KAPL-P-000191

(K97116)

CONF-980103--

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October 1997

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THE QUANTUM EFFICIENCY OF 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 , which corresponds to an internal quantum efficiency of 95%. The structures were grown by molecular-beam epitaxy. 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, respectively. These excellent minority carrier transport properties of InGaAsSb are well-suited to efficient TPV diode operation.

INTRODUCTION

There has been a recent interest in thermophotovoltaic (TPV) electric power generation from blackbody sources at about 1300 K (Coutts 1994 and Benner 1995). 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. Nonetheless, while InGaAs diodes currently offer superior performance in terms of quantum efficiency and saturation current, owing in part to their longer development (Charache 1996), InGaAsSb is demonstrating excellent minority-carrier transport characteristics that make it a very attractive material for TPV diodes (Wang 1997 and Martinelli 1997).

Quantum efficiencies of 59% at 2 μm wavelength from an InGaAsSb/GaSb diode were measured. The electron diffusion length, as inferred from a one-dimensional diffusion model of the spectral quantum efficiency (SQE), is 29 μm in this device. Our SQE curves compare favorably with recently reported results for both InGaAsSb and InGaAs TPV diodes (Charache 1996).

EXPERIMENTAL RESULTS

The TPV diodes discussed are designed to generate electrical power from 1300 K 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. There is, hence, a trade-off 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 this 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 (Lee 1997 and Lee 1995). To study the transport properties of the diodes, 500- μm -diameter mesas were etched into the wafers, metallized, 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 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 $2 \times 10^{18} \text{ cm}^{-3}$. On top of the base the p-type emitter, Be-doped to $2 \times 10^{17} \text{ cm}^{-3}$, 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 p-on-n diode. The GaSb window layer insures very low electron recombination at the p⁺-GaSb/p-InGaAsSb window-layer/emitter interface.

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 monochromator 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.

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 .

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.

The model used to fit the SQE data is a simple, one-dimensional minority-carrier diffusion model commonly employed in SQE data analysis (Sze 1981). The measured reflectivity was used to calculate the photon flux into the diode. In some cases we used the measured absorption constant of InGaAsSb, but mostly we used calculated semi-empirical absorption data (Borrego 1994). 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 Figure 2), and the other set assuming that the window layer contributes no photo-generated electrons to the emitter (labeled "absorbing internal (or external)" in Figure 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 $S_b \gg 1$ describes an interface that acts like a sink for holes, and $S_b \ll 1$ 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 Figure 2 reasonably well using the following parameters: $L_e = 29 \mu\text{m}$, $S_e \approx 0$, $L_h = 1 \mu\text{m}$, and $S_h \approx 0$. Note that in diodes where $x_e > x_b$, as in this device, the influence on the SQE of photocurrent from the base is negligibly small, and the parameters describing hole transport are, therefore, inaccurate. The values we used in this case were obtained from diodes having $1\text{-}\mu\text{m}$ emitters and bases. The best fit to the external SQE for a lossless window layer gives $L_e = 25 \mu\text{m}$, still much longer than x_e . In Figure 2 the external SQE curve for a lossless window layer is calculated with $L_e = 29 \mu\text{m}$, 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 Figure 2. From 1 to $2.1 \mu\text{m}$ the internal QE is above 80%, and it is over 90% between 1.4 and $2.1 \mu\text{m}$. Absorption in the GaSb window layer causes the gradual decrease in the internal SQE beginning at $1.7 \mu\text{m}$. Assuming complete photo-electron collection from a lossless window layer, the internal SQE is constant at 95% for wavelengths shorter than $2 \mu\text{m}$, as indicated in Figure 2.

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 inferred values of L_e for diodes with emitter widths of 1 to $8 \mu\text{m}$. The dashed line in Figure 3 denotes $L_e = x_e$. Twenty-one of the twenty-four data shown in Figure 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, values of L_e larger than $29 \mu\text{m}$ 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.

The vertical axis at the right in Figure 3 indicates the electron lifetimes τ_e in the emitter. τ_e is calculated from the relation $\tau_e = (kT/q)\mu_e/L_e^2$, in which μ_e , the minority electron mobility, is assumed equal to the majority electron mobility: namely, $1600 \text{ cm}^2/\text{Vs}$. An estimate of the radiative lifetime in 0.56-eV InGaAsSb doped to $2 \times 10^{17} \text{ cm}^{-3}$ is 50 ns (Varshni 1964), which corresponds to $L_e = 14 \mu\text{m}$. The inferred electron lifetimes in $8\text{-}\mu\text{m}$ emitters are between 100 and 200 ns. One of the possible explanations for these long lifetimes is photon recycling (Garbuzov 1977 and Khalfin 1978): the creation of electron-hole pairs through the re-absorption of luminescent photons arising from radiative recombination. The lifetime-enhancing effect of photon recycling has been observed in other III-V compounds, such as GaAs (Ahrenkiel 1989).

To a lesser extent, we 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 4 shows the dependence of L_h on base width. 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 to an estimated 5 ns, which corresponds to $L_h = 1.6 \mu\text{m}$. For $6\text{-}\mu\text{m}$ wide bases the inferred lifetimes exceed this estimate, suggesting the presence of photon recycling.

FIGURE 3. The Inferred Electron Diffusion Length for TPV Diodes with Emitter Widths of 1 to 8 μm .

FIGURE 4. The Inferred Hole Diffusion Length for TPV Diodes with Base Widths of 1 to 6 μm .

CONCLUSION

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. Given these results, an optimized InGaAsSb/GaSb p-on-n TPV diode with a 6- to 8- μm -wide emitter should have an excellent SQE.

Acknowledgments

We gratefully acknowledge the technical assistance of M. G. Harvey, R. Farkas, D. R. Capewell, and R. J. Matarese.

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