Energy 101 (2016) 421–426

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Performance evaluation and optimum design of a new-type electronic cooling device

Guozhen Su [a], Tianjun Liao [a], Liwei Chen [b], Jincan Chen [a, *]

[a] Department of Physics, Xiamen University, Xiamen 361005, People's Republic of China
[b] School of Mechanical & Electronic Engineering, Sanming University, Sanming 365004, People's Republic of China

ARTICLE INFO

Article history:
Received 18 October 2015
Received in revised form
5 February 2016
Accepted 8 February 2016
Available online 24 March 2016

Keywords:
Electronic cooling
Energy filter
Cooling power
Coefficient of performance

ABSTRACT

Most electronic cooling devices consist of two reservoirs linked by an energy filter, which only allows high-energy electrons to transport from the cold reservoir to the hot reservoir. Here we propose a new type of cooling device, in which a cold reservoir is connected with two hot reservoirs by two energy filters and cooling is achieved by simultaneously removing high energy electrons from and injecting low energy electrons into the cold reservoir. The effects of key parameters such as the chemical potential difference of two hot reservoirs, the center interval and half width of two energy filters, etc. on the performances of the cooling device are discussed in detail. The optimal operating regions of the device are determined. Compared with the traditional electronic cooling device with a single energy filter between the cold and hot reservoirs, the optimal cooling power is doubly enhanced without reducing the COP (coefficient of performance) of the system.

1. Introduction

Electronic cooling in principle is the process by which high energy electrons are extracted from the cold reservoir [1,2], which is essentially the same as evaporative cooling. In order to realize this goal, two conditions should be satisfied: i. a current of electrons must be driven in the device; ii. energy filters, such as barriers [3] or other energy selection mechanisms including resonant tunneling [4,5] or gaps in the density of states [6], are employed to limit the energy of electrons flowing between the cold and hot reservoirs in particular ranges. For this reason, all cooling devices by using the transport of electrons may be referred to as the ESE (energy selective electron) refrigerators.

Traditional macroscopic electronic cooling devices, such as thermoelectric and thermionic refrigerators [7–9], are designed to operate in the vicinity of ambient temperatures. Recent advances in nanotechnology make it possible to produce micro/nano-scaled cooling devices which can be designed to operate at cryogenic temperatures below 1 K. For example, NIS (normal-insulating-superconductor junction) refrigerators [10], which utilize the energy gap in a superconductor as the barrier only selecting high energy electrons for transport, were experimentally demonstrated [10–13] and shown to be able to achieve an electronic temperature of around 100 mK. A QDR (quantum-dot refrigerator) [14,15] was proposed by Edwards et al., in which the electron reservoir is cooled by the removal of hot electrons and holes through the resonant levels of quantum dots. The performances of ESE devices were investigated by Humphrey et al. [16–20] and it was shown that by using a suitably chosen energy filter, ESE refrigerators and power generators can be quasistatically operated with the efficiency close to the Carnot value. Other investigations, such as ESE refrigerators with a single and double resonances [21,22], ESE refrigerators affected by heat leaks [23,24], three-terminal quantum-dot refrigerators [25,26] and heat engine [27], and an electronic cooling device powered by hot electrons [28], etc., were recently reported.

In most of the previous works dealing with electronic refrigerators, cooling is achieved by merely removing high energy electrons from the cold reservoir. The removed electrons are compensated by the electrons from the external circuit to keep the number of electrons in the cold reservoir constant. In the present paper, a new model of ESE cooling devices is proposed, in which two energy filters are incorporated to respectively select low- and high-energy electrons for transport, and cooling is achieved by simultaneously removing high energy electrons from and injecting low energy electrons with the same number into the cold reservoir.

---

* Corresponding author.
E-mail address: jcchen@xmu.edu.cn (J. Chen).

http://dx.doi.org/10.1016/j.energy.2016.02.059

Nomenclature

h	Planck constant, J s^{-1}
k_B	Boltzmann constant, J K^{-1}
$\dot{N}$	net electron flux s^{-1}
$\dot{Q}$	net heat flux, J s^{-1}
$\dot{Q}_C$	cooling power, J s^{-1}
$\dot{Q}_{C,\eta}$	cooling power at maximal coefficient of performance, J s^{-1}
T	temperature, K
V_0	voltage applied between two hot reservoirs, V
$\dot{W}$	input power, J s^{-1}

Greek symbols

δ	half width at half maximum of energy filters, eV
ε	resonant level, eV
η	coefficient of performance
$\eta_{\dot{Q}_C}$	coefficient of performance at maximal cooling power
μ	chemical potential, eV
ΔS	entropy increase, J K^{-1}
$\Delta\varepsilon_{\dot{Q}_C}$	center interval of two energy filters at maximal cooling power, eV
$\Delta\varepsilon_\eta$	center interval of two energy filters at maximal coefficient of performance, eV
$\Delta\mu_{\dot{Q}_C}$	chemical potential difference of two hot reservoirs at maximal cooling power, eV
$\Delta\mu_\eta$	chemical potential difference of two hot reservoirs at maximal coefficient of performance, eV

Subscripts

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

The performances of the device varying with the positions and half widths of the two energy filters are analyzed and the configuration of the device is optimally designed. The main advantage of the proposed model over the traditional electronic cooling device is that the optimal cooling power can be doubly enhanced without reducing the COP (coefficient of performance) of the system. The possibilities of being miniaturized and operated at low temperatures suggest that the proposed cooling device may be practically used in micro/nano electronic settings where ultra low temperatures are needed.

2. Model description

The ESE cooling device considered consists of a cold electronic reservoir C at temperature T_C and two hot electronic reservoirs L and R at the same temperature T_H, as shown in Fig. 1. The cold and hot reservoirs are thermally insulated from each other and can exchange electrons only via two energy filters with the resonant levels ε_L and ε_R, respectively. The distances between reservoirs are assumed to be much less than the electron mean free path for inelastic processes, so that the transport of electrons through energy filters can be treated as ballistic. The voltage V_0 applied between the two hot reservoirs drives a steady electronic current in the device and creates a difference in the chemical potentials μ_L and μ_R of two reservoirs, i.e., $\mu_L - \mu_R = eV_0$, where e is the absolute value of the electron charge. It is assumed that $\mu_{L/R} >> (k_B T_{C/H}, \mu_R - \mu_L)$, where k_B is the Boltzmann constant. The chemical potential of the cold reservoir μ_C is determined by the conservation of charges and condition of steady current. When the electronic current flows through two energy filters, cooling is achieved by removing high energy electrons from and simultaneously injecting low energy electrons into the cold reservoir.

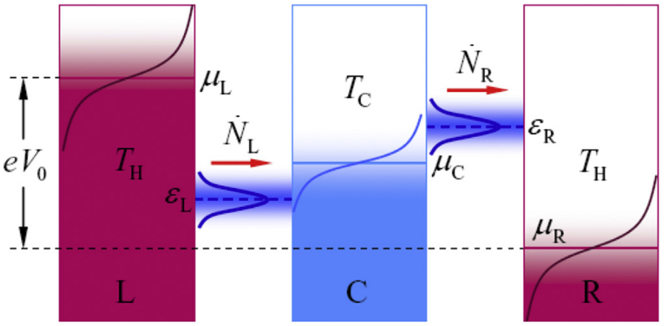

Fig. 1. The schematic diagram of an energy selective electron cooling device.

3. Main parameters of an electronic cooling device

The net electron fluxes transmitted from reservoir L to reservoir C, $\dot{N}_L$, and from reservoir C to reservoir R, $\dot{N}_R$, are governed by the Landauer equation [16,29]

$$\dot{N}_{L/R} = \pm\frac{2}{h}\int_0^\infty \left[f\left(\varepsilon,\ \mu_{L/R}, T_H\right) - f(\varepsilon,\ \mu_C, T_C)\right]\gamma\left(\varepsilon, \varepsilon_{L/R}\right)d\varepsilon, \tag{1}$$

where

$$f(\varepsilon,\ \mu, T) = \frac{1}{\exp[(\varepsilon-\mu)/(k_B T)] + 1} \tag{2}$$

is the Fermi-Dirac distribution function, h is the Planck constant, $\gamma(\varepsilon,\varepsilon_{L/R})$ is the transmission function of each energy filter and is taken as a single Lorentzian resonance

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

with a resonant level $\varepsilon_{L/R}$ and a half width δ at half maximum, and the upper and lower signs in "±" refer to L and R, respectively.

According to the conservation of charges, $\dot{N}_L = \dot{N}_R$ must be satisfied in the case of steady current, from which the chemical potential μ_C is determined. The condition $\dot{N}_L = \dot{N}_R$ also implies that the net electronic current from the cold to hot reservoirs is zero.

Due to the transport of electrons through the energy filters between the cold and hot reservoirs, heat is absorbed from the cold reservoir and released to the hot reservoirs. The net heat fluxes transferred from the cold reservoir $\dot{Q}_C$, which is conventionally referred to as the cooling power, and into the hot reservoirs $\dot{Q}_H$, are given by [16,29]