IMECE01/2-16-9-4

BIAS-DEPENDENT PELTIER COEFFICIENT IN BIPOLAR DEVICES

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ABSTRACT

Temperature stabilization is important in many microelectronic devices due to thermal constraints on device operation and lifetime. The work described here is an investigation of thermoelectric phenomena in bipolar devices, specifically the *p-n* diode. Current injection can modify the Peltier coefficient at interfaces; this can give rise to thermoelectric cooling or heating depending on device parameters. The bias-dependent Peltier coefficient is modeled using self-consistent drift-diffusion, and implications for device design are examined. The different regimes of bias for which cooling is achieved are described, as well as the effects of device length, doping, and heterojunction band offset. Extensions of the model are given for applications such as the internal cooling of semiconductor laser diodes.

INTRODUCTION

Excessive heat can cause deterioration in performance and lifetime for many microelectronic devices, necessitating thermal management in device packaging. This is often accomplished through the use of external thermoelectric (Peltier) coolers. Recently an approach more amenable to integration has been developed which takes advantage of thermionic and thermoelectric effects in III-V semiconductor heterostructures to obtain cooling power densities of several hundred W/cm^2 in micron-thick films (Shakouri et al., 1997; LaBounty et al., 2000). While the thermoelectric properties of traditional Peltier cooler are well understood, the theory describing the thermoelectric properties of the microelectronic devices themselves during operation is less worked out. This is the subject of the current work, specifically regarding the *p-n* diode.

PELTIER HEAT EXCHANGE

The Peltier effect describes heat exchange which 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 an electron transports can vary from material to material; when crossing between two such materials, a carrier compensates for this energy difference by exchanging heat energy with the surrounding atoms. A material's thermoelectric Peltier coefficient Π is related to the average energy transported by its electrical carriers through $\overline{E_{tr}} = \Pi * q$; the amount of heat exchanged for a given current I across a junction is equal to $\Delta\Pi * I$. For a semiconductor, the Peltier coefficient is given by

$$\Pi = \frac{1}{q}\frac{\int \sigma(E)(E-E_F)(-\frac{\partial f_{eq}}{\partial E})dE}{\int \sigma(E)(-\frac{\partial f_{eq}}{\partial E})dE} \tag{1}$$

where the "differential" conductivity $\sigma(E)$ gives the contribution of a carrier at energy E to the overall conductivity (Goldsmid, 1986; Rowe, 1995). From this equation it is apparent that Π increases as the carrier distribution becomes more asymmetric with respect to the Fermi level. The Peltier coefficient thus has an inverse relationship with doping, as decreased doping moves

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the Fermi level further into the bandgap while the carriers are constrained to stay above the band edge.

In the case of a layer of semiconductor material between two metal contacts, current ﬂow causes heat to be extracted at one metal/semiconductor junction and deposited at the other junction. In this case, current is carried by majority carriers which can be either electrons or holes, depending on whether the semiconductor is doped with donors (*n*-type doping) or acceptors (*p*-type doping), respectively. Since electrons and holes have opposite charge, carriers in *n*-type and *p*-type regions ﬂow in opposite directions for a given direction of current ﬂux, and heat will be extracted/deposited at opposite junctions. If a series of alternating *n*-type and *p*-type layers are connected by metal contacts, the heat exchange at the junctions will also alternate between cooling and heating. By fabricating a structure such that the cooling and heating junctions are on opposite sides of a ﬂat array, an overall heat ﬂux can be achieved from one side of the array to the other. This method of connecting an array of *n*-type and *p*-type materials with metal junctions such that they are electrically in series and thermally in parallel is the traditional scheme for most Peltier coolers. The operation of a traditional Peltier cooler is intrinsically unipolar, since the electrical current which contributes to the thermoelectric effect is carried only by majority carriers. The average energy transported by carriers is constant through each semiconductor region and does not vary with applied voltage bias.

P-N DIODE

While minority carrier effects are negligible in an *n*/metal/*p* device, they are crucial in a device such as a *p-n* diode, which is made up of a *p*-type region and an *n*-type region that are directly connected. In the case of an unbiased diode, a large built-in electric ﬁeld exists at the interface of the *n*-type and *p*-type regions; the drift current caused by this ﬁeld balances the diffusion current out of the doped regions. As the diode is forward biased, the potential barrier seen by carriers at the interface is decreased, and a net current develops according to the standard diode equations (Sze, 1981).

Since the current through a *p-n* diode can be carried by injected minority carriers in addition to majority carriers, it is fundamentally different than the case in which the *n*-type and *p*-type regions are connected by a metallic layer. The energy transported by minority carriers is strongly inﬂuenced by the applied forward voltage bias, due to the fact that the minority carrier concentration in the vicinity of the junction is exponentially related to the bias. The bipolar Peltier coefﬁcient is made up of both majority and minority carrier components, and the heat exchanged at the junction is no longer simply proportional to the current due to the decrease of the minority carrier Peltier coefﬁcient with increasing bias.
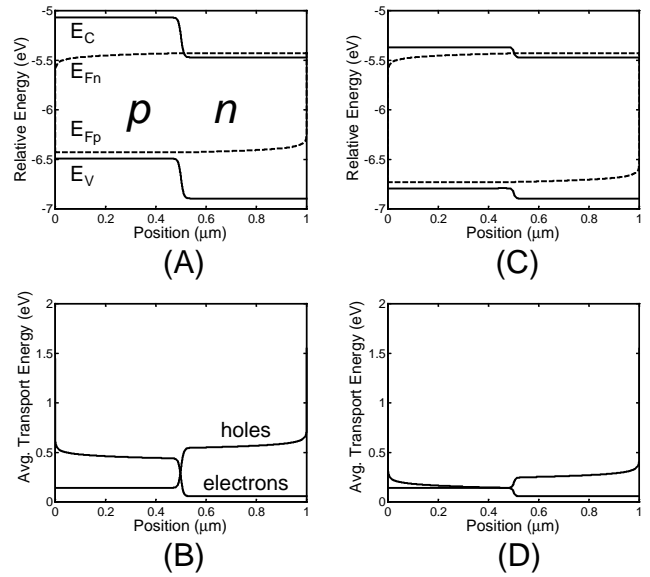

Figure 1. HOMOJUNCTION DIODE: BAND STRUCTURE (A,C) AND AVERAGE TRANSPORT ENERGY (B,D) AT 1.00V AND 1.30V RESPECTIVELY.

Homojunction Diode

An example of the relationship between Peltier coefﬁcient and bias voltage is shown in Figure 1. In this case, the drift-diffusion equations are solved self-consistently with Poisson's equation for a 1 μm GaAs diode doped symmetrically at $N_D = N_A = 5 \times 10^{17}$. Under a greater bias, the injected minority carrier concentration increases; this is reﬂected by the decrease of ($E_C - E_{Fn}$) within the *p*-type region and ($E_{Fp} - E_V$) within the *n*-type in Figures 1A and 1C. As these quantities decrease, the minority carrier Peltier coefﬁcients decrease within each region according to equation (1). This is shown in Figures 1B and 1D by the decrease in average transport energy for electrons in the *p*-type region and holes in the *n*-type region as the bias is increased. The decrease of the bipolar Peltier coefﬁcient within the *p*-type region is depicted in Figure 2, where the coefﬁcient is averaged over the thickness of the layer. Notice that the majority-carrier component stays roughly constant while the minority-carrier component decreases sharply. Because the hole effective mass is much greater than the electron effective mass, the hole current is much smaller than the electron current; the thermoelectric heat exchange is therefore expected to be dependent only on the electron components of the bipolar Peltier terms in the device.

Heterojunction Diode

In the case of a heterojunction diode, the difference in bandgap between the *p*-type and *n*-type regions places an additional constraint on carrier energy. Figure 3 shows the band
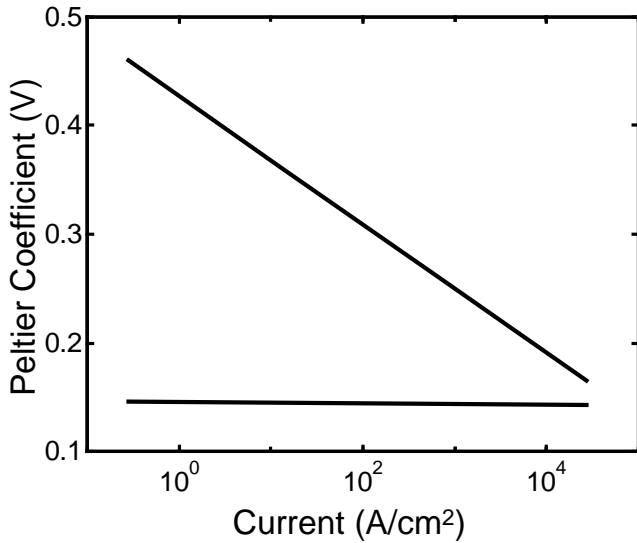
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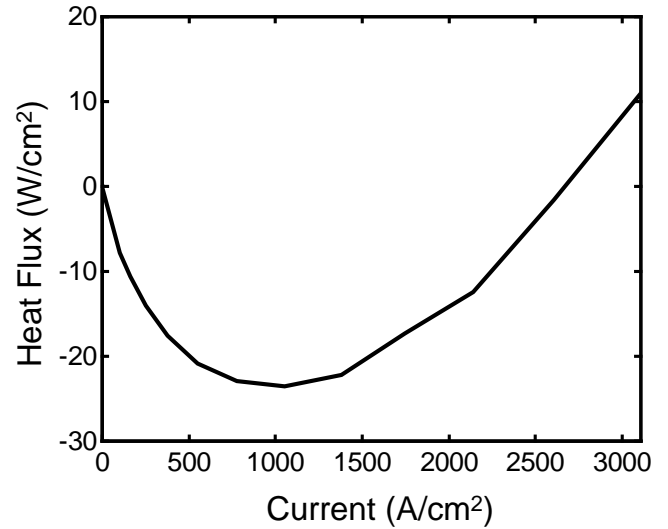Figure 2. BIAS DEPENDENCE OF THE BIPOLAR PELTIER COEFFI-CIENT OF THE P-TYPE REGION.

Figure 4. BIAS DEPENDENCE OF THE THERMOELECTRIC HEAT EXCHANGE IN A HETEROJUNCTION DIODE: BOTH COOLING AND HEATING CAN BE ACHIEVED DEPENDING ON THE BIAS POINT
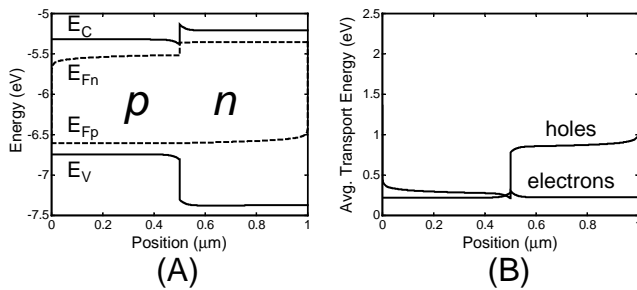

Figure 3. HETEROJUNCTION DIODE: BAND STRUCTURE (A) AND AVERAGE TRANSPORT ENERGY (B) AT 1.25V.

diagram and corresponding average carrier transport energy of a biased GaAs/AlAs diode doped symmetrically at $N_D = N_A = 5 \times 10^{16}$. The discontinuity in electron quasi-Fermi level at the junction will appear as a Joule heating source. By averaging the bipolar Peltier coef£cients on either side of the junction and calculating the respective carrier currents, the thermoelectric heat exchange at the junction can be derived. It is important to notice that this Peltier term can produce cooling or heating at the interface depending on the injection level, as shown in Figure 4.

CONCLUSION

In the calculations performed above, the variation of carrier density through a region was averaged so that it could be assigned a single Peltier coef£cient. For longer devices or in ar-

eas near ohmic contacts, in which the injected minority carrier density approaches its intrinsic value, the above method would need to be modi£ed. In a more detailed description, the thermoelectric heat exchange distribution changes in shape as a function of bias (but not in overall ¤ux due to energy conservation). Since the carrier Fermi level and energy bands stay roughly ¤at within each region under diffusive transport conditions, the heat exchange depicted in Figure 4 can be associated with the area very near (within the carrier energy relaxation length) the junction. Complementary terms which are not shown exist at the side ohmic contacts.

This model of the bipolar Peltier coef£cient can be extended to *p-i-n* devices, such as those used in laser structures (Pipe, 2001). Injection currents into the intrinsic core region are large when the laser is above threshold, and the standard unipolar thermoelectric model breaks down. By engineering the heterojunction band offsets appropriately, the thermoelectric heat source distribution can be rearranged to place cooling sources near the core.

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