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MULTILAYER THERMIONIC COOLING IN SEMICONDUCTOR HETEROSTRUCTURES

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Abstract

The feasibility of using semiconductor heterostructures as cooling devices is currently being studied. Utilising thermionic emission is proposed because of its potentially high cooling power. Multilayer devices have higher efficiency than single layers due to reduced phonon transport, or increased thermal resistance. We have studied the behaviour of thermionic cooling in periodic barriers using 10-layer $GaAs/Al_xGa_{1-x}As$ heterostructures. Two methods of measuring cooling and heating are currently being investigated. Micro-thermocouples show temperature changes, but may affect readings because of their finite thermal mass. Also being investigated is the use of a non-contact optical method that relies on the temperature dependence of features in the reflected spectrum of the devices. Preliminary measurements have been carried out on direct band-gap bulk materials such as GaAs and InP and show strong temperature dependence. Cooling, either relative or absolute, has not yet been observed in our first generation devices. Any such cooling may be masked by joule heating in the comparatively large substrate on which the devices are built. Simulations are currently being carried out to determine where the most power is being dissipated in the devices.

Introduction

Thermionic refrigeration is based upon the principle of thermionic emission. That is, electrons are ejected from any hot surface. A voltage is used to sweep away energetic electrons ejected from the surface. As they leave they take energy with them and in doing so cool the surface.

All thermionic devices are based upon Richardson's equation:

$$J(\phi,T) = AT^2 \exp(\frac{e\phi}{k_b T}) \qquad (1)$$

J: Current Density (Am^{-2})

ϕ: Work Function of Interface (eV)

A: Richardson's Constant $= \frac{emk_b^2}{2\pi^2\hbar^3} \approx 120\frac{A}{cm^2}$

T: Temperature of Interface (K)

Solid-State Thermionic Devices

Low work-function materials are required to produce useable cooling power at room temperature (<0.3eV). Metal-Vacuum diodes have work-functions of around 0.7eV at room temperature. Mahan et. al.[1] suggested the use of semiconductor-semiconductor heterostructures as they can be engineered to have work functions of 0-0.4eV. Fig. 1 shows the schematic of a single-barrier thermionic device with an applied bias of δV.

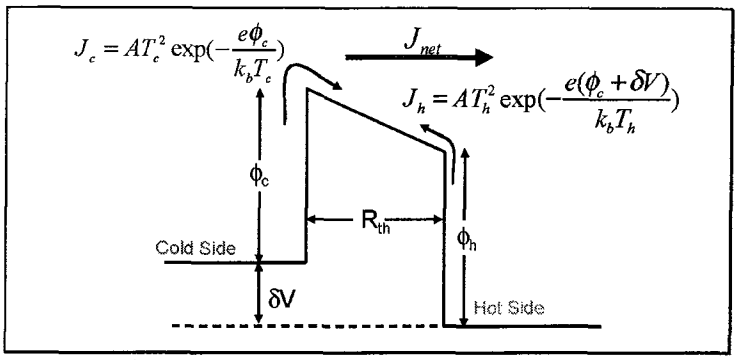

Figure 1: Schematic of Single-Barrier Device

At equilibrium, electrical current leaves the left electrode and enters the right electrode. Another current leaves the right electrode and enters the left. This second current can be much less than the first due to the applied voltage appearing in the exponential term. This results in a net current leaving the left electrode. Only electrons with enough (thermal) energy to overcome the barrier (ϕ_c) contribute to the electric current. There is a filtering of relatively high-energy electrons. The net electrical current is given by:

$$\begin{aligned} J_{net} &= J_c - J_h \\ &= J(\phi_c, T_c) - J(\phi_c, T_h)\exp(-\frac{e\delta V}{k_b T_h}) \\ &= AT_c^2 \exp(-\frac{e\phi_c}{k_b T_c}) - AT_h^2 \exp(-\frac{e(\phi_c + \delta V)}{k_b T_h}) \end{aligned} \tag{2}$$

while the net heat current is given by:

$$\begin{aligned} J_Q &= (\phi_c + \frac{2k_b T_c}{e}) J(\phi_c, T_c) \\ &- (\phi_c + \frac{2k_b T_h}{e}) J(\phi_c, T_h)\exp(-\frac{e\delta V}{k_b T_h}) \\ &- \frac{T_h - T_c}{R_{th}} \end{aligned} \tag{3}$$

The last term in the equation represents the heat conduction from the hot (right) to cold (left) side. It is important to reduce this term as much as possible – either by increasing R_{th} or decreasing ($T_h - T_c$). For this reason, Mahan[1] proposed an N-barrier device, so that each barrier only has ~[($T_h - T_c$) / N] Kelvin across it. Increasing R_{th} depends on increasing the width of the barrier. The maximum width of the barrier is constrained by the mean free path of electrons in the barrier. Richardson's equations depend on electrons traversing the barrier *ballistically*, that is, without interacting with the barrier. For semiconductors this value is typically 50-100nm.

Numerical Methods

The authors have developed a system for solving the electrical and heat current equations. For an N-barrier system there are 2(N-1) unknowns and 2(N-1) equations meaning there is a unique solution. The Newton-Raphson method was employed in order to solve these equations. This method converges vary rapidly (quadratically) as long as some reasonable estimates for the unknowns are specified.

A numerical solution to the equations is attractive because Richardson's equation is derived using the Maxwell-Boltzmann (MB) distribution as an approximation of the Fermi-Dirac (FD) distribution. It is valid when $\phi > \sim 3k_bT$(~75meV@ room temperature). When we start modelling low work-function systems, it is necessary to use the FD, which cannot be solved analytically. In addition to this, the solution gives a lot of information about the system such as the temperature and voltage profile throughout the device. It also allows easy modification of the model to include other effects not included originally, such as barrier lowering due to space-charge effects.

An example of information obtained from the solution is shown in Fig. 2. Its shows that the maximum cooling achievable is much greater for a multi-barrier device than for a single barrier device.

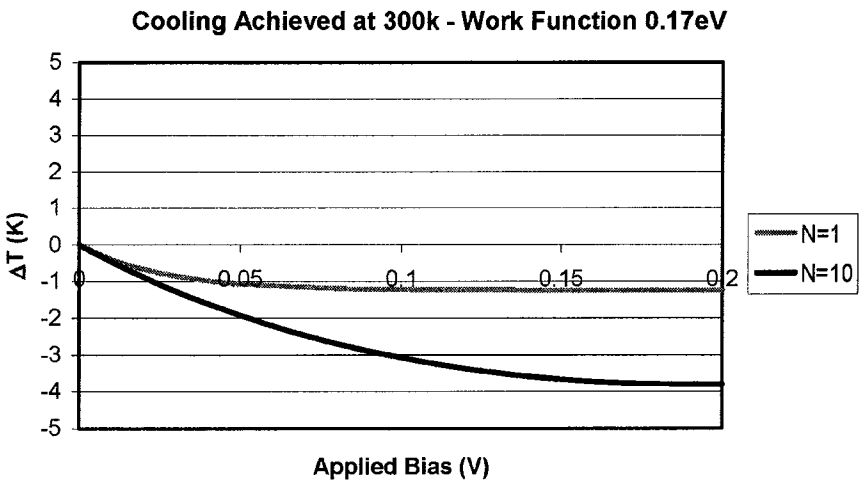

Figure 2: Comparison of Maximum cooling for single and 10-barrier device.

Conclusion

Solid state thermionic devices may be a viable alternative to conventional refrigeration systems. Multi-barrier devices theoretically perform much better than single-barrier devices in that they can transfer larger amounts of heat current and, as a result, produce a lower temperature for the side being cooled.

References

[1] Mahan, G. D., Sofo, J. O., Bartkowiak, M. 1998. Multilayer thermionic refrigerator and generator, *J. Appl. Phys.*, 83:4683-4689.