0.6-eV Bandgap $In_{0.69}Ga_{0.31}As$ Thermophotovoltaic Devices Grown on $InAs_yP_{1-y}$ Step-Graded Buffers by Molecular Beam Epitaxy

M. K. Hudait, Y. Lin, M. N. Palmisiano, and S. A. Ringel, *Senior Member, IEEE*

***Abstract*—Single-junction, lattice-mismatched (LMM) $In_{0.69}Ga_{0.31}As$ thermophotovoltaic (TPV) devices with bandgaps of 0.60 eV were grown on InP substrates by solid-source molecular beam epitaxy (MBE). Step-graded $InAs_yP_{1-y}$ buffer layers with a total thickness of 1.6 μm were used to mitigate the effects of 1.1% lattice mismatch between the device layer and the InP substrate. High-performance single-junction devices were achieved, with an open-circuit voltage of 0.357 V and a fill factor of 68.1% measured at a short-circuit current density of 1.18 A/cm^2 under high-intensity, low emissivity white light illumination. Device performance uniformity was outstanding, measuring to better than 1.0% across a 2-in diameter InP wafer indicating the promise of MBE growth for large area TPV device arrays.**

***Index Terms*—InAsP, InGaAs, lattice-mismatch, MBE, TPV.**

I. Introduction

$In_xGa_{1-x}As$-based thermophotovoltaic (TPV) devices grown on InP substrates are of interest for a variety of terrestrial and space energy conversion applications [1]–[7]. Most TPV systems are designed to generate electricity from thermal sources that operate in the temperature range of 1000 to 2000 K. The irradiance spectrum from such sources requires InGaAs TPV cells with bandgaps from 0.50 eV–0.74 eV for conversion efficiency and reasonable power density. To achieve these bandgaps requires an In content (x) of the active $In_xGa_{1-x}As$ TPV layers well in excess of the 53% composition that provides a convenient lattice match to InP substrates. The subsequent lattice mismatch between the $In_xGa_{1-x}As$ TPV device and InP substrate, which for 0.6-eV bandgap TPV cells is 1.1%, necessitates a buffer scheme to reduce the high threading dislocation density that would otherwise propagate through the relaxed device layers.

To date, all reported $In_xGa_{1-x}As$-based lattice-mismatched (LMM) TPV devices have been grown by metal-organic vapor-phase epitaxy (MOVPE) on InP substrates using either $In_xGa_{1-x}As$ or $InAs_yP_{1-y}$-graded buffers [2], [6]–[12]. However, solid-source molecular beam epitaxy (MBE) is now receiving interest for TPV applications due to its extreme precision and growth uniformity, and since it provides an opportunity to investigate and potentially optimize LMM TPV structures within a very different growth regime compared to MOVPE. Using MBE, we have recently reported very high-performance lattice-matched $In_{0.53}Ga_{0.47}As$/InP TPV devices with a bandgap of 0.74 eV [1]. This paper reports the first LMM $In_{0.69}Ga_{0.31}As$ single-junction (SJ) TPV devices grown by MBE. High performance devices are demonstrated for a bandgap of 0.6-eV using $InAs_yP_{1-y}$ buffers on InP.

Manuscript received April 9, 2003; revised June 26, 2003. This work was supported in part by the National Science Foundation Focused Research Group (FRG) under Grant DMR-0076362. The review of this letter was arranged by Editor T. Mizutani.

M. K. Hudait, Y. Lin, and S. A. Ringel are with the Department of Electrical Engineering, the Ohio State University, Columbus, OH 43210 USA (e-mail: ringel@ee.eng.ohio-state.edu).

M. N. Palmisiano is with Bechtel Bettis Inc., West Mifflin, PA 15122 USA.

Digital Object Identifier 10.1109/LED.2003.816591

II. MBE Growth and Device Processing

LMM $In_{0.69}Ga_{0.31}As$ TPV structures were grown on (100) semi-insulating InP substrates having a 2° off-cut toward the $\langle 110 \rangle$ direction in a solid-source MBE system equipped with valved cracker sources for arsenic and phosphorus. InP substrate oxide desorption was done at 510 °C under a phosphorus overpressure of $\sim 1 \times 10^{-5}$ torr, which was verified by observing a strong (2×4) reflection high-energy electron diffraction (RHEED) pattern, indicating a clean (100) InP surface. An undoped 0.2 μm thick InP buffer layer was then deposited under a stabilized P_4 flux $(P_4/In = 24/1)$ prior to the growth of an $InAs_yP_{1-y}$ step-graded buffer. The step-graded $InAs_yP_{1-y}$ buffer consisted of four steps, with the final compositions of $InAs_{0.32}P_{0.68}$ providing a lattice-matched "virtual" substrate for 0.6-eV $In_{0.69}Ga_{0.31}As$ TPV overgrowth. The total buffer thickness was 1.6 μm. Triple axis x-ray diffraction verified near complete relaxation of each layer. Full details on the growth and properties of the $InAs_yP_{1-y}$ step-graded buffer was previously reported in [13].

The schematic cross section of a basic n-p-n TPV structure shown in Fig. 1 allows the use of the desired n-on-p cell configuration with an n-type lateral conduction layer (LCL) to interconnect strings of lateral devices in series to achieve a TPV monolithic interconnected module (MIM) [1]–[3], [6]–[12]. Ti/Au (200 Å/3 μm) metallization was used for both front and back ohmic contacts, and a SiO_2 dielectric layer was sputter-deposited to prevent the interconnect metallization from short-circuiting the individual cells. No intentional anti-reflection coating (ARC) was deposited on the top surface, and the heavily doped $In_{0.69}Ga_{0.31}As$ cap layer was removed prior to performing quantum efficiency measurements.

III. Results and Discussion

Fig. 2 shows current density versus voltage (*J–V*) results obtained from a single-junction TPV cell, under high-intensity,

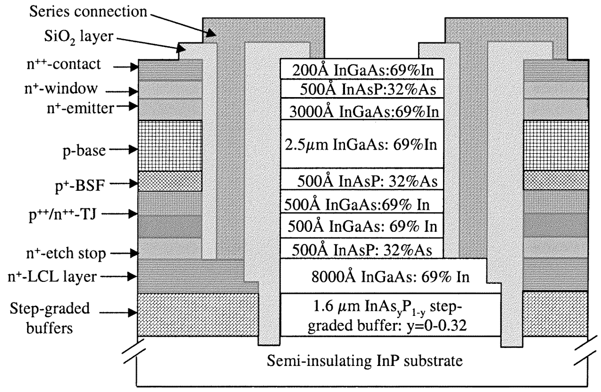

Fig. 1. Schematic cross section of a typical LMM $In_{0.69}Ga_{0.31}As$ n-p-n TPV test structure using $InAs_yP_{1-y}$ step-graded buffers. The doping concentration in the p-type $In_{0.69}Ga_{0.31}As$ base and n-type $In_{0.69}Ga_{0.31}As$ emitter was $8 \times 10^{16}\ cm^{-3}$ and $5 \times 10^{18}\ cm^{-3}$, respectively.

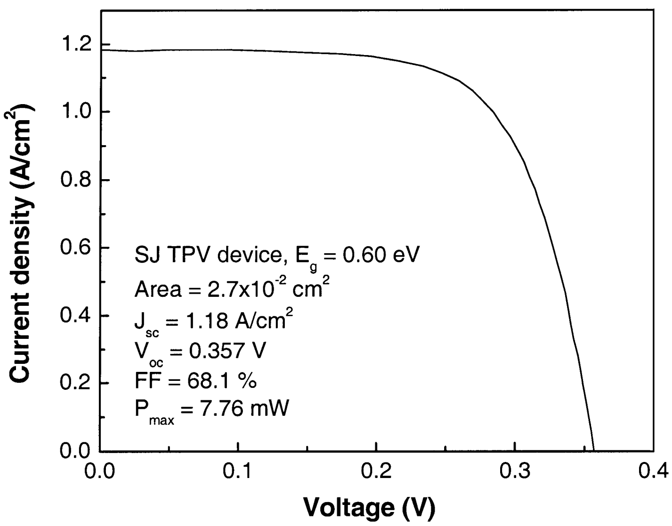

Fig. 2. Current density versus voltage (*J–V*) characteristic of a SJ TPV cell with $Eg = 0.60$ eV. The light source is a quartz halogen tungsten lamp whose spectral emission fits a graybody spectrum with a temperature of 2050 K and emissivity of 0.0252.

low-emissivity white light illumination. The light source is a quartz halogen tungsten lamp whose spectral emission fits a graybody spectrum with a temperature of 2050 K and emissivity of 0.0252. At a short-circuit current density (J_{sc}) of 1.18 A/cm^2, an open-circuit voltage (V_{oc}) value of 0.357 V was obtained from a SJ TPV cell. Note that for a J_{sc} value that is consistent with that of a graybody radiator temperature of approximately 1000 °C [11], the SJ V_{oc} becomes 390 mV assuming the same extracted values for the diode ideality factor and J_o (see below). Moreover, it is commonly observed that the V_{oc} per junction of a completed MIM device is increased by ~25–30 mV compared to the V_{oc} values obtained for SJ structure [7]. Under this assumption we would expect V_{oc}/junction for a fully processed MBE-grown MIM device of ~415–420 mV. These V_{oc} values are comparable to values obtained for similar 0.6-eV bandgap TPV devices grown by MOVPE, which employed $InAs_yP_{1-y}$ buffers twice the thickness of the MBE buffers reported here [7], [11], [12]. The fact that high performance was achieved with the thinner buffer

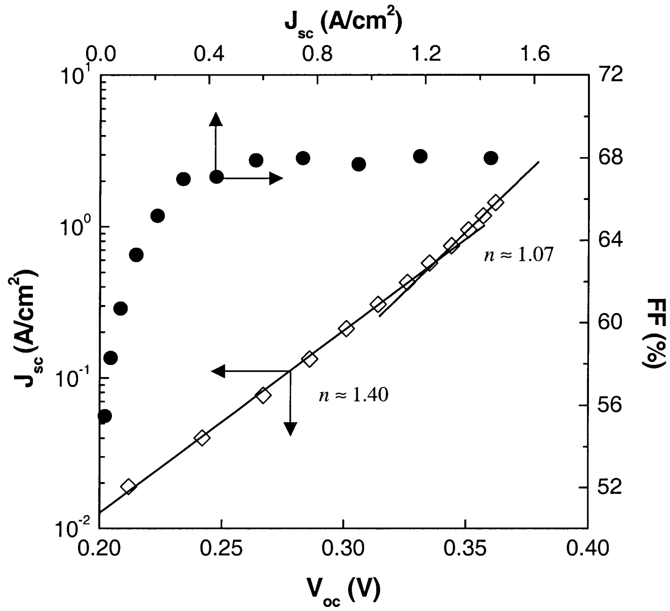

Fig. 3. Variation of short-circuit current density (J_{sc}) with open-circuit voltage (V_{oc}) and fill factor (FF) with J_{sc} for a SJ TPV with $Eg = 0.60$ eV obtained as a function of incident light intensity.

should have advantages for processing and uniformity of TPV arrays.

Fig. 3 shows J_{sc} versus V_{oc} data for a SJ TPV device as a function of illumination intensity, where an increase in J_{sc} corresponds to an increase in light intensity for the *J–V* measurements. It can be seen from this figure that V_{oc} increases logarithmically with J_{sc}, as expected, and by performing a linear fit of the data in Fig. 3 and using the ideal diode equation

$$J_{sc} = J_o \left\{ \exp\left(\frac{qV_{oc}}{nkT_{\mathrm{Cell}}} \right) - 1 \right\}, \qquad (1)$$

n, the diode ideality factor and J_o, the dark saturation current density were estimated [4]. In this expression, k is the Boltzmann constant and T_{Cell} is the temperature of the cell during measurement (298 K). The linear fit yielded $n \approx 1.40$ at low injection and $n \approx 1.07$ at high injection levels, indicating that minority carrier diffusion $(n = 1)$ is dominant in the higher injection regime where TPV devices typically operate. The extracted value for J_o was determined to be 2.69 $\mu A/cm^2$. The fill factor (FF) as a function of J_{sc} is also shown in Fig. 3, which approaches ~68.1% at higher illumination intensities. External quantum efficiency (EQE) measurements, shown in Fig. 4, are consistent with the *J–V* data, with EQE values of ~65% between 1.2 and 2 μm demonstrated without anti-reflection coating, and a sharp band edge cutoff being observed, consistent with a long carrier diffusion length.

Fig. 5 shows a tabulated map of measured SJ TPV cell parameters across a 2-in wafer, taken at identical illumination conditions and intensities (1920 K graybody spectrum; emissivity of 0.0230). Note these are lower intensities (and thus lower currents) than shown in Fig. 2, which would cause slightly poorer cell characteristics, but was chosen since all cells were initially measured at this condition. Very good uniformity of cell parameters is apparent. This is particularly noteworthy for V_{oc} and FF, which are extremely sensitive to small variations in material

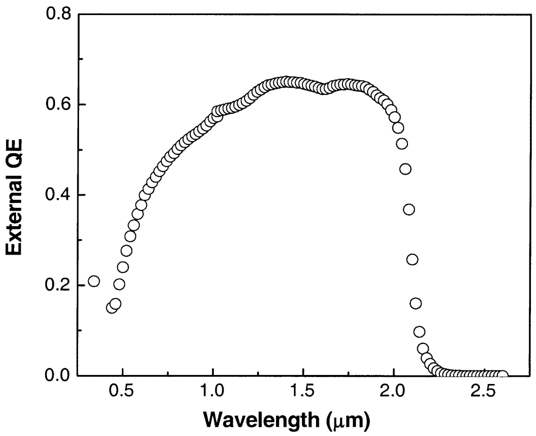

Fig. 4. External quantum efficiency (with no anti-reflection coating) of a SJ TPV with $\mathrm{Eg} = 0.60\ \mathrm{eV}$.

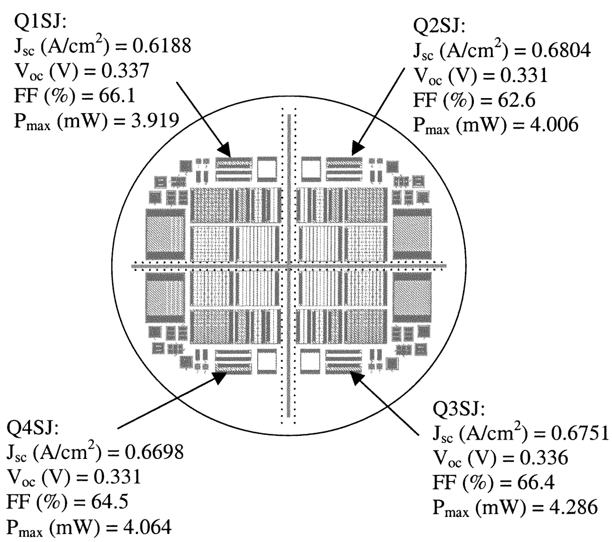

Fig. 5. Device uniformity ($\mathrm{J_{sc}}$, $\mathrm{V_{oc}}$, FF, and $\mathrm{P_{max}}$) across a 2-in InP wafer. Q1–Q4 refers to the quarter of the wafer. The light source is a quartz halogen tungsten lamp whose spectral emission fits a graybody spectrum with a temperature of 1920 K and emissivity of 0.0230.

quality via recombination and shunting. The high uniformity is attributed to the thin, InAsP buffers which provided nearly full relaxation with extremely uniform and relatively low RMS roughness metamorphic growth surface as detailed in an earlier publication [13].

IV. Conclusion

The first MBE-grown, LMM $In_{0.69}Ga_{0.31}As$ TPV cells were grown, fabricated and tested. High-performance devices were obtained, with SJ cells displaying a $\mathrm{V_{oc}}$ of 0.357 V and a FF of 68.1% measured at a $\mathrm{J_{sc}}$ value of 1.18 A/cm^2. The outstanding uniformity of cell parameters with less than 1% variation across the wafer was attributed to very high-quality, relatively thin compositionally graded InAsP buffers, which yield very uniform and low roughness surfaces for TPV cell growth. The results suggest great promise for achieving high efficiency, high yield, large area, low bandgap InGaAs TPV modules and arrays grown by MBE.

Acknowledgment

The authors would like to thank D. M. Wilt of the NASA Glenn Research Cente, Cleveland, OH, for technical discussions.

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