FIRST DEMONSTRATION OF MONOLITHIC InP-BASED InAlAs/InGaAsP/InGaAs TRIPLE JUNCTION SOLAR CELLS

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ABSTRACT

Spectrolab has demonstrated the first lattice matched InAlAs/InGaAsP/InGaAs triple junction solar cell grown on InP substrate. X-ray diffraction characterization shows high quality solar cell materials. Preliminary 1-sun AM1.5D testing of the triple junction solar cell shows promising results with an open circuit voltage (V_{oc}) of 1.8V, a short-circuit current density (J_{sc}) of 11.0 mA/cm^2, a fill factor of 64.4 %, and a 1-sun AM1.5D efficiency of 13.8%. The same cell also passes 27-suns under concentration. Improvements in layer design and crystal quality of advanced features can further raise the 1-sun and concentrated AM1.5D conversion efficiency of the InP-based triple junction cell beyond 20%.

INTRODUCTION

High-efficiency III-V multijunction solar cells for terrestrial applications have traditionally been grown lattice matched to either bulk Ge or GaAs substrates. However, reaching even higher cell efficiency requires solar cell designs with optimal bandgap combination, which in turn, requires materials that are outside of Ge or GaAs lattice constants. One of the existing solutions in the III-V solar cell community is the use of highly metamorphic materials in the upright or inverted configuration [1-2]. An upright metamorphic approach requires the active cells be grown on top of metamorphic buffer grade; whereas, an inverted metamorphic approach requires the thick low bandgap cell to be grown last. Both cases require meticulous material engineering against defects induced by large mismatch and long thermal history.

One alternative approach to existing solutions is to explore InP or near InP lattice space parameter, as low bandgap (~0.7-1.2-eV) component subcells at the InP or near InP lattice constant are becoming one of the key components in the ultra-high efficiency multijunction solar cell structure such as inverted metamorphic, upright metamorphic [1-4] and semiconductor-bonded multi-junction solar cell [5]. However, high bandgap materials available in InP or near InP lattice constant are scarce and have not been intensively studied. The ternary compound $In_xAl_{1-x}As$ stands out as a potential candidate for middle to high bandgap materials for those lattice space parameters. Recently, $In_{0.52}Al_{0.48}As$ single junction solar cell lattice matched to InP lattice constant has been demonstrated [6]. In this paper, we take one step further and focus on the development of lattice matched monolithic InAlAs/InGaAsP/InGaAs triple junction solar cell on InP substrate as shown in Figure 1. Preliminary 1-sun AM1.5D testing of the first triple junction cell shows promising results.

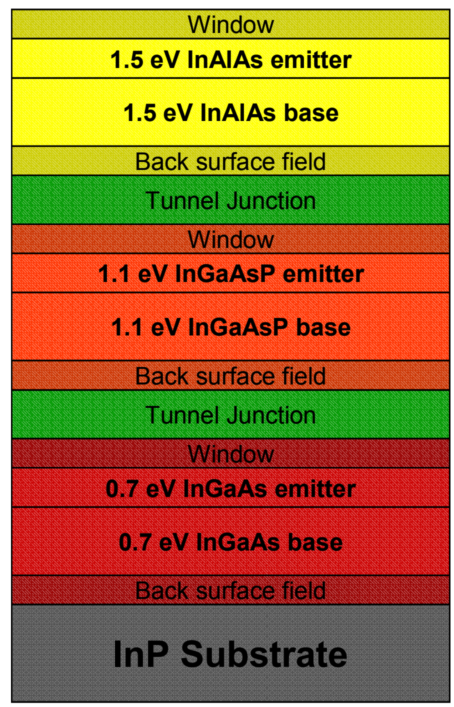

Figure 1: A schematic drawing of lattice matched monolithic InAlAs/InGaAsP/InGaAs triple junction solar cell design on InP substrate.

EXPERIMENTAL METHODS

The growth of InAlAs/InGaAsP/InGaAs triple junction solar cell was carried out in Spectrolab's Veeco E-400 metalorganic vapor phase epitaxy reactor. For the first 3J cell test structure, advanced features such as a transparent tensile InAlAs window and back surface field layers of subcell 1 were omitted. In addition, subcell 2 and subcell 3 thicknesses were reduced to 1μm from their optimal thicknesses.

The epitaxial materials were characterized by x-ray diffraction. The grown wafer was processed into 1x1

cm^2 devices using a shadow space metal mask, which has excess metal coverage shown in Figure 2. The cells were coated with a standard space anti-reflection coating. Illuminated current-voltage characteristics of the triple junction cells was measured under both 1-sun AM1.5D equivalent spectrum and 1-sun AM0 spectrum using filters under an advanced Spectrolab X25 solar simulator calibrated with Lear jet flight flown 3J-IMM (inverted metamorphic) standards for a quick feedback. The device performance of the cell under concentration was also measured under an advanced Spectrolab X25 solar simulator to determine the health of the tunnel diodes used in the triple junction cell.

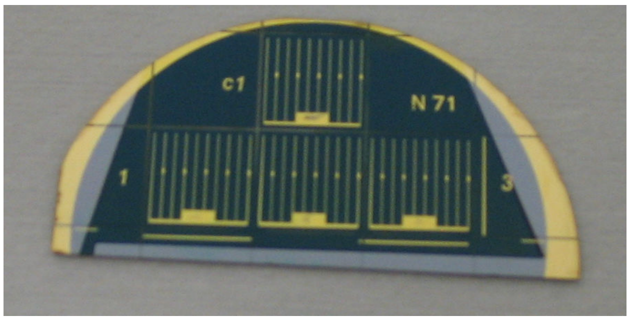

Figure 2: A photograph of 1-cm^2 InAlAs/InGaAsP/InGaAs triple junction cells grown on InP substrate.

MATERIAL CHARACTERIZATION

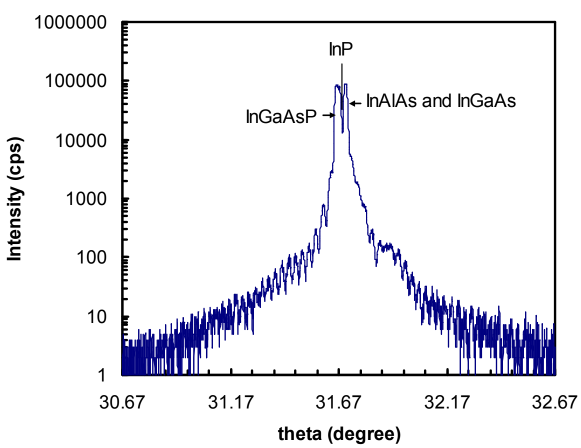

Figure 3: X-ray diffraction rocking curve of InP-based InAlAs/InGaAsP/InGaAs triple junction solar cell grown on InP substrate.

Shown in Figure 3 is x-ray diffraction (XRD) measurement around the InP (004) reflection. The sharp peak at 31.67° corresponds to InP substrate. The peak at approximately 50 arc-sec compressive (on the left of InP peak) is due to InGaAsP-subcell 2 material. The peak at approximately 105 arc-sec tensile (on the right of InP peak) is due to InGaAs-subcell 3 and InAlAs-subcell 1 material. Full-width-half-maximum of the XRD θ scan for InAlAs, InGaAsP, and InGaAs subcell are approximately 70 arc-sec, 80 arc-sec, and 65 arc-sec, respectively. XRD data indicates that all three subcell components are at high material quality.

DEVICE CHARACTERIZATIONS

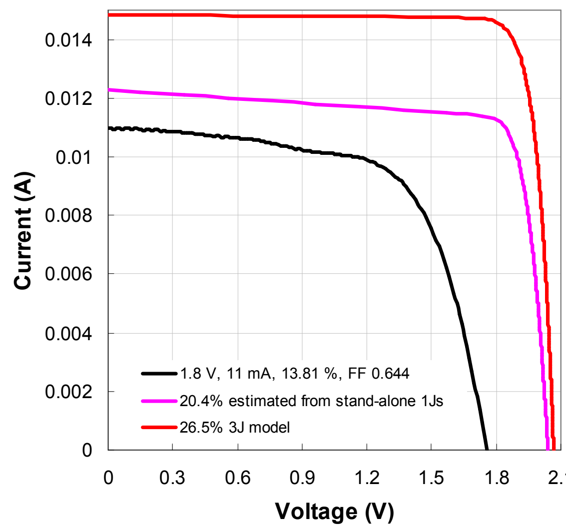

Figure 4: Illuminated current-voltage characteristic of InAlAs/InGaAsP/InGaAs triple junction cell as measured on AX25 and estimated efficiency based on single junction component subcells and maximum available short circuit current density.

Figure 4 shows the preliminary illuminated current

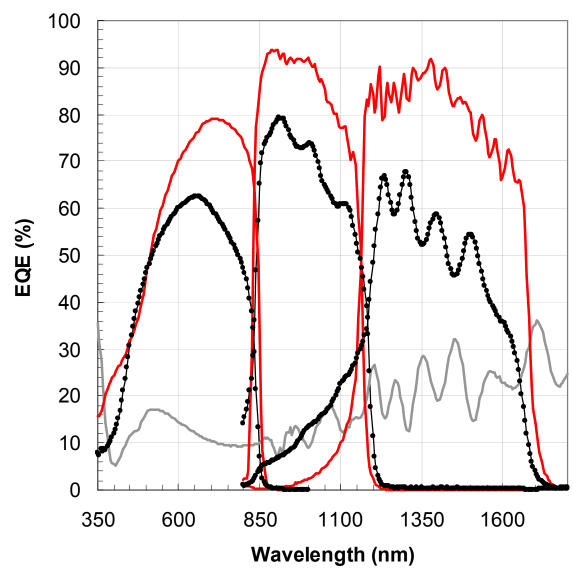

Figure 5: External quantum efficiency of InP-based InAlAs/InGaAsP/InGaAs triple junction cell plotted in (-●-); external quantum efficiency of stand-alone InAlAs, InGaAsP, InGaAs single junctions plotted in red; reflectance of triple junction cell plotted in gray.

voltage characteristics of the InP-based InAlAs/InGaAsP/InGaAs triple junction solar cell. The cell achieved an open circuit voltage (V_{oc}) of 1.8V, a short-circuit current density of (J_{sc}) of 11.0 mA/cm^2, a fill factor of 64.4%, and a 1-sun AM1.5D efficiency of 13.8%. Based on currently available InAlAs, InGaAsP, and InGaAs single junction device performance, a 1-sun AM1.5D conversion efficiency of 20.4% is estimated. Further improvement in crystal quality, better current matching, and optimized anti-reflection coating for this bandgap combination can push the InP-based InAlAs/InGaAsP/InGaAs triple junction cell efficiency closer to ideal efficiency of 26.5%.

External quantum efficiency (EQE) data of the same triple junction cell are presented in Figure 5. All subcells show peak EQE performance ranging from 60% to 80%. Also included in Figure 5 is EQE of our current stand-alone InAlAs, InGaAsP, and InGaAs single junction cells. These current densities of single junction cells measured from spectral responses were used to estimate the conversion efficiency of 20.4% shown in Figure 4. There are two factors that contributed to the disparity in spectral response between the stand-alone single junction component cells and integrated 3J cells. The first is, the stand-alone InAlAs single-junction solar cell has a transparent tensile InAlAs window and back surface field layers. The second difference is, subcells 2 and 3 have thicker base layers. If we were to include those features alone in the integrated 3J cells, we estimate a cell efficiency of 20.4% can be achieved in this design. High reflectivity is also observed from these cells as shown in reflectance data plotted in gray color.

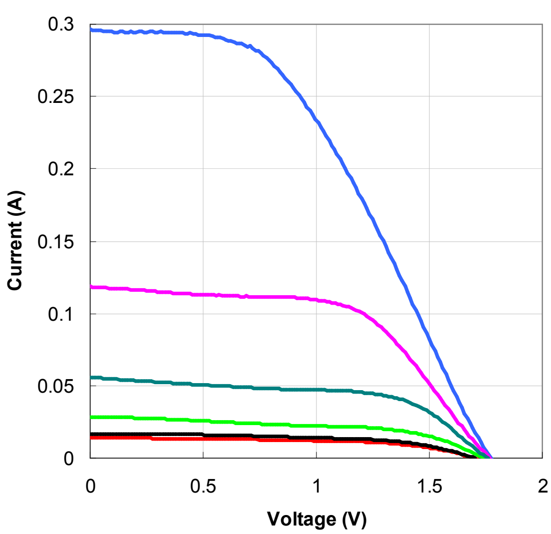

Figure 6: Performance of the InP-based InAlAs/InGaAsP/InGaAs triple junction cell as a function of AM0 concentration.

The InP-based triple junction cells were also tested under concentrated AM0 spectrum since concentrated AM1.5D spectrum was not readily available at the time. Figure 6 shows the preliminary performance data of a triple junction cell as a function of AM0 concentration. The cell passes 27 suns, which is promising for terrestrial applications. Note that high series resistance is due to contact metal design, which is not suitable for concentrations.

From the device performance of these first demonstration solar cells, Spectrolab identifies a few crucial design and/or process improvements. One is the insertion of a transparent passivating window and back surface field layers to InAlAs-subcell 1, which can reduce front and back surface recombination velocity and light absorption loss. The second improvement is to thicken the base layers of InGaAsP-subcell 2 and InGaAs-subcell 3 to fully absorb the long wavelength portion of the solar spectrum without compromising design integrity. The third is to develop a highly conductive layer that can be used as a front contact to improve contact resistance. The Fourth is to develop an anti-reflection coating optimized for this bandgap combination.

CONCLUSIONS

Spectrolab has demonstrated the first InP-based InAlAs/InGaAsP/InGaAs triple junction solar cell with an open circuit voltage (V_{oc}) of 1.8V, a short-circuit current density (J_{sc}) of 11.0 mA/cm^2, a fill factor of 64.4%, and a 1-sun AM1.5D efficiency of 13.8%. Although the efficiency of the first demonstrated cells is far from theoretical AM1.5 predictions of over 26%, the results are promising and provide valuable feedback on design improvements needed to further increase cell efficiency. In addition, the first high quality 3J cell growth demonstration provides confidence and confirmation that Spectrolab can grow high quality high Al-containing materials lattice-matched to InP as a stand-alone component or in an integrated cell.

ACKNOWLEDGMENTS

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