Thermionic and Thermoelectric Refrigeration and Power Generation using Semiconductor Nanostructures

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Thermionic devices have great potential for application as scalable refrigerators and power generators. We discuss how the electrical transport in such devices may be optimised for maximum efficiency or power. Novel device structures which block phonons whilst retaining good electrical transport may offer significant performance gains.

1. Introduction

Semiconductor nanostructure based thermionic devices offer great potential for refrigeration and power generation due to their reliability, scalability, environmental soundness and potential for high efficiency operation. The use of semiconductor heterostructures in thermionic devices was first suggested by Shakouri and Bowers [1] and whilst there have been a number of reports of successful cooling devices being developed which utilise thermionic emission, the efficiencies required for practical use are yet to be realised. This is in part to a lack of understanding of the fundamental physics involved. Here we outline research into the electronic properties of thermionic devices and discuss how the principles may be applied to realise better thermionic and thermoelectric devices.

2. Thermionics overview

A thermionic device consists of a hot and cold reservoir, separated by a potential barrier, or system of potential barriers. Electrons in the reservoirs have energies distributed according to Fermi-Dirac statistics and are emitted across the barrier according to quantum mechanical processes which may be expressed in terms of a transmission probability. The simplest case is a single barrier device where all electrons with energies sufficient to overcome the barrier are transmitted. In other systems quantum mechanical effects such as reflection of electrons with energies above the barrier height may occur.

Each electron which leaves a reservoir removes energy from it. Depending on the system configuration, the device may either generate power using heat in the hot reservoir, or act as a refrigerator removing heat from the cold reservoir.

We will distinguish between two classes of thermionic devices here. The first corresponds to a conventional device which filters transmitted electrons according to their momentum in the direction of transport only. These shall be dubbed k_x devices. A second, yet to be experimentally realised class, corresponds to devices which filter transmitted electrons according to their *total* energy. These devices will be referred to as k_r devices. Experimental efforts are underway to realise k_r thermionic devices.

3. The effect of the electron energy spectrum

The Carnot efficiency may be theoretically achieved in a thermionic device when the *total* energy of transmitted electrons is equal to 'the energy specific equilibrium energy', E_0. Whilst a k_r device may approach this limit, conventional k_x devices are limited to efficiency below this because they filter electron energies in the direction of transport only, resulting in a finite spread of total energies due to the unfiltered spatial degrees of freedom [2]. Increasing the width of the filter decreases the efficiency of the device up to a point at which it remains stable, as shown in Fig. 1. With lattice heat leaks (which are a significant issue for thermionic devices), maximum efficiency is achieved by transmitting electrons with energies over a range with tuned lower and upper limits.

Maximum power is achieved in a thermionic refrigerator by transmitting all electrons between the Fermi energy and E_0 and in a heat engine by transmitting all electrons with energies greater than E_0 [3].

Total momentum filtering k_r devices outperform k_x device due to a greater number of electrons being involved in transport and therefore increased heat currents [2].

Efficiency is also increased by having an electron transmission probability which sharply switches from zero to full transmission. A gradual rise in the transmission probability (which may occur, for instance, by having a narrow barrier which allows significant tunneling) significantly reduces efficiency [2].

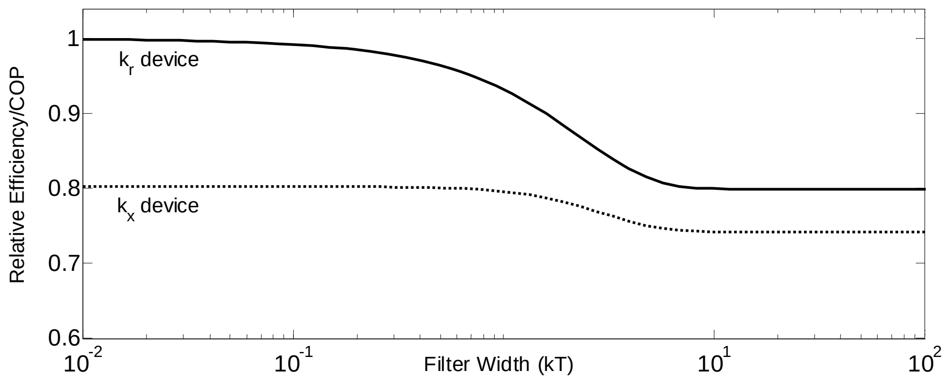

Fig. 1. Efficiency versus filter width.

4. The effect of the barrier system

It is desirable to have a barrier system which is as wide as possible to both minimise lattice leaked heat and ensure a sharply rising electron energy spectrum [4]. Electron collisions in the barrier reduce efficiency however, so we are limited to widths of the order of an electron mean free path. Wide single barriers give good power and efficiency due to near uniform electron transmission above the barrier height, as shown in Fig. 2. Novel barrier shapes may also be used, for instance an array of thinner barriers which together give total width of around the electron mean free path. In such cases it must be ensured that quantum mechanical reflection of electrons above the barrier does not significantly reduce device power. Such barrier arrays may be used to form transmission minibands (as shown in Fig. 2), whose shapes may be tailored to approximate the tune energy range filters described above.

We have two, often conflicting, design goals in thermionic devices: the optimisation of electron transport and minimisation of phonon transport. Multibarrier devices have been shown to significantly reduce thermal conductivity, however, the barrier periodicity for minimum thermal conductivity is typically around 2-5 nm compared to the ideal width in terms of electron transport of ~100 nm. We propose a device structure which incorporates both desirable features, by superimposing an array of ‘mini-barriers’ onto the mean free path length barriers. The mini-barriers may be incorporated in such a way that they do not significantly disrupt electron transport, but should be effective in reducing thermal conductivity. Such a device may give a significant efficiency improvement over conventional designs. The potential profile and associated transmission probability of a mini-barrier device are shown in Fig. 3.

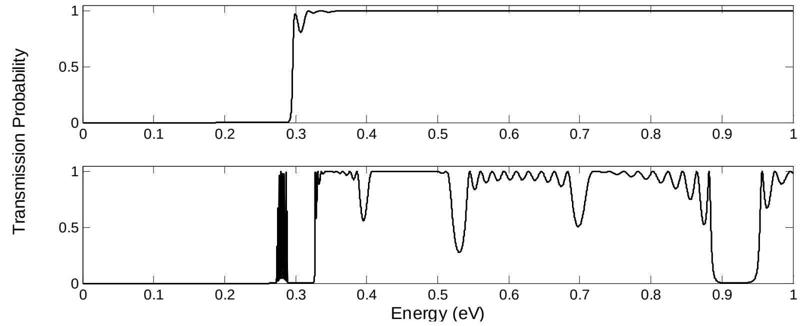

Fig. 2. Transmission probabilities for a single barrier system (top) and ten barrier system (bottom) with effective mass $0.57m_e$ and barrier height 0.3 eV.

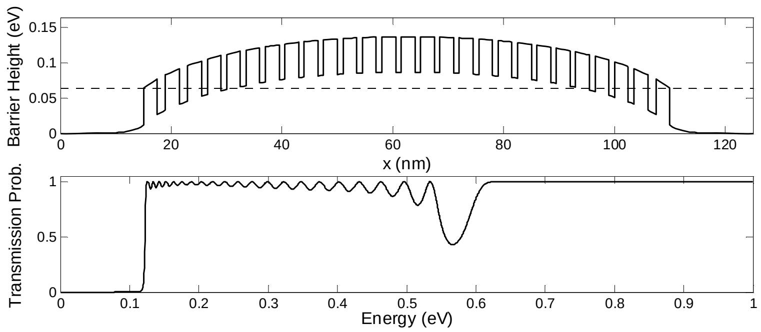

Fig. 3. The barrier shape of a mini-barrier thermionic device (top) and associated transmission probability (bottom).

5. Links between thermionic and thermoelectric devices

It may be shown that the thermionic formalism, which deals with ballistic electron transport, and the thermoelectric formalism, which deals with diffusive electron transport, reduce to the same mathematical form when considered over equivalent length scales [2,4]. Many of the phenomena suggested for enhancement of the performance of thermionic devices may also therefore be useful in thermoelectric devices.

6. Conclusions

Thermionic devices offer great potential for scalable refrigeration and power generation devices. The performance of thermionic devices may be enhanced by tuning the spectrum of transmitted electrons, which may be achieved using novel barrier arrangements. Phonon blocking structures which preserve electrical transport using mini-barriers structures might give significantly enhanced performance.

Acknowledgments

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