Minority-Carrier Thermoelectric Devices

Kevin P. Pipe and Rajeev J. Ram
Research Laboratory of Electronics
Massachusetts Institute of Technology, Cambridge, MA 02141, USA

Ali Shakouri
Jack Baskin School of Engineering
UC Santa Cruz, Santa Cruz, CA 95064-1077, USA

Abstract

Traditional Peltier coolers employ majority carriers within doped semiconductor regions to transport heat energy between metal contacts. An alternative approach to using such coolers in an external fashion to cool electronic devices is to optimize the thermoelectric performance of the electronic devices themselves. Recognizing that minority carriers play an important role in many electronic and optoelectronic devices, we have developed a general theory for thermoelectric effects in a *p-n* diode (a prototypical electronic and optoelectronic component) where diffusion of minority carriers is essential to the device's operation. Differences with the traditional Peltier effect are highlighted. It is also shown that the heat energy can be transported from the diode junction to the side contacts, producing temperature gradients within the device and internally cooling the junction. Analytic expressions for quantities such as the effective ZT are derived, as well as optimization conditions for doping, region width, and current density. Predicted heat gradients over micron-scale devices are approximately 7 degrees for InGaAs and 30 degrees for HgCdTe under optimal heat-sinking conditions. Other numerical results are given for several common material systems.

Introduction

Thermoelectric effects have traditionally been utilized in dedicated structures such as Peltier coolers that stabilize the temperatures of nearby devices. External coolers of this sort can be difficult or costly to integrate, motivating a study of thermoelectric effects within active devices themselves. This represents a first step toward a new class of *active thermoelectric* devices that can be employed for switching, amplification, and light generation. Devices can be designed which use the operating current to optimally cool critical internal areas such as the gain region of a laser diode [1].

Due to the bipolar nature of such devices during operation, the optimization of internal thermoelectric heat exchange requires a model that takes into account the presence of minority carriers [2,3]. Here we examine thermoelectric heat exchange in a biased *p-n* diode (a prototypical active device) and quantify the cooling that takes place at the device's internal junction.

Thermoelectric Model

The Peltier effect describes heat exchange that takes place at the junction of two different materials when electrical current flows between them. It is caused by the fact that the average energy that electrons transport can vary from material to material; when crossing between two such regions, charged carriers compensate for this energy difference by exchanging heat energy with the surrounding lattice. A material's Peltier coefficient Π is related [4] to the average energy (with respect to the Fermi energy) transported by its electrical carriers through Etr = q|Π|; the amount of heat exchanged for a given current I across a junction is equal to $\Delta\Pi$*I. For a semiconductor with carriers characterized by a Fermi-Dirac distribution f_{eq} with quasi-Fermi energy E_{Fn}, the Peltier coefficient is given by:

$$\overline{E_{tr}} = \frac{\int s(E)(E - E_{Fn})(-\frac{\partial f_{eq}}{\partial E})dE}{\int s(E)(-\frac{\partial f_{eq}}{\partial E})dE} \tag{1}$$

where the "differential" conductivity *s(E)* gives the contribution of a carrier at energy E to the overall conductivity [5]. The Peltier coefficient has an inverse relationship with doping, since decreasing the doping moves the Fermi energy further into the bandgap while the carriers are constrained to stay in the band. Approximate analytical expressions are given in terms of local carrier concentrations n and p by

$$\Pi_e \approx -\frac{kT}{q}\left(\ln\frac{N_C}{n} + \frac{5}{2}\right)$$
$$\Pi_h \approx \frac{kT}{q}\left(\ln\frac{N_V}{p} + \frac{5}{2}\right) \tag{2}$$

where N_C and N_V are the effective densities of states for electrons and holes respectively.

In Figures 1a and 1c we show a traditional Peltier cooler composed of *n*-type and *p*-type semiconductor regions that are connected by metallic junctions. In this case, energy transport takes place through the net motion of majority carriers, and the current-voltage relationship is that of a resistor. In Figures 1b and 1d, however, we have removed the center metallic junction, creating a *p-n* diode. This alters the energy transport considerably, as current is now carried by diffusing minority carriers. These carriers move against a large built-in field at the junction and consequently remove a relatively large amount of thermal energy from the lattice near the junction, depositing this energy upon recombination.

Optimization

In order to maximize the thermoelectric cooling that takes place at the junction, we find the current, doping levels, and region widths that balance Joule heating in the regions with Peltier cooling at the junction. We assume that the metal contacts constitute perfect heat sinks and that the diode is in the short-length limit for which all recombination takes place at the contacts; in a typical device, some recombination heat will be generated internally or will flow back from the contacts to the junction. As shown in Figure 2, there is an optimum current density for which the diode junction is maximally cooled. Notice that the optimal region widths are not symmetric; this is due to the fact that electrons are the preferred current carrier due to their higher mobility and consequently less Joule heating.

Using the standard model for carrier transport in a diode [REF SZE], we find that the maximum temperature difference between the contact heat sinks and the junction is given for a symmetric diode ($N_A = N_D$) in terms of carrier mobilities m_e and m_h by

$$\Delta T_{\mathrm{opt}} = \frac{1}{2 l r_n}\left(\frac{kT_j}{q}\right)^2\left(0.42 - 0.07 \ln \frac{m_e}{m_h}\right) \qquad (3)$$

where the thermal conductivity λ is assumed to be constant, r_n is the resistivity of the n-type region, and T_j is the junction temperature. We plot this in Figure 3 for several common material systems. In contrast to carrier concentration optimization for tranditional Peltier coolers, diode coolers perform best at the highest possible doping levels (neglecting the dependencies of recombination length and thermal conductivity on doping). For $Hg_{0.8}Cd_{0.2}Te$ diodes, ZT (equal to $2\frac{\Delta T_{\mathrm{opt}}}{T_j}$) can be as high as 0.2.

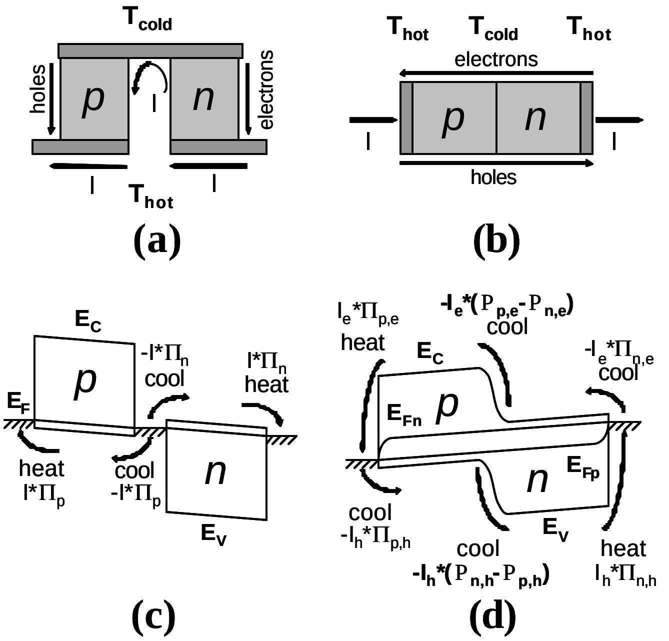

Figure 1. Structure and band diagram for (a,c) traditional Peltier cooler and (b,d) diode cooler.

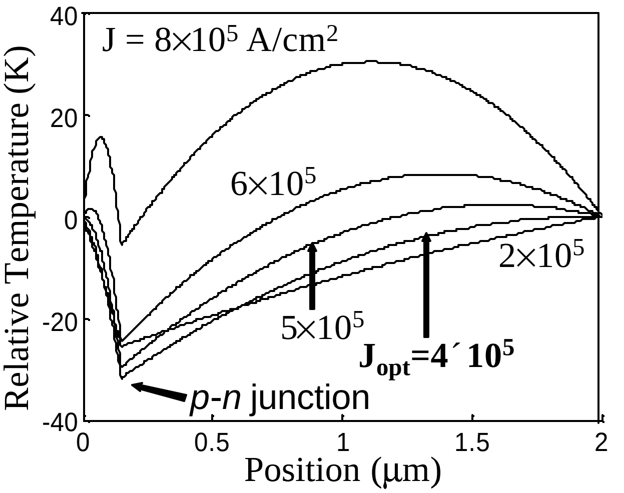

Figure 2. Temperature distribution for several current densities in a $Hg_{0.8}Cd_{0.2}Te$ diode doped symmetrically at 1×10^{19}.

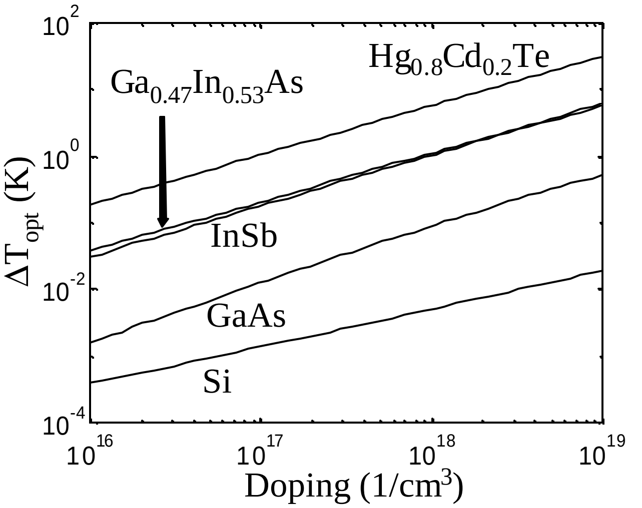

Figure 3. Maximum ΔT for several common materials.

Conclusions

Diode cooling effects show promise for the internal cooling of electrical devices. Recent efforts to probe the Seebeck coefficient on a small spatial scale in *p-n* diodes show promise as a means to verify experimentally minority-carrier thermoelectric cooling [6]. Although values of ZT are not as large as those found in conventional Peltier coolers, they can be useful in targeting specific device regions. In the case of semiconductor laser diodes, many characteristic parameters such as wavelength and efficiency are strongly dependent on the junction temperature, and the effects discussed here are expected to improve performance [1].

References

1. K. P. Pipe, R. J. Ram, and A. Shakouri, “Internal cooling in a semiconductor laser diode”, *IEEE Phot. Tech. Lett.* **14**, 453 (2002).

2. Yu. G. Gurevich, O. Yu. Titov, G. N. Logvinov, and O. I. Lyubimov, “Nature of the thermopower in bipolar semiconductors.” *Phys. Rev. B* **51**, 6999 (1995).
3. K. P. Pipe, R. J. Ram, and A. Shakouri, "Bias-dependent Peltier coefficient and internal cooling in bipolar devices", *Phys. Rev. B*, to be published Sept. 15 2002.
4. H. J. Goldsmid. *Electronic Refrigeration*. London, UK, Pion, 1986.
5. W. Nakwaski. “The Peltier coefficient in degenerate and non-degenerate semiconductors.” *Elect. Tech.* **14**, 81 (1983).
6. The L. Shi, J. Zhou, C. Yu, D. Kim, and Q. Hao. "Thermoelectric and thermal imaging and property measurements of nanostructures." U.S. - Japan Nanotherm Seminar: Nano. Therm. Sci. and Eng. Berkeley, CA, June 2002.