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Upper Limitation to the Performance of Single-Barrier Thermionic Emission Cooling

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ABSTRACT

We have re-examined solid-state thermionic emission cooling from first principles and report two key results. First, electrical and heat currents over a semiconductor – semiconductor thermionic barrier are determined by the chemical potential measured from the conduction band edge, not the energy band offset between the two materials as is sometimes assumed. Second, we show the upper limit to the performance of thermionic emission cooling is equivalent to the performance of an optimized thermoelectric device made from the same material. An overview of this theory will be presented and instrumentation being developed to experimentally verify the theory will be discussed.

INTRODUCTION

Solid state thermionic emission cooling has received interest in the last decade as a possible alternative to standard thermoelectric cooling. It has been proposed that greater cooling power may be achieved with thermionic emission cooling [1,2]. Thermionic emission coolers comprised completely of semiconducting materials, such as in the diagram of figure 1, are also

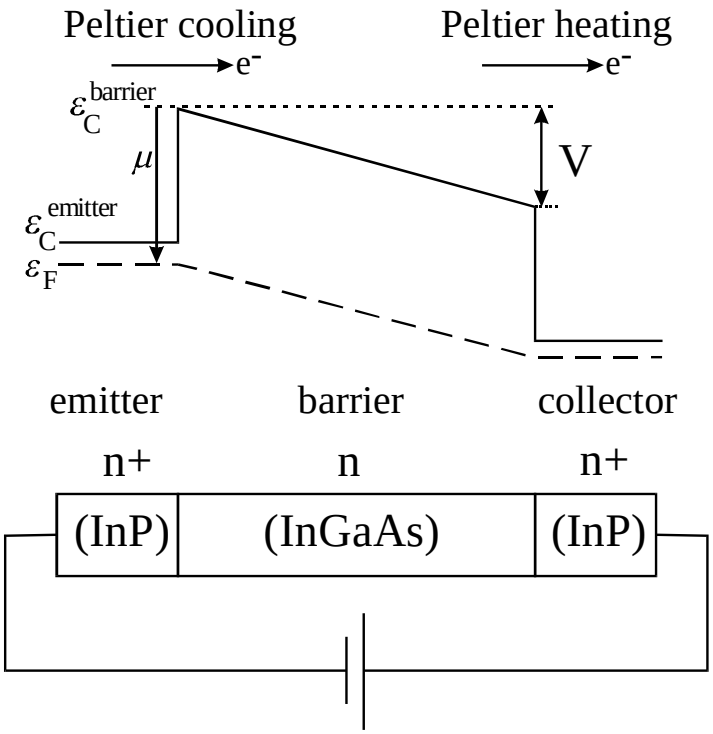

Figure 1. Schematic and block diagram of a thermionic emission cooler. The arrows show the direction of electron flow causing Peltier cooling on the left and Peltier heating on the right.

desirable because they can be monolithically integrated with solid state devices that require temperature control. The basic principle of cooling in thermionic emission devices, modeled in figure 1, is the transport of heat utilizing the Peltier effect.

The purpose of this paper is to present a first principles derivation of the electronic contributions to the cooling power for a semiconductor thermionic device and from this to determine the maximum cooling possible for both the ballistic and diffusive limits.

FIRST PRINCIPLES DERIVATION

The electrical current density, J_E, and heat current density, J_Q, over a semiconductor-semiconductor heterojunction barrier are derived from statistical mechanics [3]:

$$J_E = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{p_x^{free}}^{\infty} f(p)g(p)\,q\,v_x\,d^3p\,, \tag{1}$$

$$J_Q = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{p_x^{free}}^{\infty} f(p)g(p)\left(\varepsilon(p)-\varepsilon_F\right)v_x\,d^3p\,, \tag{2}$$

where $f(p)$ is the Fermi Dirac distribution function, $g(p)$ is the density of states, q is the elementary charge, v_x is the electron velocity in the x-direction, $\varepsilon(p)$ is the electron kinetic energy measured from the conduction band edge, ε_F is the Fermi level measured from the conduction band edge, and p_x^{free} is the momentum in the x-direction necessary to surmount the barrier. If a large barrier height is considered the results of these integrals are the historical Richardson equation for the electrical current density [4] and its equivalent for the heat current density. But, the Richardson approximation is the first term in a series expansion, so any arbitrary barrier height can be considered if all terms in the series are kept. This will also allow for fast numerical calculations at any barrier height. The complete series solutions for these integrals are:

$$J_E = A^* T^2 \sum_{n=1}^{\infty} \frac{(-1)^{n-1}}{n^2} \exp\left(n\frac{q\mu}{kT}\right), \tag{3}$$

$$J_Q = A^* T^2 \sum_{n=1}^{\infty} \frac{(-1)^{n-1}}{n^2} \left(-\mu + \frac{2kT}{nq}\right) \exp\left(n\frac{q\mu}{kT}\right), \tag{4}$$

where A^* is the effective Richardson constant, T is the temperature at the heterojunction, k is the Boltzmann constant, and μ is a chemical potential defined as the following, and is shown in figure 1:

$$\mu = \varepsilon_F - \varepsilon_C^{barrier}\,, \tag{5}$$

where $\varepsilon_C^{barrier}$ is the conduction band edge of the barrier and ε_F is the fermi level measured in the emitter. This solution is valid for negative or zero μ. We define μ outside the barrier to avoid problems with ballistic transport for which a chemical potential cannot be defined in the barrier. Equation 5 agrees with Wu and Yang's more detailed development of electrical current over a

semiconductor heterojunction [5]. Our derivation extends the model to include the heat current density. Equation 5 is the correct barrier height for a semiconductor – semiconductor heterojunction and we have not seen it applied in the calculations of thermoelectric energy conversion. A chemical potential is defined as the energy necessary to add a particle to a system. Thus, the chemical potential governs the electrical and heat currents across a barrier as opposed to the energy difference between the adjacent conduction band edges, as is often assumed.

In order to apply equations 3 and 4 to thermionic emission cooling we consider ballistic transport across the barrier with an applied voltage and do not neglect the reverse current densities. For a thermionic emission cooler, the total current densities are:

$$J_E = A^* T_E^2 \sum_{n=1}^{\infty} \frac{(-1)^{n-1}}{n^2} \exp\left(n \frac{q\mu}{kT_E} \right) - A^* T_C^2 \sum_{n=1}^{\infty} \frac{(-1)^{n-1}}{n^2} \exp\left(n \frac{q(\mu - V)}{kT_C} \right), \tag{6}$$

$$J_Q = A^* T_E^2 \sum_{n=1}^{\infty} \frac{(-1)^{n-1}}{n^2} \left(\frac{2kT_E}{nq} - \mu \right) \exp\left(n \frac{q\mu}{kT_E} \right) - A^* T_C^2 \sum_{n=1}^{\infty} \frac{(-1)^{n-1}}{n^2} \left(\frac{2kT_C}{nq} - \mu \right) \exp\left(n \frac{q(\mu - V)}{kT_C} \right), \tag{7}$$

where T_E is the temperature at the emitter-barrier junction, T_C is the temperature at the barrier-collector junction, and V is the voltage across the barrier as shown in figure 1. To proceed analytically, we consider only the n = 1 term of equations 6 and 7 and combine the equations and eliminate the applied voltage. Thus, the heat current density removed from the emitter junction in terms of the electrical current density through the device is:

$$\begin{aligned} J_Q &= \left(-\mu + \frac{2kT_E}{q} \right) J_E + \frac{2k}{q} J_E \Delta T - \frac{2k}{q} \left(A T_E^2 \right) \exp\left(\frac{q\mu}{kT_E} \right) \Delta T \\ &\equiv \Pi J_E + \frac{2k}{q} J_E \Delta T - \kappa_e \Delta T. \end{aligned} \tag{8}$$

The first term is the Peltier effect where Π is the Peltier coefficient, the second looks like a Thomson effect, and the third is the electronic contribution to the thermal conductivity, κ_e. ΔT is the temperature difference between the emitter and collector and is positive if the collector is at a higher temperature. The close correspondence between equation 8 and conventional thermoelectric theory is reassuring.

TOTAL HEAT TRANSPORT

To examine a thermionic emission cooler, lattice effects are added directly into equation 8. In the ballistic limit, only lattice thermal conduction must be considered and the heat current density is:

$$J_Q = \Pi J_E + \frac{2k}{q} J_E \Delta T - \left(\kappa_e + \frac{\kappa}{d} \right) \Delta T , \tag{9}$$

where κ is the lattice thermal conductivity of the barrier and d is the barrier width. In the diffusive limit joule heating must also be considered. The solution to the one dimensional heat transport equation for electrical current through a resistive material with a temperature difference between the ends shows that half of the joule heat returns to the cold end [6]. Thus, in the diffusive limit the heat current density is:

$$J_Q = \Pi J_E + \frac{2k}{q} J_E \Delta T - \left(\kappa_e + \frac{\kappa}{d} \right) \Delta T - \frac{1}{2} J_E^2 \frac{d}{\sigma}, \tag{10}$$

where σ is the electrical conductivity of the barrier. Equation 10 is exactly the equation for heat transport through bulk thermoelectric devices. This shows that a thermionic emission cooler in the diffusive limit will behave the same as a bulk thermoelectric device [1]. This provides a simple way of comparing a thermionic structure to a thermoelectric structure of the same material.

DEVICE OPTIMIZATION

We examine the cooling ability of a thermionic emission cooler by optimizing the maximum temperature difference that can be achieved. We consider the full series for the electrical and heat current densities and solve numerically. We use parameters for an InGaAs barrier because the InP-InGaAs family is an important semiconductor family in which many devices would benefit from integrated cooling. The mobility is taken to be 8000 cm^2-V/sec. The lattice thermal conductivity is taken to be 5 W/K-cm, which corresponds to the bulk value. There are two variables that can be optimized: the chemical potential and the barrier width.

Figure 2 shows the maximum temperature difference achievable as a function of the chemical potential for ballistic transport across a .2 micron barrier. The dashed line assumes saturation of the electrical current. The solid line is determined by limiting the electrical current density to be less than or equal to 100kA/cm^2. This limit is chosen because above this current density, joule heating in the contacts will be a significant issue [7] and electromigration may also threaten device stability [8]. With this self-imposed limit, the optimum chemical potential is approximately (–1.5kT/q).

Figure 3 shows the maximum temperature difference as a function of the barrier width in both the ballistic and diffusive limits for a chemical potential of (–1.5kT/q). Clearly there is an advantage to the cooling for the ballistic limit if relatively large barrier widths can be used. Using a mobility of 8000 cm^2-V/sec, the mean free path is only .1 micron. In this purely ballistic limit, no more than 2 degrees of cooling is possible, whereas a thick device in the diffusive regime could provide about 4.5 degress of cooling. The conclusion of this is two-fold. First, a single barrier ballistic InGaAs thermionic device will not be able to achieve better cooling than a standard InGaAs thermoelectric device. Second, between the ballistic and diffusive limits, it may be possible to achieve cooling greater than either limit. Because InGaAs is a good representation of the important thermoelectric parameters for ternary III-V materials, we expect similar results for other III-V material systems.

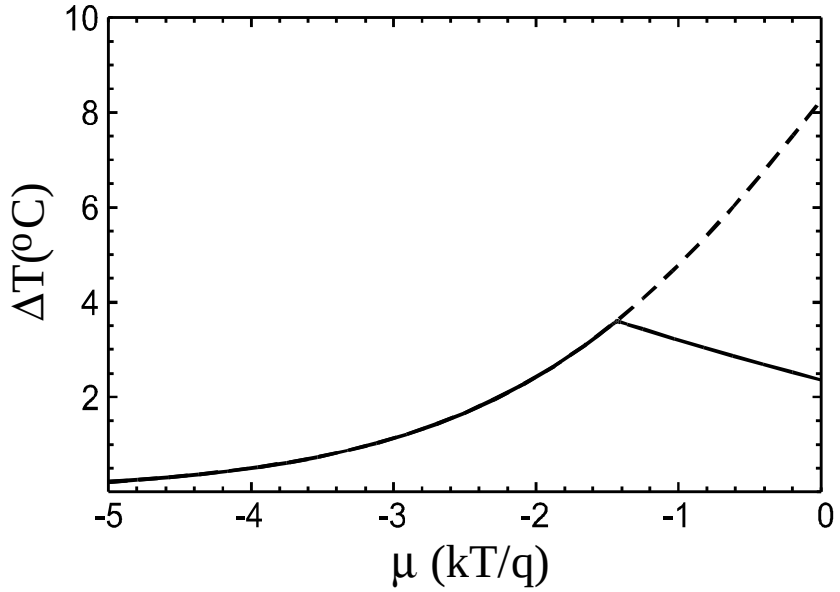

Figure 2. Maximum temperature difference of a ballistic InGaAs thermionic emission cooler as a function of the chemical potential for unlimited current (dotted line) and current limited to 100kA/cm^2 (solid line).

CONCLUSIONS

We provide analytical solutions for the electrical and heat current densities over a heterojunction barrier that allow for fast numerical calculations for any chemical potential. The Peltier coefficient for a semiconductor – semiconductor heterojunction boundary must be defined

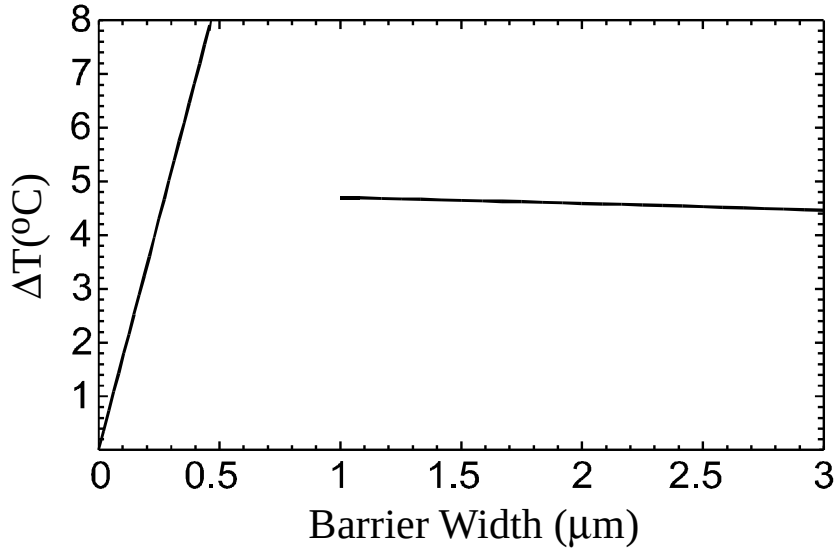

Figure 3. The maximum temperature difference as a function of the barrier width for an InGaAs device with μ = -1.5kT/q, in both the ballistic limit (on the left) and diffusive limit (on the right).

using the chemical potential in equation 5 and shown in figure 1. The optimum chemical potential for thermionic emission cooling should be determined from a physically reasonable electrical saturation current density. Maximum cooling may occur between the ballistic and diffusive limits (see figure 3 for barrier widths from .5μm to 1μm) of a thermionic device and more investigation in this area is necessary.

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