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FILL FACTOR OF InGaAsSb/ GaSb TPV CELLS**

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A NOVEL APPROACH FOR THE IMPROVEMENT OF OPEN CIRCUIT VOLTAGE AND FILL FACTOR OF InGaAsSb/GaSb THERMOPHOTOVOLTAIC CELLS

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Abstract

Heterojunction $n\text{-Al}_{0.25}\text{Ga}_{0.75}\text{As}_{0.02}\text{Sb}_{0.98}$ / $p\text{-In}_{0.16}\text{Ga}_{0.84}\text{As}_{0.04}\text{Sb}_{0.96}$ thermophotovoltaic (TPV) cells were grown by molecular-beam epitaxy on $n\text{-GaSb}$ -substrates. In the spectral range from $1\text{ }\mu\text{m}$ to $2.1\text{ }\mu\text{m}$ these cells, as well as homojunction $n\text{-p-In}_{0.16}\text{Ga}_{0.84}\text{As}_{0.04}\text{Sb}_{0.96}$ cells, have demonstrated internal quantum efficiencies exceeding 80%, despite about a 200 meV barrier in the conduction band at the heterointerface. Estimation shows that the thermal emission of the electrons photogenerated in p -region over this barrier can provide high efficiency for hetero-cells if the electron recombination time in $p\text{-In}_{0.16}\text{Ga}_{0.84}\text{As}_{0.04}\text{Sb}_{0.96}$ is longer than 10 ns. Keeping the same internal efficiency as homojunction cells, hetero-cells provide a unique opportunity to decrease the dark forward current and thereby increase open circuit voltage (V_{∞}) and fill factor at a given illumination level. It is shown that the decrease of the forward current in hetero-cells is due to the lower recombination rate in n -type wider-bandgap space-charge region and to the suppression of the hole component of the forward current. The improvement in V_{∞} reaches 100% at illumination level equivalent to 1 mA/cm^2 and it decreases to 5% at the highest illumination levels ($2\text{-}3\text{ A/cm}^2$), where the electron current component dominates in both the homo- and heterojunction cells. Values of V_{∞} as high as 310 meV have been obtained for a hetero-cell at illumination levels of 3 A/cm^2 . Under this condition, the expected fill factor value is about 72% for a hetero-cell with improved series resistance. The heterojunction concept provides excellent prospects for further reduction of the dark forward current in TPV cells.

INTRODUCTION

Thermophotovoltaic (TPV) cells intended for direct conversion of blackbody radiation to electrical energy should be based on the narrow band gap (E_g) materials which provide effective absorption of the blackbody infrared radiation. For example, given a blackbody at a temperature of $1000\text{ }^{\circ}\text{C}$, materials with $E_g \leq 0.55\text{ eV}$ are desirable (Wojtczuk 1994). $\text{In}_x\text{Ga}_{1-x}\text{As}$ compounds with $x = 0.7\text{-}0.75$ grown on InP substrates were the first materials successfully used for TPV application. However, the fact that $\text{In}_{0.7}\text{Ga}_{0.3}\text{As}$ layers are lattice mismatched with InP substrate can limit the device performance. Recently, $\text{In}_{0.16}\text{Ga}_{0.84}\text{As}_{0.04}\text{Sb}_{0.96}$ layers lattice matched to GaSb substrate were utilized for TPV cell fabrication and the results comparable to the best achievements for InGaAs/InP devices have been obtained. (Wang 1997, Martinelli 1997 and Charache 1997). Both types of TPV cells display internal quantum efficiencies (η_i) higher than 80% for radiation from $1\text{ }\mu\text{m}$ to $2.1\text{ }\mu\text{m}$; hence, the potential for improvement in η_i for these materials is very small. On the other hand, the open circuit voltage for TPV cells designed for $1000\text{ }^{\circ}\text{C}$ blackbody radiation is only about 55% of the 0.55 eV material band gap (Charache 1997), and a search for V_{∞} improvement is very reasonable.

The opportunities of increasing V_{∞} using a heterojunction cell design is considered in this paper. High quality heterojunctions in the AlGaAsSb/InGaAsSb system lattice matched with GaSb are well developed

for the laser diode applications, while the possibility of growing a heterojunction between $\text{In}_{0.7}\text{Ga}_{0.3}\text{As}$ and a wider bandgap compound is questionable. This fact enhances the advantages of GaSb lattice-matched materials for TPV application compared with those of InGaAs/InP system.

STRUCTURES, DEVICE FABRICATION AND MEASUREMENTS

The TPV cells under consideration were prepared from three structures grown by solid-source, molecular-beam epitaxy. Two structures (A and B) were identical and comprise a homo-p-n-junction in $\text{In}_{0.16}\text{Ga}_{0.84}\text{As}_{0.04}\text{Sb}_{0.96}$, while the third structure (C) includes a $\text{n-Al}_{0.25}\text{Ga}_{0.75}\text{As}_{0.02}\text{Sb}_{0.98}$ / $\text{p-In}_{0.16}\text{Ga}_{0.84}\text{As}_{0.04}\text{Sb}_{0.96}$ heterojunction. The heterojunction structure C was different from structures A and B only in the composition of the n-region of p-n junction. As seen from Fig. 1a, the layers comprising these structures were grown on n-GaSb substrates in the following order: a 0.5 μm -thick n-GaSb buffer layer; a 1 μm -thick Te-doped n-region; a 3 μm -thick, Be-doped, p- $\text{In}_{0.16}\text{Ga}_{0.84}\text{As}_{0.04}\text{Sb}_{0.96}$ -region; and a 50 nm-thick, heavily Be-doped, GaSb-window layer. In the case of structures A and B, the n-region has the same composition as the p-region, but was Te-doped to $n = 3 \times 10^{17} \text{ cm}^{-3}$. In the case of the heterojunction structure, the $\text{n-Al}_{0.25}\text{Ga}_{0.75}\text{As}_{0.02}\text{Sb}_{0.98}$ layer doped with Te to $n = 5 \times 10^{17} \text{ cm}^{-3}$ served as the n-region of the heterojunction. The p-region in all the structures was doped to $p = 1 \times 10^{18} \text{ cm}^{-3}$, while the top GaSb window had a hole concentration of $2 \times 10^{19} \text{ cm}^{-3}$.

Small-area, mesa-configuration cells were prepared from structures A and C and large area, $4 \times 4 \text{ mm}^2$ plane cells were fabricated from structures B and C. The mesa-devices (Figure 1a) had a ring contact on the p-side around the 500 μm -diameter illuminated area. The configuration of the finger-stripe contact on the surface of the planar devices is shown in Figure 1b. Ti-Pt-Au/Ti-Au and Cr-Au multi-layer compositions were used for p-contact preparation in the planar- and mesa-devices, respectively. In the case of the planar cells, 5- μm -thick layers of Au were plated on the top of the stripe-contacts to reduce device resistance. For both types of devices, after p-contact deposition the wafers were thinned to 150 μm and then Au/Ge/Ni/Au (planar devices) or Sn-Au (mesa cells) ohmic contacts were prepared on the substrate side.

The TPV cells of both types were mounted with In solder into the copper heatsinks and bolted to a water-cooled, temperature-controlled block. A high-power 1.5 μm diode laser was used as the radiation source for the mesa-device testing. An incandescent microscope illuminator was used to obtain uniform illumination for the large area planar cells. A lens focused illuminator light provided photocurrent densities comparable to or higher than those obtained from the 1000 $^{\circ}\text{C}$ blackbody radiation source. For both types of cells the short circuit current density (J_{sc}) and open circuit voltage were measured as a function of illumination. Some precautions were undertaken during J_{sc} measurements for large area devices to maintain short-circuit conditions under high illumination levels. The photocells were connected to a load by 1 mm diameter, 5-cm-long wires soldered to the cells. The resistance of the circuit without any load resistance was less than 0.002 Ω . A 0.1 Ω load resistance was used for the J_{sc} measurements. Besides J_{sc} versus V_{oc} characteristics, the absolute values of the external quantum efficiency (η_e) and the spectral dependence of η_e were measured, using technique described earlier (Martinelli 1997).

QUANTUM EFFICIENCY AND BAND DIAGRAM OF HETEROJUNCTION CELLS

The spectral dependencies of η_e for uncoated heterojunction mesa-cell (structure C, solid line) and homojunction cell (structure A, dashed line) are shown in Figure 2. For both devices η_e exceeds 50% in the broad spectral range from 1 μ to 2.1 μm . Taking into account that the reflectivity of uncoated cell surfaces varies from 42% to 39% in this spectral range, one can find that for both devices more than 80%

(a)

(b)

FIGURE 1. (a) Cross Section of Mesa-Cell, (b) p-side-Contact Configuration for Planar Cell.

of the photogenerated carriers contribute to the photocurrent. Two conclusions follow from this result: (1) the diffusion length for the excess electrons in $p\text{-In}_{0.16}\text{Ga}_{0.84}\text{As}_{0.04}\text{Sb}_{0.96}$ layers is considerably longer than p -layer thickness (Martinelli 1997), and (2), the heterojunction barrier does not increase the recombination losses in the p -region.

FIGURE 2. Spectral Dependence of External Quantum Efficiency for Uncoated Hetero- and Homojunction Mesa-Cells.

Figure 3 shows the energy-band diagram of the $n\text{-Al}_{0.25}\text{Ga}_{0.75}\text{As}_{0.02}\text{Sb}_{0.98}/p\text{-In}_{0.16}\text{Ga}_{0.84}\text{As}_{0.04}\text{Sb}_{0.96}$ heterojunction cell under an illumination level corresponding to $V_{oc} = 300$ mV. Tsou's band parameters were used for the energy-band diagram (Tsou 1992). The hetero-barrier of 220 meV height in the conduction band might block the flow of the excess electrons generated in p -region. The value of the additional recombination loss caused by this barrier depends on the ratio of the rate of the electron thermal emission over the barrier to the recombination rate in the p -region. Estimations show that greater than 80% electron thermal injection efficiency over this barrier can be reached if the electron lifetime in p -region, τ_e , is longer than 10 ns. Taking a value of $1600 \text{ cm}^2/\text{V s}$ for electron mobility, μ_e , in $p\text{-InGaAsSb}$, one can obtain a value of $6 \mu\text{m}$ for electron diffusion length, L_e , in p -region ($L_e = \sqrt{\tau_e \cdot D_e}$). This value is in agreement with estimation from the data on the shape of the spectral response (Martinelli 1997).

FIGURE 3. Energy-Band Diagram of a Heterojunction Cell.

CURRENT-VOLTAGE AND J_{sc} VERSUS V_{oc} CHARACTERISTICS

The dark forward I-V characteristics for homo- and heterojunction mesa-cells are shown in Figure 4. The excess current in homojunction is caused by the recombination in the space-charge region and by the hole injection into the n-region of the p-n junction. In the case of the heterojunction with a heavily doped p-InGaAsSb region, the main part of the space-charge region is located in the wider band gap AlGaAsSb material. Assuming that the deep level concentration in $n\text{-Al}_{0.25}\text{Ga}_{0.75}\text{As}_{0.02}\text{Sb}_{0.98}$ does not exceed significantly that in the $n\text{-In}_{0.16}\text{Ga}_{0.84}\text{As}_{0.04}\text{Sb}_{0.96}$, the rate of recombination via deep levels in the space charge region will be decreased by the factor $\exp(-\Delta E_g/2kT)$. Where $\Delta E_g = 400$ mV is the difference between the bandgaps of $\text{Al}_{0.25}\text{Ga}_{0.75}\text{As}_{0.02}\text{Sb}_{0.98}$ and $\text{In}_{0.16}\text{Ga}_{0.84}\text{As}_{0.04}\text{Sb}_{0.96}$. The offset barrier in the valence band of the heterojunction should also lead to reduction of the hole injection current.

Due to the reduction of these two current components, the I-V characteristics of heterojunction cells, at the 200 to 300 mV voltage range, can be approximated by the exponent with ideality factor of $n = 1.1$. Thus the corresponding current component is the result of the electron injection into $p\text{-In}_{0.16}\text{Ga}_{0.84}\text{As}_{0.04}\text{Sb}_{0.96}$. The electron current components in hetero- and homojunction TPV cells should be equal at a given voltage (V), and solid and dashed curves converge at $V > 350$ meV, confirming this fact. This convergence also shows that the series resistances are the same for hetero- and homojunction devices.

It is clear that there is a direct correspondence between the dark forward I-V characteristic and the V_{oc} value at a given illumination level. The open circuit voltage at a given illumination level can be found from the relation:

FIGURE 4. Dark Forward I-V Characteristics of the Homojunction (Structure A) and Heterojunction (Structure C) Mesa-Cells.

$$\eta_e \cdot P = S \cdot J(V)_{V=V_{oc}} / q, \quad (1)$$

where: P (photon/s) is the photon flux incident on the device active area (S), η_e is a TPV cell external quantum efficiency, and $J(V) = J_0 e^{(qV/nkT)}$ is the diode dark forward current density at $V = V_{oc}$. It follows from equation (1) that a decrease of the forward current at a given voltage increases the photovoltage at a given illumination.

Figure 5 demonstrates the dependencies of the short current densities on the open circuit voltage, measured for the compared mesa-devices using a high-power 1.5 μm laser as the radiation source. In accordance with difference in dark I-V-characteristics shown in Fig. 4, the V_{oc} values are higher for the heterojunction cell throughout the range of the illumination levels used. The V_{oc} difference is 70 meV at the lowest excitation level, 30 meV at $J_{sc} = 0.1 \text{ A/cm}^2$, and about 12 meV at $J_{sc} = 2 \text{ A/cm}^2$. At the maximum laser power, the measured values of J_{sc} and V_{oc} were 30 A/cm^2 and 375 meV for the heterojunction cell, and these values were lower (27 A/cm^2 and 360 mV) for the homojunction cell.

The fraction of the J_{sc} versus V_{oc} dependence corresponding to the electron injection current (Figure 5) is significantly more pronounced than in the case of I-V characteristics (Figure 4), because of the absence of the series resistance "masking" effect. The value of J_0 found for the electron current component (Figure 5) is about $30 \pm 10 \mu\text{A/cm}^2$.

FIGURE 5. J_{sc} versus V_{oc} Dependencies for Homojunction (Structure A) and Heterojunction (Structure C) Mesa-Cells.

The dependencies of J_{sc} versus V_{oc} for planar, $4 \times 4 \text{ mm}^2$ hetero- and homojunction (structure B) cells are shown in Figure 6. The comparison of these dependencies demonstrates the same features as seen in Figure 5 and confirms that the difference between homo- and heterojunction devices is not related to structure or device fabrication peculiarities. The J_{sc} - V_{oc} characteristic for the heterojunction cell in Figure 6 can be well fitted exponentially with an ideality factor of 1.05 ± 0.04 . The 4% variation of the ideality factor leads to the variation of J_0 in the range from 25 to $50 \mu\text{A}/\text{cm}^2$.

SERIES RESISTANCE AND FILL FACTOR

There are reasons to assume that in the planar cells the area-distributions of the forward current and photocurrent are similar and uniform over the device area. The solid circles in Figure 6 represent dark forward I-V characteristic of the heterojunction cell. The voltage difference in I-V and J_{sc} - V_{oc} characteristics can be attributed to the effect of the series resistance on I-V characteristic. The values of the device specific resistance ($\Omega \text{ cm}^2$) calculated from these differences are shown in Figure 7. As shown, the series specific resistance strongly depends on the current density in the range of the current density less than $700 \text{ mA}/\text{cm}^2$, and it is approximately constant ($0.02 \Omega \text{ cm}^2$) at higher current densities.

The obtained values of R_s were used to calculate the fill factor (FF) for the hetero-cell under discussion. The FF experimental data are shown by the large solid circles in Figure 8. To obtain these data-points, the measurements of the photovoltage and photocurrent as a function of the load resistance were performed at five levels of illumination. The optimum load for the point measured at the lowest illumination level was 13.2Ω , and 0.67Ω at the highest illumination levels.

FIGURE 6. Solid Squares and Open Circles Present $J_{sc} - V_{oc}$ Characteristics for Planar Homojunction Cell (Structure B) and Heterojunction Cell (Structure C). Dark I-V Characteristic for Planar Hetero-Cell is Shown by Solid Circles.

FIGURE 7. Dependence of Series Specific Resistance on Current for Planar Heterojunction Cell Determined from the Comparison of $J_{sc} - V_{oc}$ and the Forward Dark I-V Characteristics Shown in Figure 6.

FIGURE 8. Curves 1 and 2, are the Fill Factor Calculated for a Planar Hetero-Cell with $R_s = 0$ and with Data on R_s Taken from Figure 7. The large Solid Circles Represent Experimental Fill-Factor Data for a Planar Hetero-Cell.

The fill factor for the considered hetero-cell was calculated under two different assumptions: (1) curve 1 in Figure 8 gives "ideal" FF calculated neglecting series resistance and (2) curve 2 was calculated using values of the series specific resistance shown in Figure 7. Unexpectedly, the FF experimental values at low and moderate illumination levels were higher than those calculated with the experimental values of series resistance. This means that series resistance for photocurrent is less than the series resistance for the dark current in the range of current densities $100 < J < 1000 \text{ mA/cm}^2$. The difference in the area distribution for the dark current and photocurrent, or the incorporation of an additional rectifying junction could be the reasons for this phenomena. At the excitation level of practical interest ($J \geq 1000 \text{ mA/cm}^2$) measured values of FF are in reasonable agreement with those calculated for cell specific resistance $R_s = 0.02 \Omega \text{ cm}^2$ that weakly depend on current in this region of current densities. At the highest illumination levels the influence of non-ohmic resistance components on FF become insignificant in comparison to the ohmic series resistance. However, the corresponding value of specific resistance $R_s = 0.02 \Omega \text{ cm}^2$ is too high in comparison with expected bulk device specific resistance, and it leads to the decrease of FF for studied photocells from an "ideal" value of 0.72 to an observed value of 0.55 at the highest illumination level. Some improvements in TPV cell fabrication should decrease R_s to the level at which FF values close to the ideal will be achieved. The estimation for this "ideal" case shows that for radiation with photon energy equal to the p-region bandgap a power conversion efficiency as high as 42% could be achieved for heterojunction cells at photocurrent density of 3 A/cm^2 , and possibly can be even higher at higher illumination levels.

CONCLUSION

In conclusion, heterojunction $n\text{-Al}_{0.25}\text{Ga}_{0.75}\text{As}_{0.02}\text{Sb}_{0.98} / p\text{-In}_{0.16}\text{Ga}_{0.84}\text{As}_{0.04}\text{Sb}_{0.96}$ TPV cells lattice-matched with GaSb have been demonstrated. Their internal efficiency in the spectral range from $1 \mu\text{m}$ to $2.1 \mu\text{m}$, as well as efficiency of homojunction $n\text{-p-In}_{0.16}\text{Ga}_{0.84}\text{As}_{0.04}\text{Sb}_{0.96}$ cells, exceeds 80%, despite about a 200 meV barrier in the conduction band at the heterointerface. The forward dark current at a given voltage is less in the heterojunction cells than that in homojunction devices because the space charge recombination rate and

current hole component of this current are considerably suppressed. This leads to a 100% increase of the open circuit voltage in the heterojunction cell at low illumination levels. The improvement in V_{oc} decreases to 5% at the illumination levels of practical interest ($2-3 \text{ A/cm}^2$) because the electron component of the dark current dominates at this condition in both homo- and heterojunction devices. The reduction of the electron dark current component (which can be related to both intrinsic, bulk recombination and surface recombination in the p-region) seems to be a key factor for further improvement in the TPV cell performance. The corresponding improvement is expected to be more significant for the heterojunction cells, since other current components are already suppressed in this case.

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References

- Charache, G. W. et al. (1997) "Infrared Materials for Thermophotovoltaic Applications" presented at the Electronic Materials Research Conference, Ft. Collins, CO, June 25-27, 1997.
- Martinelli, R. U. et al. (1997) "Minority Carrier Transport in InGaAsSb Thermophotovoltaic Cells, presented at Thermophotovoltaic Generation of Electricity: Third NREL Conference, Coutts, T. J., Allman, C. S. and Benner, J. P., eds, AIP Conf. Proc 401, Colorado Springs, CO, 401:389-395.
- Tsou, Y., A. Ichii, and E. M. Garmire (1992) "Improving InAs Double Heterostructure Lasers with Better Confinement," IEEE J. Quantum Electronics" 28:1261-1266.
- Wang, C. W., H. K. Choi, G. W. Turner, and M. J. Manfra, (1997) "Lattice-Matched Epitaxial GaInAsSb Thermophotovoltaic Devices" presented at Thermophotovoltaic Generation of Electricity: Third NREL Conference, Coutts, T. J., Allman, C. S. and Benner, J. P., eds, AIP Conf. Proc 401, Colorado Springs, CO.
- Wojtczuk, S., E. Gagnon, L. Geoffroy, T. Parados, (1994) "InGaAs Thermophotovoltaic Cell Performance vs. Bandgap" presented at Thermophotovoltaic Generation of Electricity: First NREL Conference, Copper Mountain, CO, Coutts, T. J., Allman, C. S. and Benner, J. P., eds AIP Conference Proceedings, 321:177-187.