Heterostructure Integrated Thermionic Refrigeration

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ABSTRACT

Thermionic emission in heterostructures is investigated for integrated cooling of high power electronic and optoelectronic devices. This evaporative cooling is achieved by selective emission of hot electrons over a barrier layer from the cathode to the anode. As the energy distribution of emitted electrons is almost exclusively on one side of Fermi energy, upon the current flow, strong carrier-carrier and carrier-lattice scatterings tend to restore the quasi equilibrium Fermi distribution in the cathode by absorbing energy from the lattice, and thus cooling the emitter junction. An analytic expression for the optimum barrier thickness is derived. It describes the interplay between Joule heating in the barrier and heat conduction from the hot to the cold junction. It is shown that by choosing a barrier material with high electron mobility and low thermal conductivity it is possible to cool electronic devices by 5 to 40 degrees in a wide range of temperatures.

INTRODUCTION

Thermoelectric (TE) coolers are important elements of many systems. TE coolers are used in most semiconductor laser modules because of the need to stabilize their characteristics (such as threshold, power output, and wavelength). TE coolers are essential in many infrared detectors applications because the sensitivity of the imaging array is much higher at low temperatures. TE coolers will become essential for many elements of modern optical telecommunications because the channel spacing of wavelength division multiplexed signals are quite close together (100 GHz or 0.5% of the optical frequency), and this wavelength will be used for many switching and routing elements. Consequently, we must stabilize not only the wavelength of the laser source, but also the wavelength of passive switching elements, tunable wavelength shifters and tunable receivers. In these cases the degree of cooling and the amount of the cooling power are not large, but the cost must be low. Since the conventional TE cooling devices based on BiTe or PbTe are not fabricated using integrated circuit technology [1], they can not be easily integrated with III-V or II-VI optoelectronic devices. This will increase the cost for packaging individual modules.

Recently, quantum wells, wires and superlattices have been extensively studied for thermoelectric cooling applications [2-5]. Modifying parameters such as electronic density of states and various relaxation time mechanisms, it is possible to alter electrical conductivity (σ) and Seebeck coefficient (S) of the material and thus increase the thermoelectric figure of merit $ZT = S^2\sigma T/\beta$, where β is the thermal conductivity. There have also been studies aiming to reduce the thermal conductivity by increasing phonon scattering at interfaces in superlattice structures. Heterostructures can modify electronic transport properties beyond *linear* regime where the concepts of electrical conductivity and Seebeck coefficient are usually defined [6]. Using the analogy with thermionic power generation by vacuum diodes, one can design new heterostructure devices (Fig.1) with high cooling power densities. More importantly, this will allow the use of conventional semiconductor materials for fabrication of cooling devices integrated with high power electronic and optoelectronic components. In the following, we will first review electrical power generation by vacuum diodes, and then look at the prospects of heterostructures for thermionic cooling. A simplified model which take into account main energy balance mechanisms is introduced [6]. It will be seen that a net cooling is achieved only for short devices (0.5-5 µm). In order to investigate accurately nonisothermal transport in these length scales, more elaborated Monte Carlo simulations are needed [7]. However, the simplified equations can give analytical expressions for the optimum device length and the maximum cooling temperature, which can be used for an initial evaluation of different material systems.

THERMIONIC POWER GENERATION

In the middle of fifties, when vacuum diodes and triodes were tested and analyzed, serious investigation of thermionic energy conversion began [8]. The idea is that a high work function cathode in contact with a heat source will emit electrons, a process which is called *thermionic emission*. These electrons are absorbed by a cold, low work function anode, and they can flow back to the cathode through an external load where they do useful work.

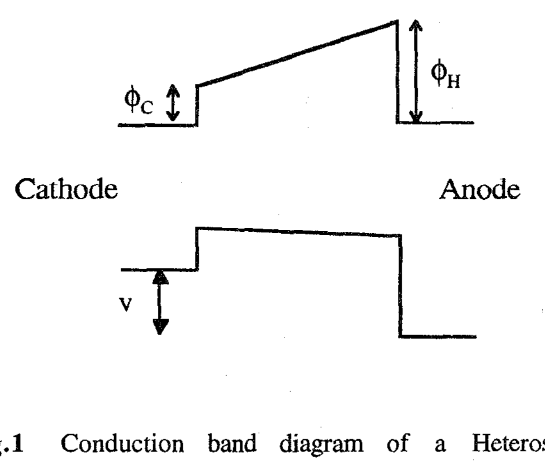

Fig.1 Conduction band diagram of a Heterostructure Integrated Thermionic (HIT) cooler at thermal equilibrium and under an applied bias.

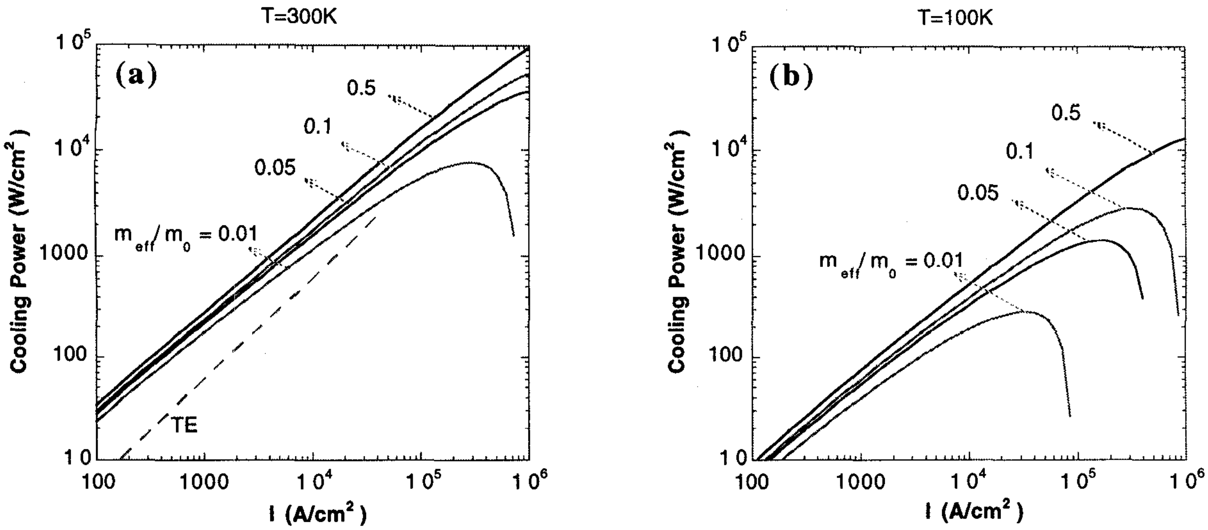

Fig.2 Thermionic cooling power as a function of current for different values of electron effective mass at (a) T=300K, (b) T=100K. The dashed curve corresponds to thermoelectric cooling power for a typical Bi_2Te_3 material.

Practical thermionic generators are limited by the work function of available metals or other materials which are used for cathodes. Another important limitation is the *space charge effect*. The presence of charged electrons in the space between cathode and anode will create an extra potential barrier, which reduces the thermionic current. Various means of reducing this space charge effect were proposed to improve the efficiency of thermionic generators, such as close-spacing of cathode and anode, or the use of a third positive electrode to counteract space charge. A major advance in the field occurred in 1957 when the introduction of positive ions (cesium vapor) in the inter-electrode space eliminated the need for close spacing and resulted in substantial improvement of performance.

The materials currently used for cathodes have work functions *> 0.7 eV*, this limits the generator applications to high temperatures *>500K*. Recently, Mahan have proposed these vacuum diodes for thermionic refrigeration [9]. Basically, the same vacuum diodes which are used for generators, under an applied bias will work as a cooler on the cathode side and heater on the anode side. Mahan predicted efficiencies over 80% of the Carnot value, but still these refrigerators only work at high temperatures (*>500K*).

HIT COOLING

The precise control of layer thickness and composition using various epitaxial growth techniques, allow the design of heterostructure devices with barrier heights in a wide range of 0 to 0.4 eV (Fig.1). Close and uniform spacing of cathode and anode is not a problem anymore and is achieved with atomic resolution. The problem of space charge can be controlled by modulation doping or bandgap engineering in the barrier region. One could use appropriate band offsets in conduction or valence band by choosing n or p type semiconductor material. The price for this flexibility is the large coefficient of barrier thermal conductivity (comparing to vacuum!). One could selectively remove this barrier material and recover the old vacuum thermionic generator but with extremely small and precise cathode-anode separation. In the following we will only consider thermionic cooling with semiconductor barriers. Because of the large backwards heat flux, these devices are not very efficient. We will see that it is still possible to pump heat at rates of 100s of W/cm^2 and maintain a steady state temperature gradients and cool the emitter junction by as much as 30-40 degrees. Cascading these devices in series and distributing the temperature gradient over longer distances might be used to increase the efficiency.

ENERGY BALANCE EQUATION

Assuming Richardson's expression for thermionic current, and Bethe criterion for voltage drop over the barrier, one can derive the following energy balance equation [6]:

$$Q_{TI} = \left(\phi_C(I,T_C) + \frac{2k_BT_C}{e}\right)I - \frac{k_B}{e}\left(T_C + \frac{\Delta T}{2}\right)\frac{d}{\lambda}I - \frac{\beta}{d}\cdot\Delta T$$

where ϕ_C is the cold side barrier height. It can be expressed as a function of the current as follows:

$$\phi_C(I,T_C) = \frac{k_BT_C}{e}\left[\ln\left(\frac{em^*k_B{}^2T_C^2}{2\pi^2\hbar^3}\right) - \ln(I)\right].$$

Here, T_C is the cold side temperature, m^* the minimum of electron effective mass in the emitter and barrier regions, λ and β are respectively electron mean-free-path in the barrier and its thermal conductivity, and d is the barrier thickness.

Fig 2a and 2b display the thermionic cooling power (the first term in the energy balance equation) for two different temperatures 300K and 100K. The only material parameter is the electron effective mass which strongly affects the cooling performance by changing the density of "supply" electrons at the cathode or the density of available states in the barrier. For comparison a typical thermoelectric cooling term is also shown in the figure ($Q_{TE}=ST_C I$, S~200 μV/K for Bi_2Te_3 at room temperature). One should note that the expression for thermoelectric cooling is derived in linear transport regime and it is expected to hold for low and moderate current densities. The reduction of the cooling power at low temperatures is similar to thermoelectric case. This is a direct consequence of Fermi-Dirac distribution function, as the energy spread of electrons within the Fermi window is reduced.

Now if we look at the net thermionic cooling, we see that there is an optimum barrier thickness which balances Joule heating in the barrier and heat conduction form the hot to the cold junction. The maximum cooling temperature (ΔT) can thus be calculated:

$$\Delta T_{\max} = T_C\left(\sqrt{1+\frac{\lambda k_B}{2e\beta}\left(\frac{e\Phi_C(I,T_C)}{k_B T_C}+2\right)^2 I}-1\right)$$

$$d_{opt} = \sqrt{\frac{e\beta\Delta T\lambda}{k_B\left(T_C+\frac{\Delta T}{2}\right)I}}$$

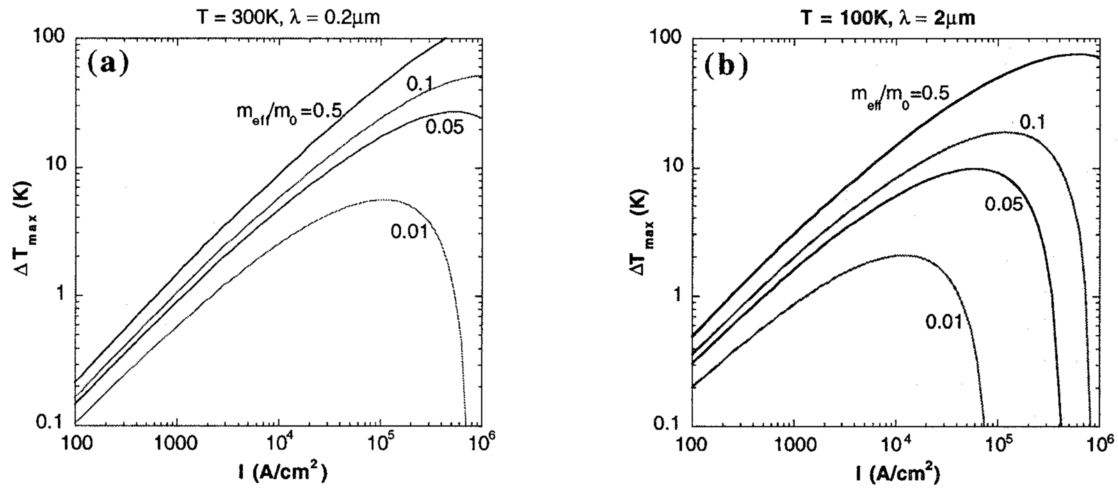

Fig.3 Maximum Cooling temperature as a function of current for different values of the electron effective mass.

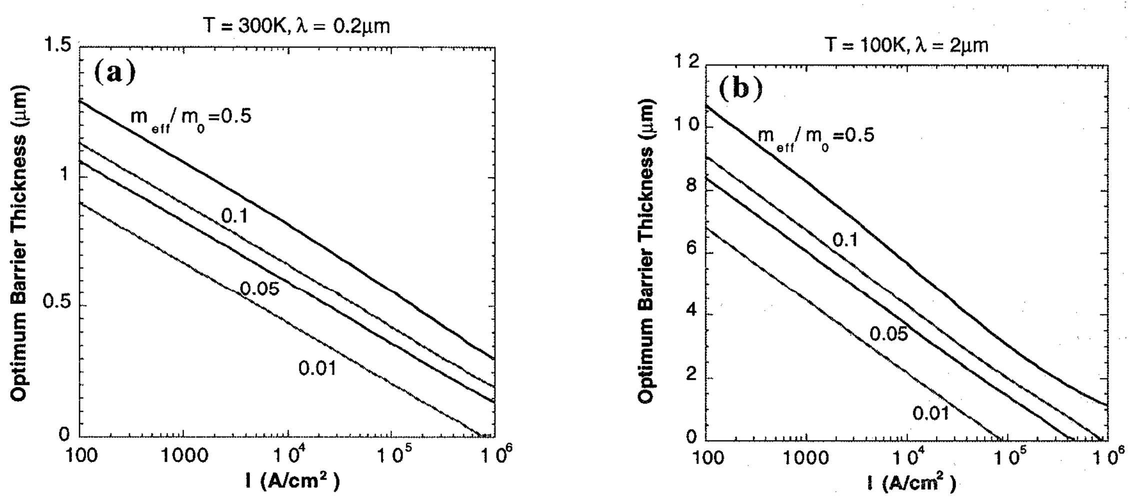

Fig.4 The optimum barrier thickness as a function of current for different values of the electron effective mass.

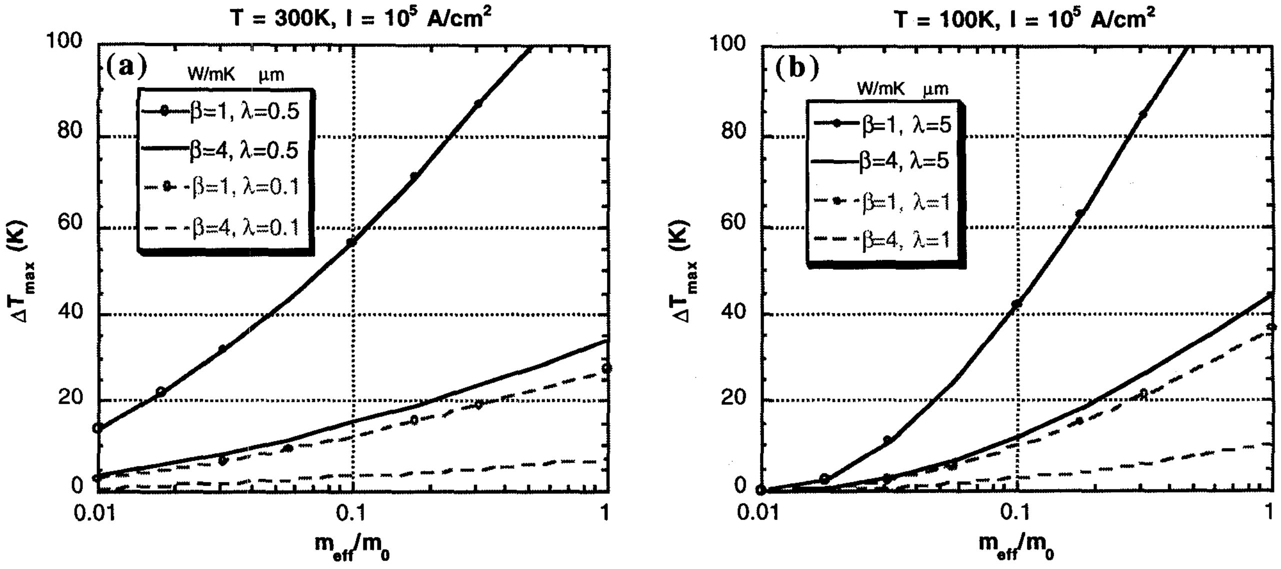

Fig.5 Effect of various material parameters on maximum cooling temperature.

ΔT_{max} at two different temperatures 300K and 100K is shown in Fig. 3a and 3b. The corresponding d_{opt} is displayed in Fig. 4a and 4b. The electron mean free path is taken to be 0.2 µm (2 µm) at 300K (100K), and a barrier thermal conductivity of 1 W/mk is assumed. One can see that cooling by 10-40 degrees (5-20 degrees) with a barrier thickness of ~0.4 microns (2 microns) is possible at 300K (100K). The required current densities are very high (10^4-10^5 A/cm^2), but this should not be a problem. The cooling area needed for an individual device is quite small and these level of currents are routinely achieved in various microelectronic devices (heterostructure bipolar transistors, lasers, etc.).

The thermionic cooling power density $((\phi_C+k_BT_C/e)I)$ is derived assuming Boltzmann distribution of carriers at the cathode junction. At high current densities the required cathode barrier height is small (on the order of k_BT), so this assumption is not valid anymore. In order to estimate more accurately the cooling power one should use the Fermi-Dirac distribution function, but we don't expect too much deviation from the above expression for ΔT_{max}. In fact, Boltzmann distribution over estimates the Joule heating term *more* than the thermionic cooling term. Electrons near the Fermi energy have a small contribution to the heat flux while their contribution to the current is identical to the high energy electrons (they both carry the same charge e!).

In order to study the importance of various material parameters, Fig. 5a (5b) shows the maximum cooling temperature as a function of the electron effective mass at 300K (100K). Different curves correspond to different electron mean free paths and barrier thermal conductivities. To improve the cooling performance, instead of maximizing Z ($=S^2\sigma/\beta$) in a regular thermoelectric material, here one has to maximize $\lambda[\ln(m^*/m_0)]^2/\beta$.

An important characteristic of HIT coolers is the very small thickness of the barrier region on the order of microns. The large amount of heat conduction from the hot to the cold side is one of the main reasons for low efficiency. One possible remedy is to modify the device structure so that the electrons at the anode junction lose their energy by e.g. emitting photons rather than heating the lattice. Two possible schemes: intersubband [10] and interband light emitting devices are shown in Fig. 6. This concept of a heat pump without a hot side would seem to violate the second law of thermodynamics by reducing the total entropy. But, in fact, the amount of entropy reduction by cooling at the cathode junction, can be compensated by entropy generation at the anode side by emitting incoherent or partially coherent light.

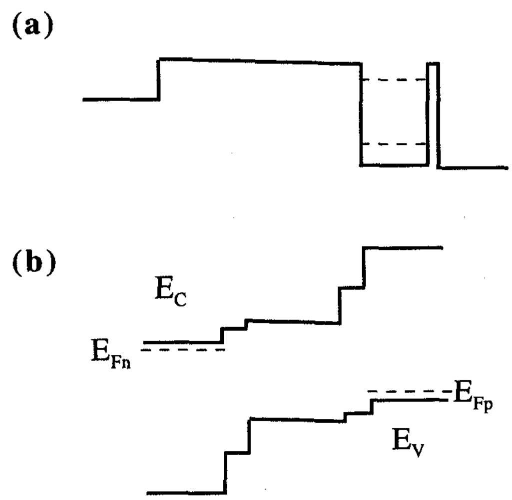

Fig.6 An intersubband (a) (interband (b)) light emitting thermionic cooler.

To realize light emitting devices with a net cooling power, further investigation of the required radiative efficiencies, and the optimum device design are needed.

In conclusion, single stage heterostructure integrated thermionic coolers are studied at different temperatures, using a simplified energy balance model. Analytic expressions for the optimum device thickness and the maximum cooling temperature are given, and important material parameters are identified.

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