T_0 and the chemical potential $\mu_C \equiv \mu_0$ are kept constant, while the chemical potentials μ_H, μ_L, and μ_R are determined by the conservation of charges under the condition of steady current.

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Nomenclature

h	Planck constant, eV s^{-1}
k_B	Boltzmann constant, eV K^{-1}
$\dot{N}$	electron flux, s^{-1}
$\dot{N}_{ij}$	electron flux from reservoir i to reservoir j, s^{-1}
q	heat transfer associated with the addition of one electron to a reservoir, eV
$\dot{Q}$	heat flux, eV s^{-1}
$\dot{Q}_C$	cooling power, eV s^{-1}
$\dot{Q}_{C,m}$	cooling power at maximal COP, eV s^{-1}
T	temperature, K

Greek symbols

δ	half width at half maximum of energy selective tunnels, eV
δ_c	cut-off value of δ, eV
δ_m	upper bound of the reasonable region of δ, eV
$\Delta_{H/C}$	two parameters defined in Fig. 2, eV
$\Delta\dot{S}$	entropy increase rate, eV K^{-1} s^{-1}
$\Delta\varepsilon_{H/C}$	difference of resonant levels of two energy selective tunnels connected to reservoir H/C, eV
ε	energy of an electron, eV
ε_{ij}	resonant level of the energy selective tunnel between reservoirs i and j, eV
$\gamma(\varepsilon,\varepsilon_{i,j})$	transmission function
μ	chemical potential, eV
ψ	COP
ψ_m	COP at maximal cooling power

Subscripts

C	cold reservoir
H	hot reservoir
L	left
max	maximum
R	right
r	reversible

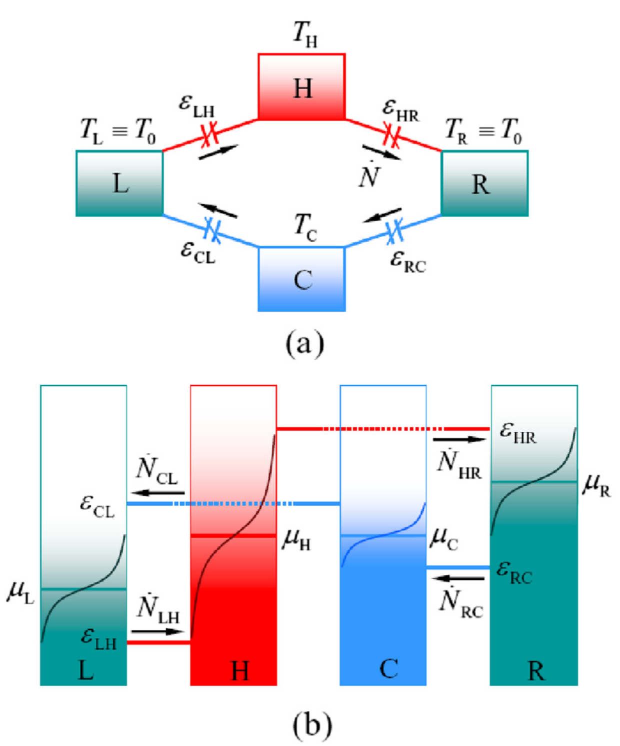

Fig. 1. Schematic diagram of an electronic cooling device. (a) Four electronic reservoirs are connected by four energy selective tunnels to form a closed circuit. (b) Resonant levels of four energy selective tunnels and Fermi-Dirac distributions and chemical potentials in four reservoirs are indicated.

It is assumed that each reservoir is in the state of equilibrium and can be described by the Fermi-Dirac distribution

$$f(\varepsilon,\mu,T) = \frac{1}{\exp[(\varepsilon-\mu)/(k_B T)]+1}, \tag{1}$$

where T and μ are the temperature and chemical potential of the reservoir and k_B is the Boltzmann constant. Additionally, the distance between each pair of reservoirs is taken to be much less than the electron mean free path for inelastic processes, so that the transport of electrons between the reservoirs can be treated as ballistic. Under this condition, the net electron fluxes transmitted from reservoir i to reservoir j are governed by the Landauer equation [23].

$$\dot{N}_{ij} = \frac{2}{h}\int\left[f(\varepsilon,\mu_i,T_i) - f\left(\varepsilon,\mu_j,T_j\right)\right]\gamma(\varepsilon,\varepsilon_{ij})\mathrm{d}\varepsilon, \tag{2}$$

where (i,j) = (L,H), (H,R), (R,C), and (C,L), h is the Planck constant, and $\gamma(\varepsilon,\varepsilon_{ij})$ is the transmission function of the energy selective tunnel between reservoirs i and j, taken as a single Lorentzian resonance

$$\gamma(\varepsilon,\varepsilon_{ij}) = \frac{1}{1+(\varepsilon-\varepsilon_{ij})^2/\delta^2} \tag{3}$$

with possibly different resonant levels ε_{ij}, but identical half width δ at half maximum for four energy tunnels.

The conservation of charges for steady currents dictates that

$$\dot{N}_{LH} = \dot{N}_{HR} = \dot{N}_{RC} = \dot{N}_{CL} \equiv \dot{N}, \tag{4}$$

by which the chemical potentials μ_H, μ_L, and μ_R can be determined for given T_H, T_C, T_0, μ_0, ε_{LH}, ε_{HR}, ε_{RC}, ε_{CL}, and δ.

The heat transfer associated with the addition of one electron carrying the energy ε to a reservoir with the chemical potential μ is $q = \varepsilon - \mu$. Consequently, the net heat fluxes transferred from reservoirs H and C are, respectively, represented by

$$\begin{aligned}\dot{Q}_H = &-\frac{2}{h}\int[f(\varepsilon,\mu_L,T_L) - f(\varepsilon,\mu_H,T_H)](\varepsilon-\mu_H)\gamma(\varepsilon,\varepsilon_{LH})\mathrm{d}\varepsilon \\ &+\frac{2}{h}\int[f(\varepsilon,\mu_H,T_H) - f(\varepsilon,\mu_R,T_R)](\varepsilon-\mu_H)\gamma(\varepsilon,\varepsilon_{HR})\mathrm{d}\varepsilon\end{aligned} \tag{5}$$

and