Temperature dependent characteristics of GaInP/GaAs/GaInNAsSb solar cell under simulated AM0 spectra

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***Abstract* — We report on the temperature characteristics of GaInP/GaAs/GaInNAsSb triple junction solar cell monolithically grown by molecular beam epitaxy. In particular, we have compared the temperature dependent light-biased current-voltage characteristics of the cell at simulated AM0 spectral conditions produced by two solar simulators: a customized three band solar simulator and a Xenon simulator equipped with an AM0 filter. For the three band simulator, the temperature coefficients corresponding to short-circuit current density and open-circuit voltage were found to be 5.3 μA/cm²/°C and -6.8 mV/°C, respectively. These values are in agreement with literature reports for GaInP/GaAs/Ge solar cells. Illumination using a filtered single Xenon lamp leads to an erroneously high temperature coefficient value for short-circuit current density.**

***Index Terms* — AM0, dilute nitride, molecular beam epitaxy, multijunction solar cell, solar simulator, temperature coefficient.**

I. INTRODUCTION

Multijunction solar cells (MJSC) based on III–V compounds are an attractive choice for concentrated photovoltaics (CPV) and space applications due to the versatility of III–V materials enabling high conversion efficiency. For example, with four junction III–V solar cells, a conversion efficiency of 46% has been demonstrated [1]. By increasing the number of junctions, the conversion efficiency of MJSCs is projected to surpass 50% in CPV applications [2].

The operating conditions (i.e. illumination conditions and temperature) have a great impact on the solar cell performance. For example, in near space the illumination intensity is higher compared to one-sun terrestrial spectral conditions where the illumination intensity is attenuated by the atmosphere. The atmosphere also affects the solar spectrum as radiation at different wavelengths are not absorbed uniformly causing variation of the terrestrial spectrum. Secondly, the operating temperatures of the cells can vary substantially depending on the application; in satellite orbit the cell temperatures can vary between -160°C and 100°C [3] whereas in typical CPV operation the cell temperature can realistically rise up to 50–60°C above ambient temperature [4]-[5].

For optimal energy harvesting, the solar cells should be tailored to fit their corresponding application, and from the design point-of-view it is vital to understand the effects of temperature and illumination conditions on the cells. In this paper, we report on the temperature characteristics of triple junction (3J) GaInP/GaAs/GaInNAsSb solar cell grown by plasma-assisted molecular beam epitaxy (PAMBE). We have measured the light-biased current-voltage (LIV) characteristics for the cell under AM0 spectral conditions. We have compared the temperature characteristics of the cell when measured with a customized three band solar simulator and a single Xenon lamp simulator.

II. EXPERIMENTAL

A. Solar cell fabrication

The cell was monolithically grown on 2” p-GaAs(100) substrate using Veeco GEN20 PAMBE reactor. The epitaxy system was equipped with SUMO type effusion cells for group III materials, valved cracker sources for As, P and Sb and a RF plasma source for introduction of atomic N. The bandgap energies of the GaInP, GaAs and GaInNAsSb sub-cells were 1.9 eV, 1.4 eV and 1.0 eV, respectively. For lattice-matching the dilute nitride bottom cell, an In concentration of ~2.7 times the N concentration was used [6]. The wafer was processed into cells with size of 4×4 mm^2 with an active area of 0.1175 cm^2, and the cells were coated with a TiO_2–SiO_2 antireflective coating.

B. Light-biased current-voltage characterization

For the LIV characterization, we used primarily a three band solar simulator comprising individually adjustable Xenon and two halogen light sources that were optically filtered to be suitable for the characterization of 3J cells. The short wavelength band for the GaInP sub-cell is produced using the Xenon lamp due to its better spectral characteristics in the UV range compared to halogen light sources. Different filter configurations are needed for the simulation of AM0 and AM1.5 spectral conditions.

The spectral bands of the illumination were generally designed such that their edges were close to the bandgaps of the sub-cells (i.e. each sub-cell would be illuminated with only one spectral band) and thus, allowing independent adjustment of intensity incident on each sub-cell. For the AM0 spectral conditions a compromise between the sharp spectral bands and UV illumination had to be made, which causes coupling between spectral bands intended for GaInP and GaAs sub-cells (see Fig. 1a). For the AM1.5 configuration, the transitions between spectral bands near the band edges of the sub-cells are sharp (see Fig. 1b), which allows the individual sub-cell currents to be determined by altering the bias light intensity incident on each sub-cell.

The intensity calibration of the three band simulator was done with single junction GaInP, GaAs, and GaInNAsSb solar cells that were calibrated by external quantum efficiency measurements. The beam size and spatial uniformity of the three band solar simulator limited the cell size to 1×1 cm^2. The long term temporal instability of the three band simulator was ± 2%. The sample stage allowed heating with a resistive element and the stage temperature was monitored with an AD590 temperature transducer. The temperature could be determined with an accuracy of 0.1°C with relative error of ± 2.5°C.

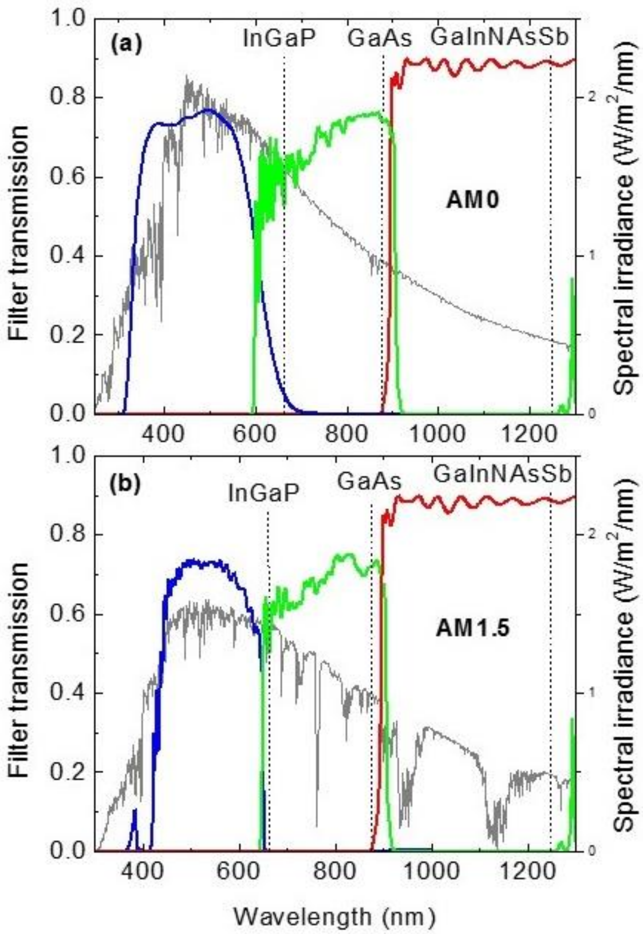

Fig. 1. (a) The filter transmissions of AM0 configuration with ASTM E490-00a reference spectrum [7] and (b) AM1.5 configuration with ASTM G173-3 AM1.5D reference spectrum (1000 W/m^2 normalization) [8]. The absorption edges of the sub-cells are indicated with dotted lines.

For comparison, the temperature dependent LIV characteristics of the 3J cell were also measured by using a 1000 W single source Xenon solar simulator manufactured by Oriel. The Xenon simulator could be equipped with AM0 or AM1.5G air mass filters. The AM0 illumination intensity of the Xenon simulator was calibrated by using a dual junction solar cell calibrated at Fraunhofer ISE. The same sample stage that was used for the three band simulator measurements was also used for the Xenon simulator measurements.

III. Results

The LIV characteristics of the 3J sample were measured in the temperature range of 25–90°C with the three band simulator under one-sun AM0 spectral conditions utilizing ASTM E490-00a AM0 [7] as the reference spectrum. The measurements were repeated by using the Xenon simulator calibrated to one-sun AM0 spectral conditions. The LIV curves measured from the 3J cell with both simulator systems are presented in Fig. 2.

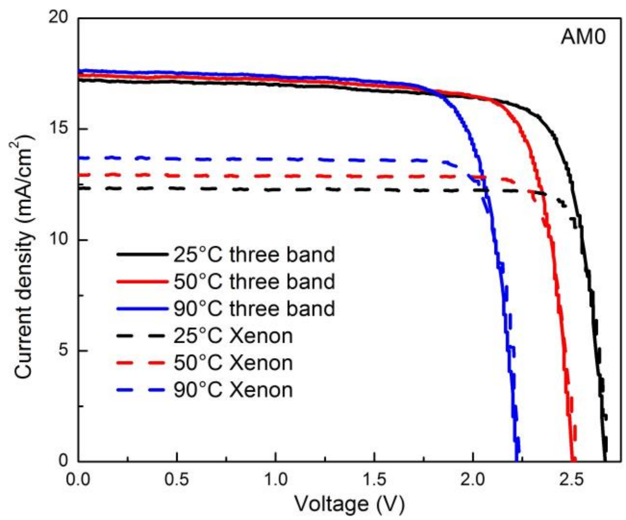

Fig. 2. Temperature dependent LIV curves measured for the 3J at AM0 spectral conditions. The solid and dashed lines present the curves measured with the three band simulator and the Xenon simulator, respectively.

From Fig. 2. we can observe a clear difference between the behavior measured with the two simulators; approximately 30% lower short-circuit current density (J_{sc}) values were measured with the Xenon simulator. Under illumination from the three band simulator, J_{sc} of the 3J cell was determined to be 17.2 mA/cm^2 at 25°C. The corresponding value under Xenon source illumination was 12.3 mA/cm^2. The large variation in the measured J_{sc} values also affects the conversion efficiency significantly; with the three band simulator the active area efficiency (η_{active}) was 26.7% whereas with illumination from the Xenon simulator η_{active} was only 21.1% at 25°C. The deviations in the J_{sc} values suggests that the spectra produced by the Xenon simulator does not sufficiently match the reference spectra and causes imbalance in the current generation between the sub-cells, thus, resulting in distorted J_{sc} values. The spectrum of the Xenon source deviates from the reference AM0 spectrum below 300 nm range as well as in the 750–1000 nm range, where the spectrum exhibits several peaks and dips with a major dip around 800–850 nm [9]. Due to the significant differences in the measured J_{sc} values, the Xenon simulator should be used with caution for MJSC characterization.

In addition, LIVs in Fig. 2. indicate that the cell current increases slightly with increasing temperature, regardless of the source of illumination, as the bandgap energies of the sub-cells red-shift with temperature causing changes in the absorption bands of the sub-cells. Fig. 3. illustrates the change in the J_{sc} when the cell temperature is varied.

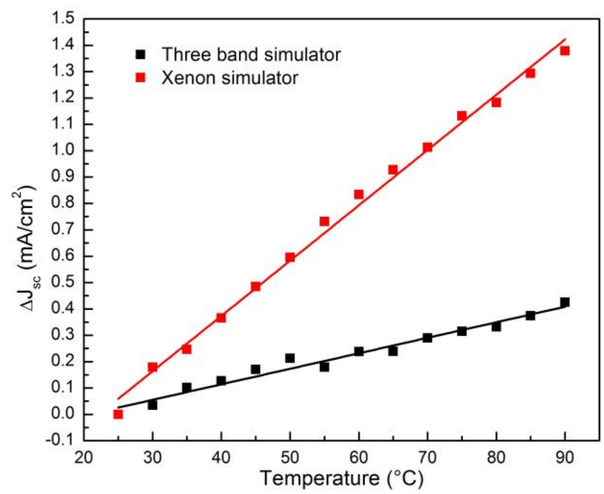

Fig. 3. ΔJ_{sc} values measured from the 3J cell between 25–90°C under AM0 illumination.

In Fig. 2. the open-circuit voltage (V_{oc}) exhibits a negative temperature dependence that is caused by increased dark current due to increased thermal generation of carriers [10]. The fill factor (FF) also decreases as function of temperature. The negative temperature dependencies of V_{oc} and FF overcome the positive change in cell current, thus, causing the temperature dependence of conversion efficiency to become negative.

All temperature induced changes are close to linear. The temperature coefficients for J_{sc} were determined from the slopes of linear fits of the experimental data. With illumination from the three band simulator a temperature coefficient of 5.3 μA/cm^2/°C was determined. The temperature coefficient is in good accordance with the value of 5 μA/cm^2/°C reported for GaInP/GaAs/Ge cell under AM0 illumination [11]. The coefficient value for J_{sc} extracted from the Xenon simulator measurements was 20.1 μA/cm^2/°C, which is significantly higher than the value presented in the literature. This supports the statement that the Xenon source is not adequate for MJSC characterization.

The temperature coefficients for V_{oc} were also extracted from the LIV data. The analysis yielded -6.8 mV/°C and -6.6 mV/°C with illumination for the three band simulator and the Xenon simulator, respectively. The measured coefficients are reasonably close to each other regardless of the source of illumination, and are also close to values that have been previously published for other III–V MJSCs [11]-[12]. The temperature dependent behavior of V_{oc} is illustrated in Fig. 4.

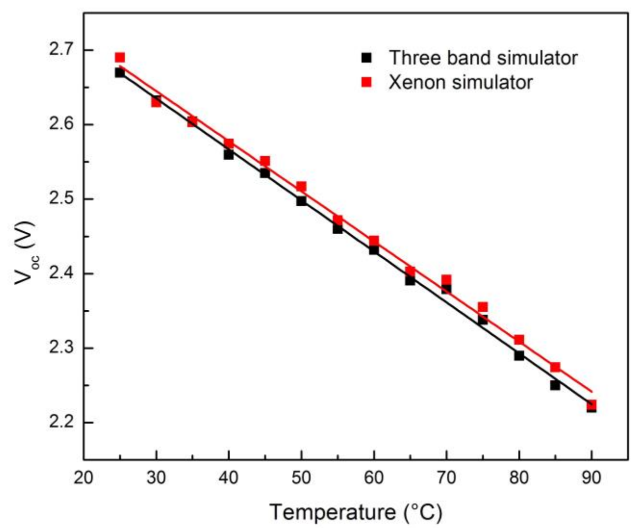

Fig. 4. Temperature dependence of V_{oc} in between 25–90°C under AM0 illumination.

The conversion efficiency of the cell decreases with increasing temperature. The temperature dependence of η_{active} for the 3J cell is illustrated on Fig. 5.

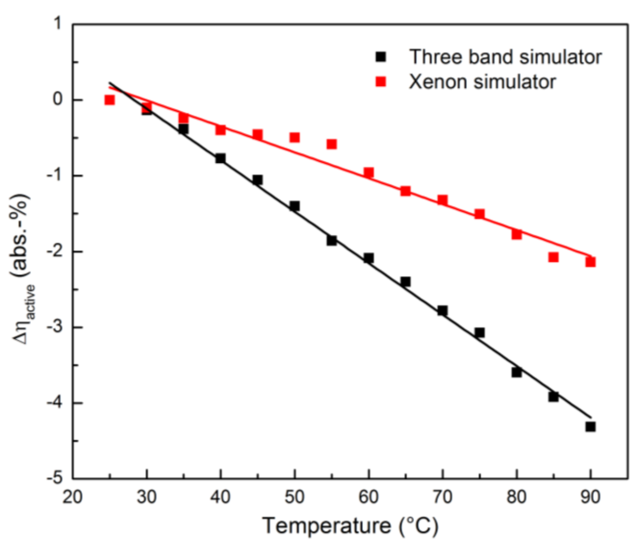

Fig. 5. $\Delta\eta_{active}$ values determined for the 3J cell in the temperature range of 25–90°C with AM0 spectral conditions.

The change in the η_{active} is significantly higher for measurements made with the three band simulator compared to the Xenon simulator. This difference in the temperature behavior of the conversion efficiency is a direct consequence from the difference in the temperature coefficients for J_{sc} obtained for the cell with different illumination (see Fig. 3.).

With illumination from the three band simulator the η_{active} decreased with a slope of -0.068 abs.-%/°C. With illumination from the Xenon simulator the temperature dependency of conversion efficiency was significantly smaller with a corresponding rate of -0.034 abs.-%/°C. The temperature coefficient for η_{active} measured with the three band solar simulator is reasonably close to temperature coefficient value of -0.057 abs.-%/°C reported for GaInP/InGaAs/Ge 3J cell [13].

IV. Conclusions

The temperature dependent behavior of a MBE-grown GaInP/GaAs/GaInNAsSb solar cell was studied at AM0 spectral conditions. The solar simulation for the experiments was realized with a single source Xenon simulator and a customized three band solar simulator. With illumination from the Xenon simulator the cell current was observed to be underestimated by ~30% compared to the three band simulator measurements. Temperature coefficients for J_{sc}, V_{oc} and η_{active} were extracted from the LIV data. In general, the determined temperature coefficient values were found to be in a reasonably good agreement with temperature coefficient values published for other 3J cells but the temperature coefficient for J_{sc} measured with the Xenon simulator was found to deviate significantly from the literature value. The large difference in the coefficient for J_{sc} is was attributed to insufficient spectral matching of the Xenon solar simulator that causes imbalance in the current generation between the sub-cells.

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