High Efficiency Inverted Monolithic Tandem GaInP/GaAs/InGaAs Solar Cells

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ABSTRACT

We have fabricated and measured extremely high-efficiency solar cells, achieving world-record 33.8% efficiency under one-sun global conditions and 39.4% efficiency at 26-suns under the direct spectrum. Higher efficiencies yet are expected with minimal effort. These three-junction single-crystal devices are grown by metal-organic vapor phase epitaxy on GaAs substrates. The device is grown in an inverted configuration because the bottom junction is lattice-mismatched to the substrates. The device is mounted to a silicon or glass handle, and the GaAs substrate removed.

1. Objectives

Concentrator photovoltaic solar systems offer the possibility of high solar conversion efficiency at low cost. At high concentration, the solar cell cost represents only a small fraction of the system cost and, thus, system costs per watt scale inversely with the cell efficiency. In this paper, we demonstrate record breaking solar cell efficiencies from a promising new III-V multijunction solar cell structure conceived and developed at NREL[1].

2. Technical Approach

Nearly optimal bandgaps for a high-efficiency triple-junction monolithic tandem solar cell are realized using lattice-matched $Ga_{0.5}In_{0.5}P$ (1.85eV) and GaAs (1.43V) junctions with a lattice-mismatched $In_{0.3}Ga_{0.7}As$ (1.0eV) junction. A schematic of the structure is shown in Fig. 1. Unlike other III-V triple-junction designs using Ge bottom junctions, all three junctions of this design are nearly current-matched in order to maximize the efficiency. The three junctions are series connected with AlGaAs/GaAs tunnel-junctions. The entire monolithic semiconductor structure is grown in a single metal-organic vapor phase epitaxy (MOVPE) process run. The high crystalline quality (and thus high solar efficiency) of the lattice-matched $Ga_{0.5}In_{0.5}P$ and GaAs junctions is preserved by growing the structure inverted on a single-crystal GaAs substrate. The bottom $In_{0.3}Ga_{0.7}As$ junction is then grown last after grading the lattice constant with steps of transparent (to the light intended for the $In_{0.3}Ga_{0.7}As$ junction) $Ga_xIn_{1-x}P$. Dislocations generated while growing the lattice-mismatched layers do not appear to affect the top two junctions. High open-circuit voltages of the bottom junction approaching 0.6V are achieved by growing the lattice-mismatched bottom junction nearly strain-free. This is accomplished by carefully choosing the lattice-constant of a strain-compensating buffer layer. The film stress and strain are characterized by an in-situ multi-beam optical stress sensor and ex-situ X-ray diffraction, respectively. The entire 10-micron monolithic structure is bonded to a handle (a mechanically supporting material) and the GaAs substrate removed. The handle material can be chosen independent of the III-V semiconductor solar cell to optimize other considerations such as flexibility or thermal conduction. In this study, we have used silicon and glass handles. This concept should may be extended to more junctions for higher efficiencies yet.[3]

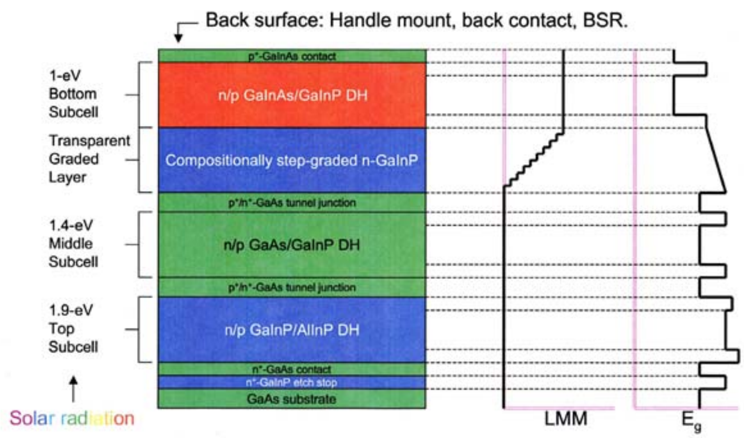

Figure 1. Cross-sectional schematic diagram of the inverted GaInP/GaAs/InGaAs tandem solar cell structure. Also shown are the relative lattice mismatch (LMM) and bandgap (Eg) profiles.[2]

3. Results and Accomplishments

A 0.25 cm^2 area device was processed with wide grid spacing for optimal one-sun operation. We achieved 33.8% efficiency with a V_{oc} of 2.96V, J_{sc} of 13.1 mA/cm^2 and a fill factor of 86.9% under AM1.5 global conditions. To the author's knowledge, this is the highest efficiency for any solar cell measured under these conditions. The current-voltage curve is shown in Fig. 2. The quantum efficiencies of the 3 junctions are shown in Fig. 3.

Smaller 0.1 cm^2 area devices were processed with closer grid spacing for use under concentrator conditions. The quantum efficiencies of these devices

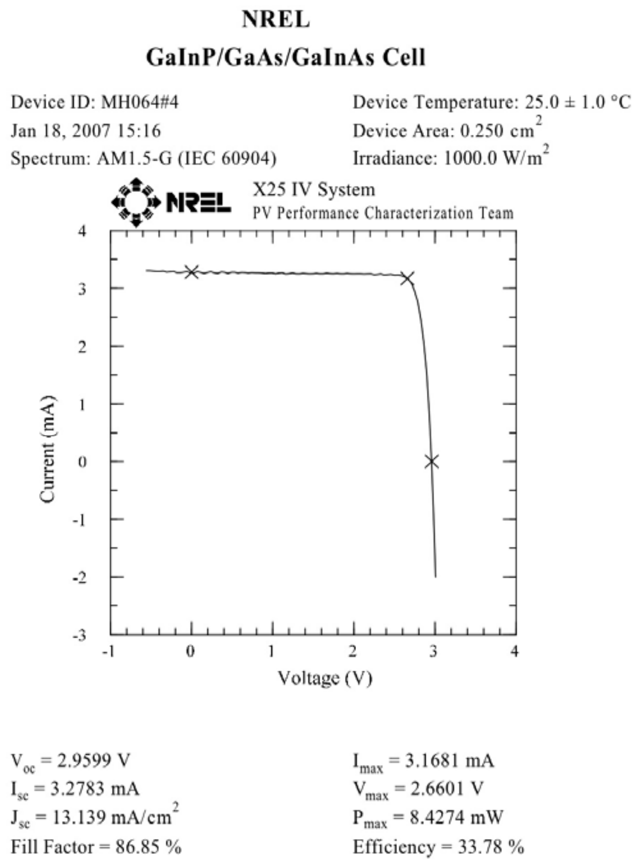

Figure 2. One-sun global current-voltage curve.

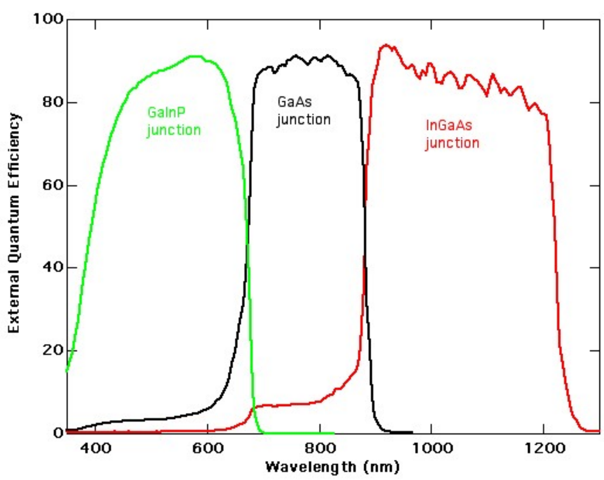

Figure 3. Quantum efficiency of 1-sun device MH064.

were similar to those shown in Fig. 3. Concentrator measurements were taken under the HIPPS flash simulator (see Fig. 4). The V_{oc} under concentration increases logarithmically with the I_{sc}. Thus the efficiency under concentration rises until series resistance losses begin to dominate, causing the fill factor to drop. The maximum efficiency we have achieved, to date, is 39.4% efficiency at 26 suns. We have maintained respectable efficiencies (>35%) to several hundred suns. Decreasing the series resistance further in these devices remains an important challenge.

4. Conclusions

We have achieved some of the highest efficiencies ever recorded for any solar cell design with the potential for significant improvement. We believe that industry will be eager to develop and market this solar cell design for concentrator[4] and space applications[5].

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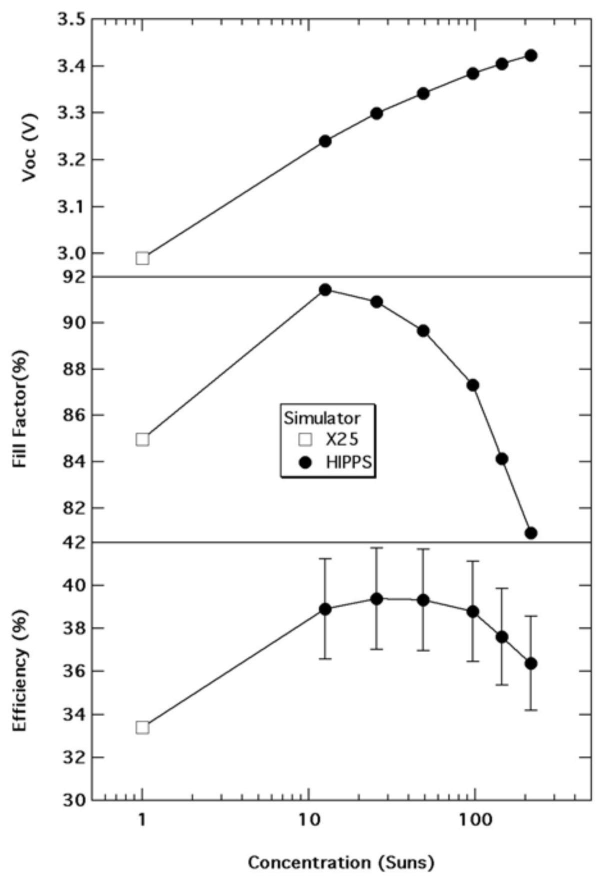

Figure 4. Summary of concentrator measurements of MG991#4.