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Inverted GaInP / (In)GaAs / InGaAs Triple-Junction Solar Cells with Low-Stress Metamorphic Bottom Junctions

Preprint

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INVERTED GaInP / (In)GaAs / InGaAs TRIPLE-JUNCTION SOLAR CELLS WITH LOW-STRESS METAMORPHIC BOTTOM JUNCTIONS

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ABSTRACT

We demonstrate high efficiency performance in two ultra-thin, Ge-free III-V semiconductor triple-junction solar cell device designs grown in an inverted configuration. Low-stress metamorphic junctions were engineered to achieve excellent photovoltaic performance with less than 3×10^6 cm^{-2} threading dislocations. The first design with band gaps of 1.83/1.40/1.00 eV, containing a single metamorphic junction, achieved 33.8% and 39.2% efficiencies under the standard one-sun global spectrum and concentrated direct spectrum at 131 suns, respectively. The second design with band gaps of 1.83/1.34/0.89 eV, containing two metamorphic junctions achieved 33.2% and 40.1% efficiencies under the standard one-sun global spectrum and concentrated direct spectrum at 143 suns, respectively.

INTRODUCTION

High-efficiency multijunction solar cells have greatly impacted the power capacities of satellites and future improvement in power-to-weight ratio is greatly anticipated. Further, the demand for high-efficiency solar cells for terrestrial concentrating solar systems is rapidly growing, with demonstration installations increasing and many new companies entering the market. The power delivered by these concentrating photovoltaic systems is directly related to the efficiency of the relatively small solar cells at the heart of the systems.

Currently, state-of-the-art high efficiency III-V solar cells utilize a three-junction design that includes a Ge bottom junction formed in the Ge substrate in conjunction with lattice-matched $Ga_{0.5}In_{0.5}P$ and Ga(In)As top junctions [1]. However, the Ge junction absorbs about twice the low energy photons than are needed for current matching with the $Ga_{0.5}In_{0.5}P$ and GaAs junctions. Spectrolab has achieved a record 40.7% efficiency under 240X concentration by reducing the band gaps of the top GaInP and GaInAs junctions [1]. While this reduction in band gap increases the theoretical efficiency, the alloy compositions of these top two junctions are no longer lattice-matched to the Ge substrate, but are lattice-matched to each other. The misfit and threading dislocations that reduce solar cell performance have been minimized in this device using a composition-graded buffer in a metamorphic structure.

Alternatively, $Ga_{0.5}In_{0.5}P$ and GaAs top junctions lattice-matched to GaAs in conjunction with a 1.0 eV bottom junction increases the theoretical efficiency of a triple junction solar cell even more [2]. $In_{0.3}Ga_{0.7}As$ can be used as the 1.0 eV junction, but it has a larger lattice constant than GaAs by about 2%. The dislocations generated by this large lattice mismatch can be reduced through the use of graded composition buffer layers, but the remaining threading dislocations would significantly degrade any subsequently grown junctions with higher band gaps. By growing in an inverted configuration [3,4], this degradation of the top junctions can be avoided. We have demonstrated excellent solar cell performance in an inverted, monolithic triple-junction structure that combines a metamorphic 1.00 eV $In_{0.27}Ga_{0.73}As$ junction with lattice-matched 1.83 eV $Ga_{0.5}In_{0.5}P$ and 1.40 eV GaAs junctions [5].

Further gains in the theoretical efficiency of a triple junction solar cell can be made if the junction band gaps are not constrained by material properties such as lattice constants. Figure 1 shows realistic theoretical efficiencies of series-connected triple-junction solar cells with a fixed top band gap of 1.84 eV. Our calculations indicate a maximum theoretical efficiency using the band gap combination of 1.85 eV / 1.34 eV / 0.93 eV [2]. For these efficiency gains to be realized, though, these junctions must be formed with excellent material quality. Fortuitously, this top band gap can be grown as a lattice-matched GaInP junction on GaAs making the inverted approach ideally suited to this device. In this paper, we demonstrate excellent performance in an inverted, monolithic triple-junction structure that incorporates a lattice-matched GaInP junction with two independently metamorphic junctions (0.89 eV $In_{0.37}Ga_{0.63}As$ and 1.34 eV $In_{0.04}Ga_{0.96}As$), thus achieving near optimal band gaps unconstrained by lattice matching.
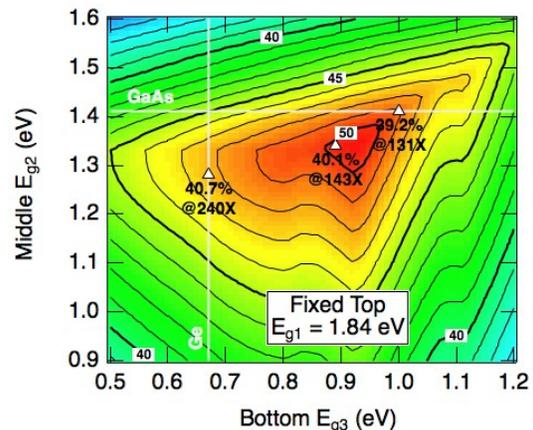

Fig. 1. Theoretical isoefficiency plots of triple-junction solar cells with variable bottom and middle junction band gaps at 500X concentration under the low AOD direct spectrum (300K). The top band gap is fixed at 1.84 eV. The performance of actual metamorphic devices is also shown.
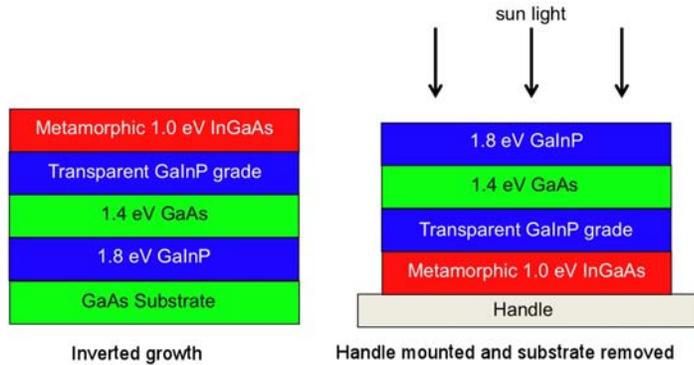
Fig. 2. Schematic of growth and processing of inverted triple junction solar cell.

INVERTED DESIGN

The semiconductor devices described here were grown in a single process step by atmospheric-pressure organometallic vapor phase epitaxy (OMVPE) on a (001) GaAs substrate miscut 2° toward (111)B. The direction of growth is inverted relative to more conventional multijunction devices, thus the top (lattice-matched) junction is grown first and the bottom (most highly lattice-mismatched) junction is grown last. This direction of growth helps prevent the threading dislocations that inevitably originate during mismatched growth from degrading the higher band gap (and more power producing) junctions. The inverted growth and processing is shown schematically in figure 2.

In order to minimize the dislocations in the metamorphic junctions, a step-graded (Al)GaInP buffer layer, which is transparent to the light intended for the junction, was grown. The grade was engineered as described in the next section to achieve a nearly strain-free metamorphic junction. The $In_xGa_{1-x}As$ junctions were clad with corresponding $Ga_xIn_{1-x}P$ window and back-surface-field layers with the same lattice constant.

After OMVPE growth of the inverted semiconductor structure, gold was electroplated onto the exposed "back" surface of the inverted structure. The sample was then mounted with a low viscosity epoxy to a structural "handle," in this case silicon wafers or glass slides, however a variety of materials could be used as a handle to optimize cost, heat management, and weight considerations [4]. The GaAs substrate was removed using a selective chemical etch that stops at a GaInP layer. As a possible future refinement, the GaAs substrate could, in principle, be reused for considerable cost savings, using a lift-off procedure [6] . The "front" grids and mesa isolation were completed using standard photolithography processing techniques. Initial devices used electroplated gold grids as an etch mask for the contact layer, but severe anisotropic etching under the grid fingers led us to transition to thinner, denser evaporated Ti/Pd/Ag/Pd grids for improved series

resistance. A Se-doped GaInNAs contact layer was employed at the front grids to inhibit Se diffusion during the subsequent inverted growth and thus maintain good contact resistance [7]. Appropriate grid designs were chosen for each measurement condition. Finally, a MgF_2 / ZnS antireflective coating (ARC) was deposited by thermal evaporation.

This process of growing an inverted solar cell and mounting on a handle is similar in concept to the common method of flip-chip LED processing. The process, therefore, should be similarly manufacturable, especially for the relatively small devices required for some concentrator systems.

STRESS AND STRAIN CONTROL

The driving force for dislocation generation and glide in lattice mismatched semiconductor layers is the film stress that results from attempting to grow a single crystal layer epitaxially on another crystal lattice with a different lattice constant. In order to grow a relatively thick strain-free 1.0 eV $In_{0.27}Ga_{0.73}As$ junction on GaAs, a total of 1.9% misfit strain must be relaxed. By growing the compositionally step-graded $Ga_xIn_{1-x}P$ layers, most of the strain is relieved gradually while maintaining a relatively defect-free, flat growth surface. But a slight residual strain is always retained in reasonably thin graded layers. The strain of the 1.0 eV junction, though, can be reduced to zero by matching the relaxed lattice constant of the active junction to the in-plane lattice constant of the slightly strained top layer of the graded buffer. This technique was developed while studying lattice-mismatched thermophotovoltaic devices [8].
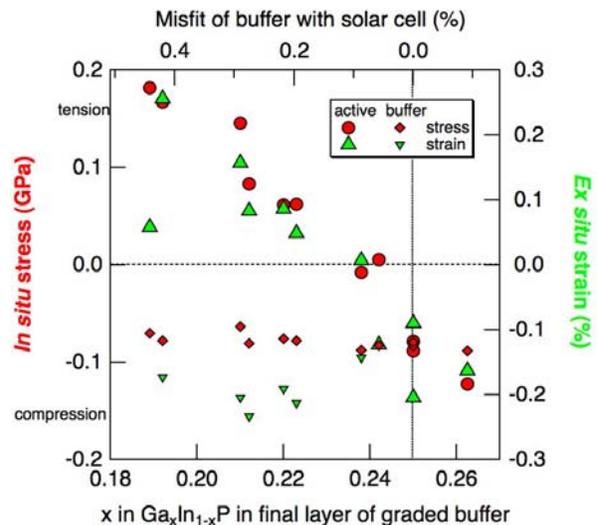

Fig. 3. Stress and strain of the active 1.0 eV solar cell (large points) and the top layer of the GaInP step-grade (small points) as a function of the composition of the top layer of the GaInP step-grade.
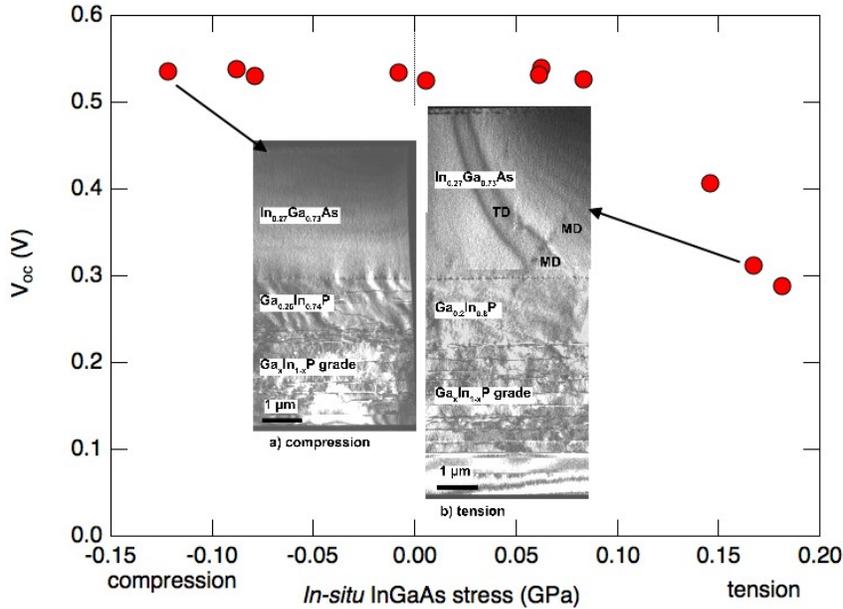
Fig. 4. V_{oc} of single-junction inverted 1.0 eV $In_{0.27}Ga_{0.63}As$ solar cells as a function of film stress during growth. Inset TEM images illustrate greater defect densities under tension.

We have investigated the effects of stress and strain on the performance of 1.0 eV $In_{0.3}Ga_{0.7}As$ solar cells [9]. The stress and strain of single-junction 1.0 eV devices were systematically varied by adjusting the maximum lattice constant of the top of the step-grade. The film stress was determined *in situ* at growth temperature using curvature measurements from a multi-beam optical stress sensor, while the strain was determined *ex situ* at room temperature from x-ray diffraction measurements. Figure 3 shows that the residual compressive stress in the top of the step-graded buffer remained constant for all samples at about 0.1 GPa, corresponding to about 0.15% strain. The stress and strain of the active 1.0 eV $In_{0.3}Ga_{0.7}As$ junction was systematically varied from compressive to tensile. The stress-free 1.0 eV solar cells had very good performance with an open-circuit voltage (V_{oc}) of about 0.54 V (see figure 4). The ideal V_{oc} of a 1.0 eV junction is not much more than about 0.6 V. Plan-view cathodoluminescence (CL) measurements revealed a dislocation density in the low 10^6 cm^{-2} range. Similar results were observed for slightly compressively strained devices, but tensile strain quickly degraded the performance because of higher dislocation densities. These techniques were used to engineer nearly strain-free metamorphic $In_xGa_{1-x}As$ junctions with excellent performance within the triple junction devices.

MULTIJUNCTION DEVICE RESULTS

Two different inverted triple-junction designs were fabricated. The first structure, described elsewhere [5], has only one low-stress metamorphic junction (hereafter referred to as 1MMJ) and two lattice-matched junctions. The junctions were 1.83 eV $Ga_{0.51}In_{0.49}P$, 1.40 eV GaAs,

and 1.00 eV $In_{0.27}Ga_{0.73}As$. Because of the non-optimal band gap combination, the top GaInP junction was thinned to 0.9 microns to current match all three junctions. This design is shown in figure 2.

The second design contains 2 low-stress metamorphic junctions (hereafter referred to as 2MMJ) and only one lattice-matched junction. They were 1.83 eV $Ga_{0.51}In_{0.49}P$, 1.34 eV $In_{0.04}Ga_{0.96}As$, and 0.89 eV $In_{0.37}Ga_{0.63}As$. This band gap combination was nearly current-matched with optically thick junctions (2.5 - 3.0 microns). A transparent (Al)GaInP compositional step-grade was included between each junction of the 2MMJ design. This design is pictured in figure 5.

Defect densities in the metamorphic junctions of actual triple-junction structures were characterized by plan-view CL and cross-sectional transmission electron microscopy (TEM). TEM samples were prepared by focused ion-beam. The TEM was performed on orthogonal <110> sections using 220 dark field conditions. Images of the 2MMJ structure are shown in figure 5. The $In_{0.37}Ga_{0.63}As$ (2MMJ) and $In_{0.27}Ga_{0.73}As$ (1MMJ) bottom junctions had ~2-3 x 10^6 cm^{-2} threading dislocations, with only about one defect visible in the entire 30 micron length of cross-sections examined. The $In_{0.04}Ga_{0.96}As$ (2MMJ) middle junction had only ~1x10^5 cm^{-2} threading dislocations, with none visible in the TEM. The defect density was very high within the step grades, but very low within the lattice-matched junctions.

Official solar cell measurements were obtained from the independent measurements team at NREL. The
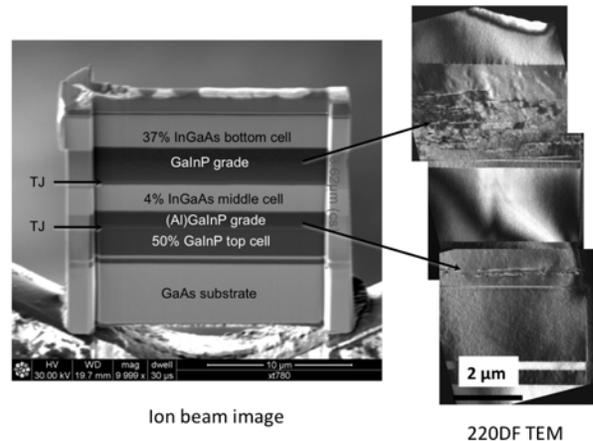

Fig. 5. Ion beam image and 220DF TEM of cross section of inverted 2MMJ device.
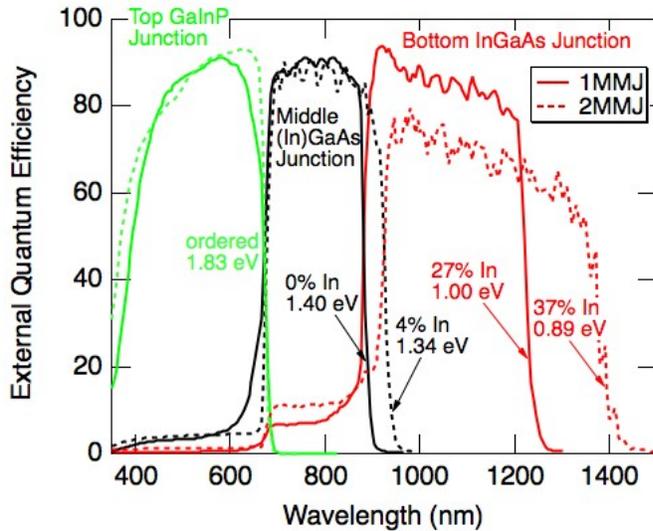
Fig. 6. External QE from both AM1.5G inverted triple-junction devices: 1MMJ (solid) and 2MMJ (dashed).

external quantum efficiency (QE) of each junction was measured separately by light biasing the other two junctions [10]. Current-voltage (IV) measurements were taken under a continuous multi-source solar simulator adjusted to the appropriate one-sun spectrum using three individual single-junction reference cells [10]. High irradiance IV measurements were taken under a flash simulator. The flash lamp voltage was adjusted to match the currents of the top two junctions under the AM1.5D spectrum (low AOD direct [11]) to their respective reference cells. This resulted in over-illuminating the bottom junction by approximately 30%. While this method was also used to measure record triple junction devices with Ge bottom junctions, the nearly current matched nature of our devices results in greater uncertainty. Future work for current matched multijunction devices must address this issue.

The external QE of all three junctions of the two designs is shown in figure 6. Integrated QE results and an alternative IV technique [12] showed the three junctions to be current matched to each other within about 10% under the measurement conditions. The simple two layer ARC used here is becoming a limiting factor for such current matched devices, requiring research into new ultra-broadband AR coatings. The unexpectedly high QE response of the bottom and middle junction at energies higher than the band gap (E_g) of the filtering junctions above them may indicate substantial radiative coupling between the junctions [13]. The relatively low QE of the bottom junction of the 2MMJ device is not characteristic of all such devices.

The current-voltage (IV) results for devices optimized for the AM1.5G spectrum with an area of 0.25 cm^2 are shown in figure 7. The 2MMJ design resulted in lower voltage but higher current operation. The 1MMJ and 2MMJ triple-junction devices had efficiencies of 33.8% and 33.2%, respectively. These are the highest efficiencies ever recorded for any solar cell device under this spectrum. The previous record of 32.0% was achieved in

a III-V multijunction solar cell using a Ge bottom junction [14]. AM0 efficiencies of 31.9% have been reported using a similar structure which Emcore refers to as the inverted metamorphic (IMM) solar cell [15].

Smaller 0.1 cm^2 devices, similar to the AM1.5G devices described above, were processed using a denser grid appropriate for concentration. Figure 8 shows the dependence of V_{oc}, FF, and efficiency on concentration for the direct spectrum. The fill factor of all devices initially rises with concentration, but eventually falls off due to unavoidably finite series resistance. The previously reported maximum efficiency of 38.9% at 81 suns concentration [5] using the sparser undercut electroplated gold grids on the 1MMJ design was limited by such a series resistance. The use of denser evaporated metal grids reduced the series resistance of the 1MMJ design resulting in a peak efficiency of 39.2% at 131 suns and efficiencies over 37% out to ~500 suns. Continued reduction in series resistance will enable greater efficiencies at higher concentrations yet. While the 2MMJ device still used the old sparse electroplated gold grids, it achieved 40.1% efficiency at 143 suns. In spite of the drop in fill factor below 100 suns, the relatively greater increase in voltage maintained high efficiencies to greater concentrations than in the 1MMJ device. The V_{oc} of all devices increased logarithmically with concentration with a slope close to the predicted value of 3kT for three "ideal" diodes in series.

CONCLUSIONS

The inverted triple-junction solar cell design has many advantages over traditional triple-junction designs utilizing Ge substrates. We have demonstrated here a world-record efficiency at one-sun and > 40% efficiency under concentration. The inverted nature of the design has facilitated the ability to grow strain-free metamorphic
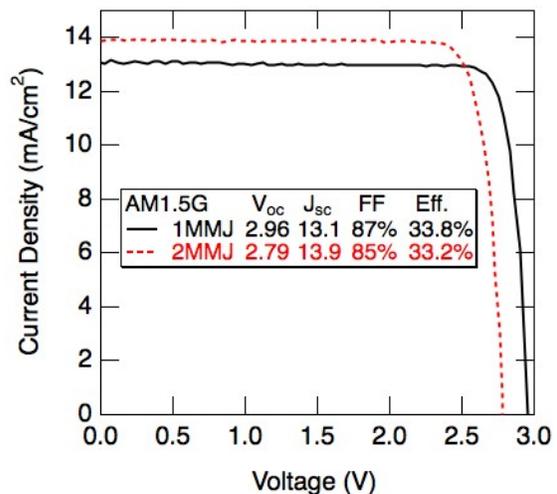

AM1.5G	V_{oc}	J_{sc}	FF	Eff.
1MMJ	2.96	13.1	87%	33.8%
2MMJ	2.79	13.9	85%	33.2%

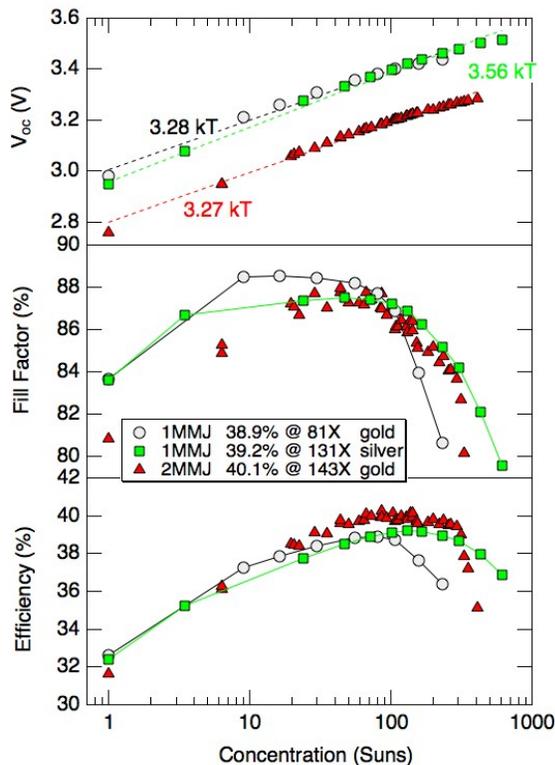Fig. 7. IV results measured at AM1.5G (IEC 60904) conditions using 1000 W/m^2 irradiance.

Fig. 8. V$_{oc}$, FF, and efficiency of inverted triple-junction devices under the AM1.5D (low AOD) conditions as a function of concentration. The V$_{oc}$ is fit with a simple diode equation (dashed lines) with labeled slope.

bottom junctions without damaging the top lattice-matched junctions. InGaAs metamorphic junctions engineered for low-stress and low-defect densities have demonstrated excellent solar cell performance in triple-junction designs with optimized band gap combinations. For the first time, we have demonstrated high efficiency in a monolithic triple-junction device with nearly optimal band gaps that are unconstrained by lattice-matching. These inverted designs allow for the possibility of cost savings through substrate reuse, flexible and light-weight devices, and rejection of unused infrared light for reduced heating. The concept can further be extended to more junctions for yet higher theoretical efficiencies.

ACKNOWLEDGEMENTS

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