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Minority-Carrier Transport in InGaAsSb Thermophotovoltaic Diodes

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Abstract

Uncoated InGaAsSb/GaSb thermophotovoltaic (TPV) diodes with 0.56 eV (2.2 µm) bandgaps exhibit external quantum efficiencies of 59 % at 2 µm. The devices have electron diffusion lengths as long as 29 µm in 8-µm-wide p-InGaAsSb layers and hole diffusion lengths of 3 µm in 6-µm-wide n-InGaAsSb layers. The electron and hole diffusion lengths appear to increase with increasing p- and n-layer widths. At 632.8 nm the internal quantum efficiencies of diodes with 1- to 8-µm-wide p-layers are above 89 % and are independent of the p-layer width, indicating long electron diffusion lengths. InGaAsSb has, therefore, excellent minority carrier transport properties that are well-suited to efficient TPV diode operation. The structures were grown by molecular-beam epitaxy.

Introduction

There has been a recent interest in thermophotovoltaic (TPV) electric power generation from blackbody sources at about 1000 °C [1, 2]. Candidate III-V compound materials for the TPV diode active region are InGaAs grown on InP and InGaAsSb grown on GaSb. Since the bandgap of the optimal TPV diode is about 0.55 eV, the InGaAs diodes have a compositionally graded layer interposed between the InP substrate and the InGaAs layer to accommodate the lattice mismatch. The InGaAsSb diodes are lattice-matched to the substrate. Lattice-matched devices may offer more possibilities in terms of bandgap engineering and the variety of material choices, but these advantages are not all clear at present. Nonetheless, while InGaAs diodes currently offer superior performance in terms of quantum efficiency and saturation current, owing in part to their longer-term development [3], InGaAsSb is demonstrating excellent minority-carrier transport characteristics that make it a very attractive material for TPV diodes.

In this paper we show quantum efficiencies of 59 % at 2 µm wavelength from an InGaAsSb/GaSb diode. The inferred electron diffusion length in this device is 29 µm. Our spectral quantum efficiency (SQE) curves compare favorably with recently reported results for both InGaAsSb and InGaAs TPV diodes [3].

Experimental Results

The TPV diodes discussed in this paper are designed to generate electrical power from 1000 °C blackbody radiation. The active region is a nominally 0.55 eV InGaAsSb p/n homojunction. To optimize the power-conversion efficiency, radiation up to the bandgap cut-off wavelength must be maximally absorbed, and the photo-generated carriers must be transported to the p/n junction with minimal loss. This places a tradeoff between widening the active region to increase optical absorption at near-bandgap wavelengths, where the absorption constant is relatively small, and decreasing the p- and n-layer thicknesses to maximize carrier collection at the junction. The values of the electron and hole diffusion lengths, L_e and L_h, are critical to the optimization of the TPV structure. In general, long diffusion lengths allow wide active regions, which lead to high quantum efficiencies. We undertook the study of the TPV diode SQE to determine the values of L_e and L_h.

The TPV structures were grown by solid-source, molecular-beam epitaxy (MBE) and were lattice-matched to the GaSb substrates in a manner very similar to that used for the growth of antimonide-based lasers [4, 5]. To study the transport properties of the diodes, 500-µm-diameter mesas were etched into the wafers, and individual mesa diodes were evaluated. Figure 1 schematically shows the vertical structure of the TPV diode.

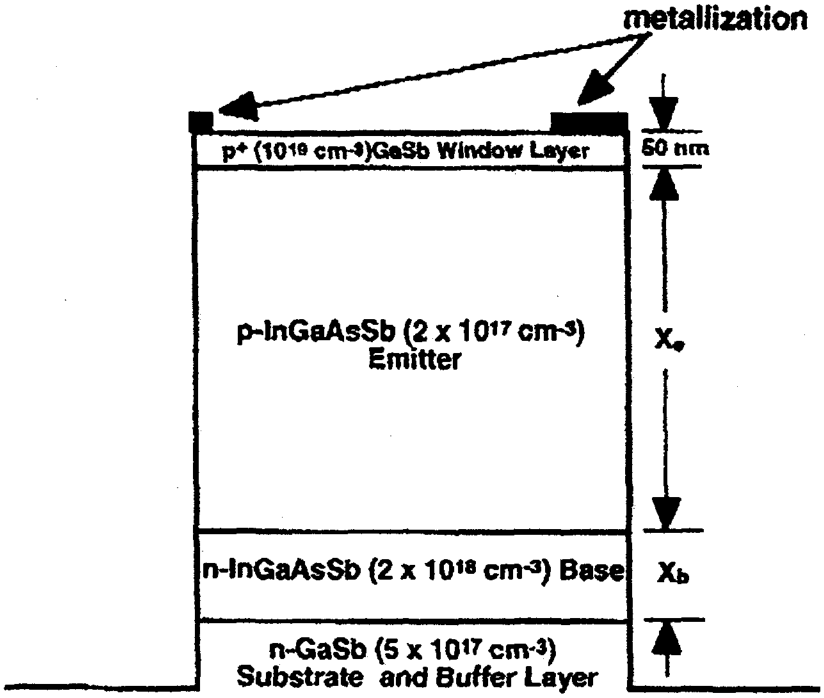

Figure 1. Vertical Layer structure of a p-on-n InGaAsSb TPV diode.

After growing a 500-nm-thick n-GaSb buffer layer on the n-GaSb substrate, the so-called base region is grown x_b µm thick. For most of the devices used in this work, x_b is 1 to 6 µm. The n-type base layers are Te-doped to about 2 x 10^{18} cm^{-3}. On top of the base the p-type emitter, Be-doped to 2 x 10^{17} cm^{-3}, is grown to thicknesses, x_e, ranging from 1 to 8 µm. A 50-nm-thick p^+ GaSb window layer, Be-doped to 10^{19} cm^{-3}, is grown on the emitter, completing MBE growth of this so-called p-on-n diode. The GaSb window layer insures very low electron recombination at the p^+-GaSb/p-InGaAsSb window-layer/emitter interface. While we have grown and characterized n-on-p TPV diodes, this work describes results from p-on-n devices.

Following growth, the wafer is thinned to 150 µm and metallized with standard Au/Ge/Ni/Au. The epitaxial surface is patterned and metallized with Cr/Au, and the mesas are etched several microns into the substrate using a bromine/methanol solution.

Relative SQE curves in the wavelength interval of 1 to 2.5 µm were obtained using a monochrometer with a known relative output-power spectrum. The diode's absolute quantum efficiency was measured using a 1.575 µm fibered diode laser with a known output-power-versus-laser-current characteristic. The relative SQE data were then adjusted to agree with the 1.575 µm absolute data. Absolute quantum efficiency measurements were also made at 632.8 nm using a HeNe laser.

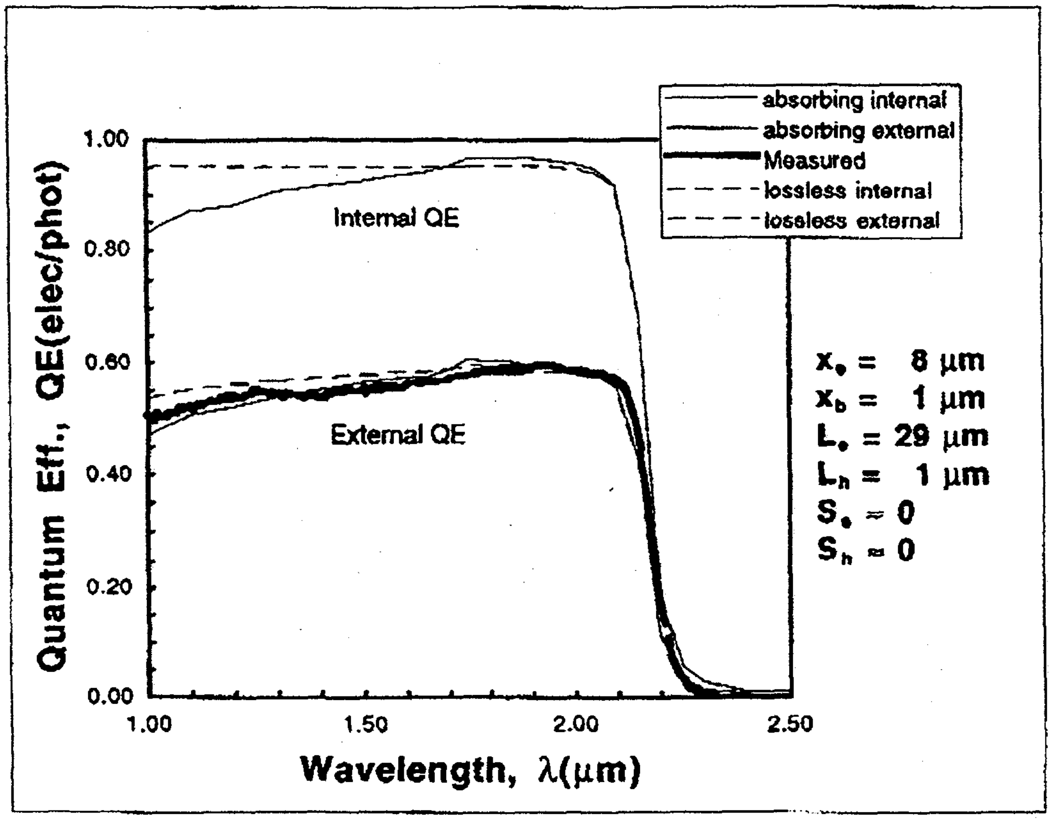

Figure 2. The spectral quantum efficiency of a p-on-n TPV diode having an 8-µm emitter and a 1-µm base. Model curves show external and internal SQE for absorbing and lossless GaSb window layers.

Figure 2 shows the SQE of a TPV diode having an 8-µm emitter and a 1-µm base, along with model curves for external and internal SQE. The measured SQE rises sharply at wavelengths shorter than the bandgap wavelength of 2.2 µm (0.56 eV), reaching a maximum QE of 59 % at 2 µm. As the wavelength decreases, the SQE slowly decreases to 50 % at 1 µm.

The model used to fit the SQE data is a simple, one-dimensional minority-carrier diffusion model commonly employed in SQE data analysis [6]. The measured reflectivity was used to calculate the photon density within the diode. In some cases we used the measured absorption constant of InGaAsSb, but mostly we used semi-empirical absorption data computed through a method similar to that of Borrego [7]. Accounting for absorption by the 50-nm-thick GaSb window layer, two sets of SQE curves were calculated: one set assuming that the window layer contributes all electrons photo-generated within it to the emitter (labeled "lossless internal (or external)" in Fig. 2), and the other set assuming that the window layer contributes no photo-generated electrons to the emitter (labeled "absorbing internal (or external)" in Fig. 2).

Electron and hole diffusion lengths, L_e and L_h, characterize minority-carrier transport. The base/substrate and the window-layer/emitter interfaces are characterized by recombination velocities S_b and S_e, respectively. Note that we normalize these recombination velocities to the "bulk" recombination velocity D/L, where D is the appropriate diffusion constant. In this way $S_b >> 1$ describes an interface that acts like a sink for holes, and $S_b << 1$, describes a nearly perfect reflecting interface. The total photo-current comprises contributions from the emitter, base, depletion-region, and possibly from the window layer.

The model curve of external SQE with an absorbing window describes the measured SQE curve in Fig. 2 reasonably well using the following parameters: $L_e = 29$ µm, $S_e \approx 0$, $L_h = 1$ µm, and $S_b \approx 0$. Note that in diodes where $x_e > x_b$, as in this device, the influence of the base on the SQE is negligibly small, and the parameters describing hole transport are, therefore, inaccurate. The values we used in this case were obtained from diodes having 1-µm bases and emitters. The best fit to the external SQE for a lossless window layer gives $L_e = 25$ µm, still much longer than x_e. In Fig. 2 the external SQE curve for a lossless window layer is calculated with $L_e = 29$ µm, which gives a curve that is slightly higher than the data.

Setting the spectral reflectivity to zero gives the internal-SQE model curves shown in Fig. 2. From 1 to 2.1 µm the internal QE is above 80 %, and it is over 90 % between 1.4 and 2.1 µm. Absorption in the GaSb window layer causes the gradual decrease in the SQE beginning at 1.7 µm. Assuming complete photo-electron collection from a lossless window layer, the internal SQE is constant at 95 % for wavelengths shorter than about 2 µm, as indicated in Fig. 2.

Remarkably long electron diffusion lengths have also been inferred from the SQE data of diodes with different emitter widths. The following relation describes the majority of our observations: $L_e \geq x_e$. Figure 3 shows our

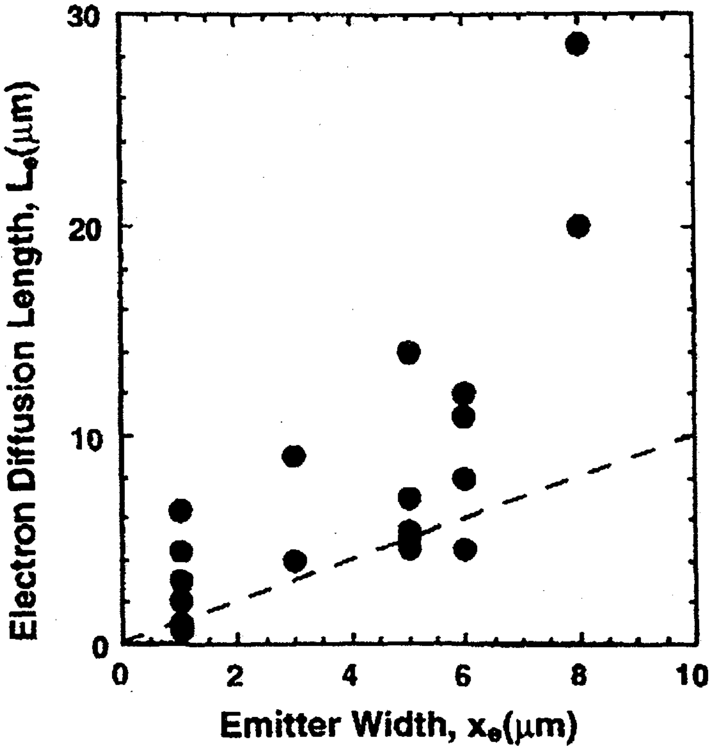

Figure 3. The inferred electron diffusion length for TPV diodes with emitter widths of 1 to 8 μm.

inferred values of L_e for diodes with emitter widths of 1 to 8 μm. The dashed line in Fig. 3 denotes $L_e = x_e$. Twenty-one of the twenty-four data shown in Fig. 3, or 88 %, lie on or above the line, strongly suggesting that the relation $L_e \geq x_e$ is valid.

The model also fits the SQE data reasonably well by assuming non-zero values of S_e, but consequently, even larger values of L_e must be used. Our approach has been to assume that the smallest value of L_e, consistent with the data, is the most prudent estimation.

Measurements of the QE at 632.8 nm of diodes with different emitter widths corroborates the above results. Figure 4 shows the inferred internal QE

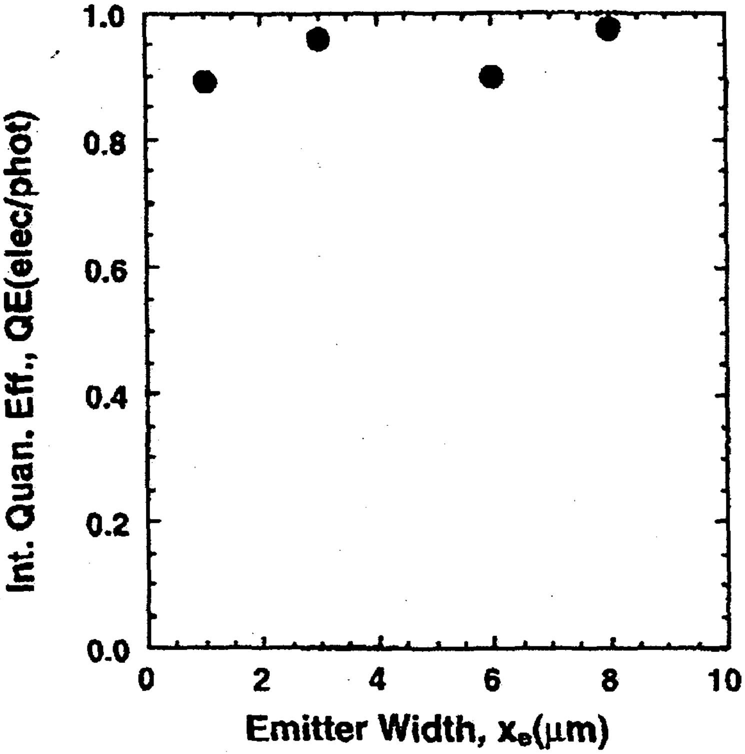

Figure 4. High internal quantum efficiency of TPV diodes at 632.8 nm.

at 632.8 nm for diodes with 1-, 3-, 6-, and 8-μm emitters. Light at 632.8 has an estimated absorption constant in 0.56-eV InGaAsSb greater than 10^5 cm^{-1}, so that photo-electrons are generated very close to the GaSb/InGaAsSb interface. It is also energetic enough to create more than one electron-hole pair in the InGaAsSb [8], which would increase the measured QE. The measured internal QE is essentially independent of emitter width. Its high values between 89 and 98 % strongly imply that $L_e >> x_e$, in basic agreement with the conclusions reached from our elementary analysis of the SQE data. They also suggest that the GaSb window is lossless.

To a lesser extent, we have observed the same phenomenon with respect to hole transport. Not as many wide-base diodes were measured, since efficient p-on-n TPV diodes will have wider emitters than bases, owing to the fact that electrons have the longer diffusion length. Figure 5 shows the dependence of

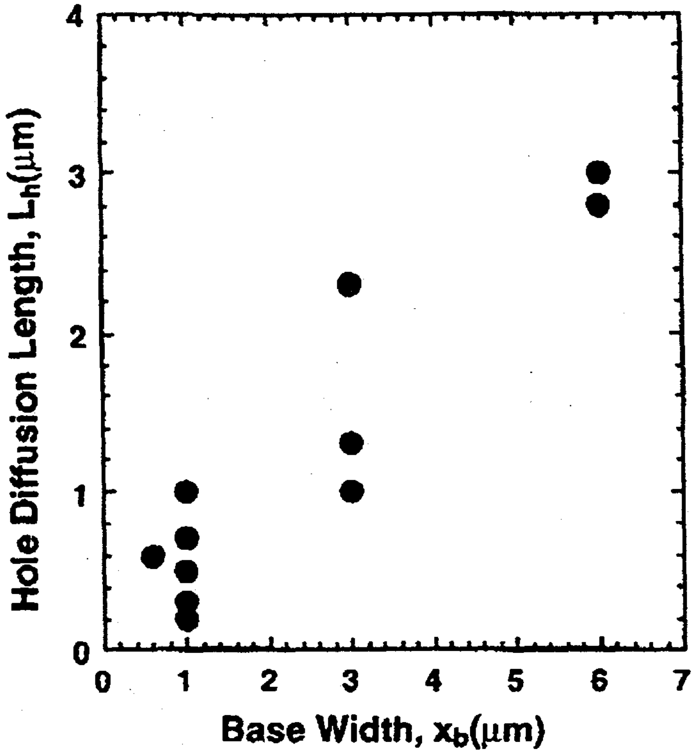

Figure 5. The inferred hole diffusion length for TPV diodes with base widths of 1 to 6 μm.

L_h on base thickness. As in the case of electrons, the values of L_h inferred from the model increase with increasing base width, but the magnitudes of L_h for a given x_b are only about one tenth that of electrons. This result may reflect the lower mobility and non-radiative lifetime of holes. The base layers of these diodes were doped an order of magnitude higher than were the emitter layers, which might decrease the holes' non-radiative lifetime.

Conclusions

In conclusion, we have shown that the transport of photo-generated electrons in p-InGaAsSb is very efficient. p-on-n TPV diodes with bandgaps of 0.56 eV have external quantum efficiencies of 59 % at 2 μm and exhibit electron diffusion lengths of 29 μm in an 8-μm-wide emitter. The electron diffusion length appears to increase with increasing emitter width. Similarly, the hole diffusion length appears to increase with increasing base width, although the hole diffusion lengths are about one tenth those of the electron. These results were corroborated by the internal quantum efficiencies greater than 89 % that were measured at 632.8 nm. Given these results, an optimized InGaAsSb/GaSb p-on-n TPV diode with a 6- to 8-μm-wide emitter will have an excellent spectral quantum efficiency.

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