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Conceptual design and simulation investigation of an electronic cooling device powered by hot electrons

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ABSTRACT

Most electronic cooling devices are powered by an external bias applied between the cold and the hot reservoirs. Here we propose a new concept of electronic cooling, in which cooling is achieved by using a reservoir of hot electrons as the power source. The cooling device incorporates two energy filters with the Lorentzian transmission function to respectively select low- and high-energy electrons for transport. Based on the proposed model, we analyze the performances of the device varying with the resonant levels and half widths of two energy filters and establish the optimal configuration of the cooling device. It is believed that such a novel device may be practically used in some nano-energy fields.

1. Introduction

Thermoelectric devices can be used as power generators or refrigerators [1–3] via the transport of electrons under a temperature and/or a chemical potential gradient. The studies of thermoelectric devices (see review articles [4–7] and references therein) have attracted significant interest due to their potential advantages over other energy converters. However, the relatively low efficiency of thermoelectric devices limits their practical applications [8]. Recent advances in nanotechnology make it possible to produce micro/nano-scaled thermoelectric materials [9,10], which may offer solutions to the present bottleneck of thermoelectric devices for practical uses. By controlling the transport of phonons and electrons in superlattices, thin-film thermoelectric materials that demonstrate a significant enhancement in the figure of merit ZT [11] were achieved at high room-temperatures [12]. An effective value of ZT up to 5 was obtained with the use of highly degenerate semiconductors or metallic superlattices and tall barriers [13]. It has been shown that a high density of interfaces in nanostructured materials can reduce the parasitic heat flow carried by the crystal lattice on a length scale comparable to the phonon mean-free path [14] and consequently increase the figure of merit of materials. In addition, the employ of energy selection mechanisms [15–18] can effectively improve the performance of thermoelectric devices and hence obtain an increased efficiency. By using a suitably chosen energy filter, Humphrey et al. [19–21] predicted that thermoelectric refrigerators and power generators can be quasistatically operated with the efficiency close to the Carnot value.

Electronic cooling in principle is the process by which high energy electrons are extracted from and/or low energy electrons injected into the cold reservoir. In order to realize this goal, a voltage is often applied to generate the directed motion of electrons in devices. In addition, energy filters are needed to limit the energy of electrons in the current in a particular range. For this reason, all cooling devices by using the transport of electrons may be referred to as energy selective electron (ESE) refrigerators.

The existing ESE cooling devices, in general, consist of two reservoirs with different temperatures connected by an energy filter and the transport of electrons is driven by an external bias applied between the cold and the hot reservoirs [22–24]. In the present paper, we propose a new model of ESE cooling devices, in which cooling is achieved by using a reservoir of hot electrons as the power source. The cooling device proposed has many advantages over conventional refrigerators, including lack of moving parts, possible miniaturization, no need for external voltage, and low working temperatures, etc. This suggests that the construction

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Nomenclature

h	the Planck constant, J s^{-1}
k_B	the Boltzmann constant, J K^{-1}
$\dot{N}_C$	net electron flux transmitted to reservoir *C*, s^{-1}
$\dot{N}_H$	net electron flux transmitted to reservoir *H*, s^{-1}
$\dot{Q}_C$	cooling power, J s^{-1}
$\dot{Q}_{C,m}$	cooling power at maximal coefficient of performance, J s^{-1}
$\dot{Q}_{C,\max}$	maximal cooling power, J s^{-1}
$\dot{Q}_H$	net heat flux transferred from reservoir *H*, J s^{-1}
$\dot{S}$	overall entropy production rate, J K^{-1} s^{-1}
T	temperature, K
T_C	temperature of electronic reservoir *C*, K
T_H	temperature of electronic reservoir *H*, K
T_M	temperature of electronic reservoir *M*, K

Greek symbols

δ	half width at half maximum of energy filters, eV
δ_c	cut-off value of half width of energy filters, eV
δ_m	up limit of the reasonable region for the half width of energy filters, eV
ε_C	resonant level of energy filter *C*, eV
ε_H	resonant level of energy filter *H*, eV
η	coefficient of performance (COP)
η_m	coefficient of performance at maximal cooling power
η_{max}	maximal coefficient of performance
η_r	reversible coefficient of performance
μ	chemical potential, eV
μ_C	chemical potential of electronic reservoir *C*, eV
μ_H	chemical potential of electronic reservoir *H*, eV
μ_M	chemical potential of electronic reservoir *M*, eV

could be practically used in micro/nano electronic settings where ultra low temperatures are needed.

2. Model description

The cooling device considered here consists of three reservoirs connected by two energy filters and an electronic conductor with negligible resistance, as shown in Fig. 1. Three reservoirs are reservoir *C* of cold electrons at temperature T_C, reservoir *H* of hot electrons at temperature T_H, and reservoir *M* of electrons at temperature T_M ($T_H > T_M > T_C$). Two energy filters, with resonant levels ε_C and ε_H, could be realized by the resonance in a quantum dot [25–27] or a superlattice [13] weakly coupled to electron reservoirs. Reservoirs *C* and *H* have the same chemical potential, which is set to be $\mu_C = \mu_H = \mu_0$, since they are connected by a resistanceless electronic conductor. Due to different temperatures and/or chemical potentials of reservoirs, an electronic current is driven in the device and the chemical potential, μ_M, of reservoir *M* is determined by the conservation of charges under the condition of steady current. Such a device may be designed to operate in two different ways as shown in Fig. 1(a) and (b).

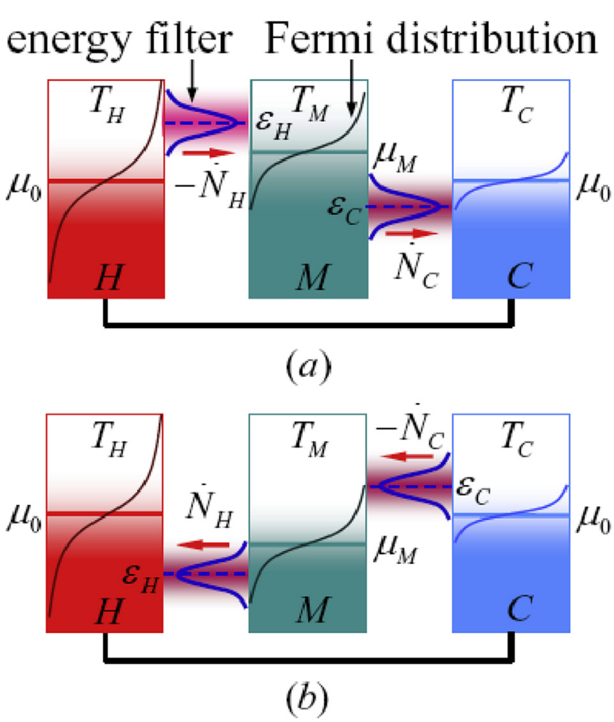

Fig. 1. The schematic diagram of an electronic cooling device powered by hot electrons. (a) Cooling is achieved by injecting low-energy electrons into the cold reservoir *C*. (b) Cooling is achieved by extracting high-energy electrons from reservoir *C*.

3. Theoretical formulation

It is assumed that the electron mean free path (EMFP) for inelastic processes is much greater than the distance between two reservoirs, so that the transfer of electrons from one to another reservoir can be regarded as ballistic. On the other hand, the EMFP is much smaller than the dimension of reservoirs, and consequently, the electrons entering reservoirs can quickly relax so as to maintain an equilibrium distribution, which is described by the Fermi-Dirac function,

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

in each reservoir, where T and μ are, respectively, the temperature and chemical potential of the reservoir and k_B is the Boltzmann constant.

Under the above assumptions, the net electron fluxes, $\dot{N}_C$ and $\dot{N}_H$, transmitted from reservoir *M* to reservoirs *C* and *H* are given by

$$\dot{N}_{C/H} = \frac{2}{h}\int \left[f(\varepsilon,\ \mu_M, T_M) - f\left(\varepsilon,\ \mu_0, T_{C/H}\right)\right]\gamma\left(\varepsilon,\varepsilon_{C/H}\right)\mathrm{d}\varepsilon \tag{2}$$

according to the Landauer equation [28], where

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

is the transmission function of each energy filter, which is assumed to take the Lorentzian form with the resonant level $\varepsilon_{C/H}$ and half width δ at half maximum. Under the condition of steady current, the conservation of charges requires

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