GaInP/GaAs/GaInAs Monolithic Tandem Cells for High-Performance Solar Concentrators

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ABSTRACT

We present a new approach for ultra-high-performance tandem solar cells that involves inverted epitaxial growth and ultra-thin device processing. The additional degree of freedom afforded by the inverted design allows the monolithic integration of high-, and medium-bandgap, lattice-matched (LM) subcell materials with lower-bandgap, lattice-mismatched (LMM) materials in a tandem structure through the use of transparent compositionally graded layers. The current work concerns an inverted, series-connected, triple-bandgap, GaInP (LM, 1.87 eV)/GaAs (LM, 1.42 eV)/GaInAs (LMM, ~1 eV) device structure grown on a GaAs substrate. Ultra-thin tandem devices are fabricated by mounting the epiwafers to pre-metallized Si wafer handles and selectively removing the parent GaAs substrate. The resulting handle-mounted, ultra-thin tandem cells have a number of important advantages, including improved performance and potential reclamation/reuse of the parent substrate for epitaxial growth. Additionally, realistic performance modeling calculations suggest that terrestrial concentrator efficiencies in the range of 40-45% are possible with this new tandem cell approach. Laboratory-scale (0.243 cm^2), prototype GaInP/GaAs/GaInAs tandem cells with terrestrial concentrator efficiencies as high as 37.9% have already been demonstrated at low concentration ratios (10.1 suns).

1. Introduction

The performance of state-of-the-art, LM, triple-junction (TJ), concentrator tandem solar cells could be improved substantially (10-12%) by replacing the Ge bottom subcell with a subcell having a bandgap of ~1 eV. For the last several years, research has been conducted by a number of organizations to develop ~1-eV, LM GaInAsN to provide such a subcell, but, so far, the approach has proven unsuccessful. Thus, the need for a high-performance, monolithically integrable, 1-eV subcell for TJ tandems still remains.

In this paper, we present a new TJ tandem cell design that addresses the above-mentioned problem. Our approach involves inverted epitaxial growth to allow the monolithic integration of a lattice-mismatched (LMM) ~1-eV GaInAs/GaInP double-heterostructure (DH) bottom subcell with LM GaAs (middle) and GaInP (top) upper subcells. A transparent GaInP compositionally graded layer facilitates the integration of the LM and LMM components. Handle-mounted, ultra-thin device fabrication is a natural consequence of the inverted-structure approach, which results in a number of advantages, including robustness, potential low cost, improved thermal management, incorporation of back-surface reflectors, and possible reclamation/reuse of the parent crystalline substrate for further cost reduction.

Our initial work has concerned GaInP/GaAs/GaInAs tandem cells grown on GaAs substrates. In this case, the 1-eV GaInAs experiences 2.2% compressive LMM with respect to the substrate. Specially designed GaInP graded layers are used to produce 1-eV subcells with performance parameters nearly equaling those of LM devices with the same bandgap (e.g., LM, 1-eV GaInAsP grown on InP).

Preliminary ultra-thin tandem devices (0.237 cm^2) have already been demonstrated with NREL-confirmed, one-sun efficiencies of 31.3% (global spectrum) [1] and 29.7% (AM0 spectrum) [2], both at 25°C. The first results of testing similar devices under concentrated sunlight are presented in this paper.

2. APMOVPE growth parameters

The GaInP/GaAs/GaInAs tandem structures discussed here were grown using atmospheric-pressure metalorganic vapor-phase epitaxy (APMOVPE) in a home-built system at NREL. Trimethylindium, triethylgallium, trimethylgallium, trimethylaluminum, arsine, and phosphine were used as the primary reactants, with hydrogen sulfide, hydrogen selenide, disilane, carbon tetrachloride, and diethylzinc used as the doping precursors. Growth on GaAs substrates was performed at temperatures ranging from 600 to 700°C in a purified hydrogen ambient.

3. GaInP/GaAs/GaInAs tandem device structure

The TJ tandem devices investigated in our preliminary tests have been grown on GaAs substrates, but similar devices could also be fabricated using Ge substrates. From the substrate up, the tandem structure consists of the following components: a LM n-GaInP etch-stop layer, a LM n-GaAs contact layer, a LM n/p-GaInP/AlInP DH subcell, a LM p^+/n^+-GaAs tunnel junction, a LM n/p-GaAs/GaInP DH subcell, a LM p^+/n^+-GaAs tunnel junction, a LMM n-GaInP compositionally step-graded layer, a LMM n/p-GaInAs/GaInP DH subcell, and a LMM p^+-GaInAs contact layer. Further details of the tandem structure, and a general processing sequence for handle-mounted, ultra-thin devices, have been published previously [1].

4. Advantages of handle-mounted, ultra-thin tandem solar cells

Some of the important advantages of our new approach are listed below:

1) The handle material can be chosen to have a wide range of advantageous characteristics (e.g., mechanical strength, flexibility, specific electrical/optical parameters, high thermal conductivity, low cost, etc.).
2) Thermal management can be optimized since the ultra-thin device layers can be placed directly on a heat sink.
3) A back-surface reflector (BSR) can be easily incorporated on the back side of the LMM bottom subcell, which is grown last.
4) Reuse/reclamation of the parent substrate is also possible, resulting in substantially reduced cost.
5) Effective co-generation of heat and electric power is possible since the new TJ tandem cells do not absorb photons with energies less than ~1 eV.
6) Monolithically interconnected module (MIM) devices are easily realizable by mounting the ultra-thin tandems on an electrically insulating material.
7) The basic concept can be expanded to include numerous subcells for increased performance (NREL patent pending [2]).

Additionally, the key advantages of including a BSR on the back side of the LMM bottom subcell are as follows:

1) The GaInAs/GaInP DH subcell is grown to 1/2 the usual thickness, which translates to less growth time and lower J_0 due to the "narrow diode" effect (~20 mV improvement in V_{oc}).
2) The BSR reflects away sub-bandgap photons leading to a reduced operating temperature.
3) Absorbed photon escape due to photon recycling is also reduced, which also lowers J_0.

5. Semi-realistic tandem performance modeling

We have performed semi-realistic modeling calculations, based on a rigorous approach for series-connected tandem subcells [4], to serve as a guide for the choice of the bottom subcell bandgap, and to predict potential performance, under operating conditions relevant to concentrator devices. We assume that the bottom subcell quantum efficiency is 0.95 (spectrally independent) in the calculations. Also, the top and middle subcells are fixed to be GaInP (1.87 eV) and GaAs (1.42 eV), respectively. For terrestrial concentrator applications, we modeled for the low-AOD Direct spectrum at 250 suns concentration, 25°C, and obtained an optimum bottom subcell bandgap of 1.01 eV, with a tandem conversion efficiency of 41.5%.

6. Properties of ~1-eV GaInAs/GaInP DH LMM subcells

The characteristics of the LMM bottom subcells are of particular interest due to the potential deleterious impact of crystalline defects in the active subcell layers. Cross-sectional transmission electron microscopic characterization of the transparent GaInP graded region and GaInAs/GaInP subcell layers shows that misfit and threading dislocation networks are present within the GaInP compositionally step-graded layers, but are not visible in the active subcell layers. The coherence between the top of the grade and the active layers is quite apparent. Plan-view cathodoluminescence images reveal active threading dislocations in the GaInAs layers, with an average areal density of 2E6 cm^{-2}. Typical device performance data for the 1-eV subcells show that the losses due the dislocations are quite small. Internal quantum efficiency data range from 95 to 100% for photon energies ranging from the band edge (~1 eV) to the bandgap of GaAs (1.42 eV), respectively. Additionally, open-circuit voltages of 0.56–0.58 V are routinely observed for photocurrent densities of 15–20 $mAcm^{-2}$, which compares favorably with ~0.60 V that we obtain for LM, 1-eV GaInAsP/InP cells tested under similar photoexcitation.

7. GaInP/GaAs/GaInAs tandem performance

In an initial effort, we have successfully grown, processed, and tested monolithic, series-connected, handle-mounted, ultra-thin GaInP/GaAs/GaInAs tandem solar cells. Performance data for the best device fabricated to date are included in this section of the paper. Quantum efficiency (QE) and reflectance (R) data are given in Fig. 1. The data generally show excellent carrier collection across a broad spectral range for all of the subcells. The R data, however, show that photocurrent gains are still possible at the far edges of the tandem response range. Improving the two-layer ZnS/MgF_2 ARC will be a focus of future work. Interference effects are also observed in the QE data for the 1.02-eV bottom subcell, which occur because the subcell is optically thin with a BSR, causing it to behave like a Fabry-Perot cavity. The interference effects are also evident in the

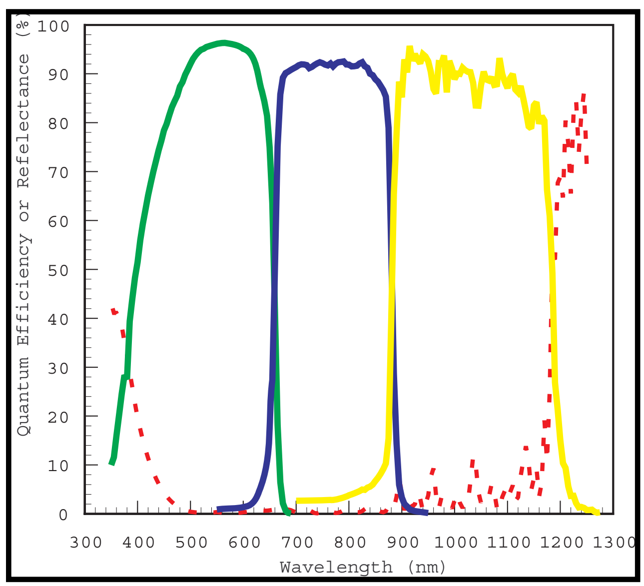

Figure 1. Composite spectral absolute external quantum efficiency (solid lines) and spectral reflectance (dotted line) data for an ultra-thin, handle-mounted GaInP/GaAs/GaInAs series-connected tandem solar cell.

R data over the response range of the bottom subcell. It is important to note that the QE for the bottom subcell is excellent despite its 2.2% LMM with respect to the GaAs substrate.

We have tested the new TJ tandem cells under mild solar concentration for the first time. The cells tested were designed for one-sun operation, but had sufficiently low resistance to allow peak performance at 5-10 suns concentration. Conversion efficiency data as a function of concentration ratio are shown in Fig. 2 for a TJ tandem cell with a total area of 0.243 cm^2. The measurements were performed using a water-filtered Xe lamp source, a cell temperature of 25°C, and a concentration ratio based on one-sun data obtained from our X25 multi-source solar simulator (Low-AOD AM 1.5 Direct reference spectrum). As shown in Fig. 2, the efficiency rises rapidly from one to five suns, and then peaks at 37.9% at 10.1 suns. Thereafter, the efficiency drops quickly with increased concentration. The peak efficiency value of ~38% at such a low concentration ratio indicates that efficiencies exceeding 40% at several hundred suns should be achievable in the near future once true concentrator versions of the devices are fabricated. Such high efficiencies should enhance the viability of terrestrial concentrator systems for cost-effective power generation.

The data shown in Fig. 3 elucidate the behavior of the data in Fig. 2. Here, open-circuit voltage (V_{oc}) and fill factor (FF) data for the same tandem cell are plotted as a function of the concentration ratio. The rapid increase in efficiency from one to five suns results from both V_{oc} and FF rising strongly over this range. The FF peaks at ~5 suns then decreases sharply with increasing concentration due to resistive losses. The V_{oc} shows a reduced rate of increase with concentration beyond ~5 suns, which we believe is due

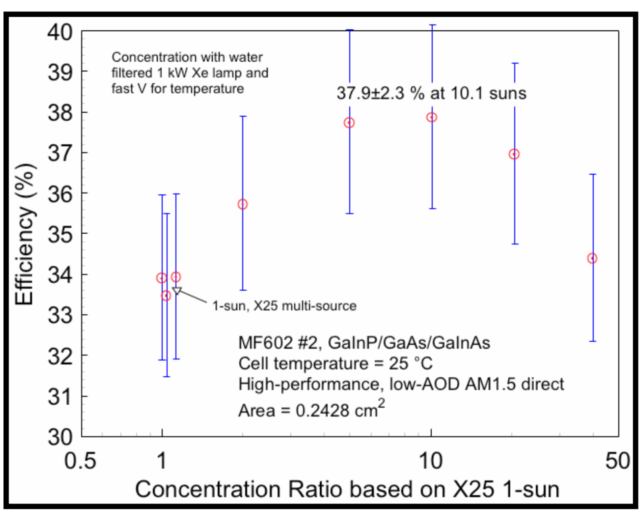

Figure 2. Conversion efficiency as a function of concentration ratio for a TJ GaInP/GaAs/GaInAs tandem solar cell.

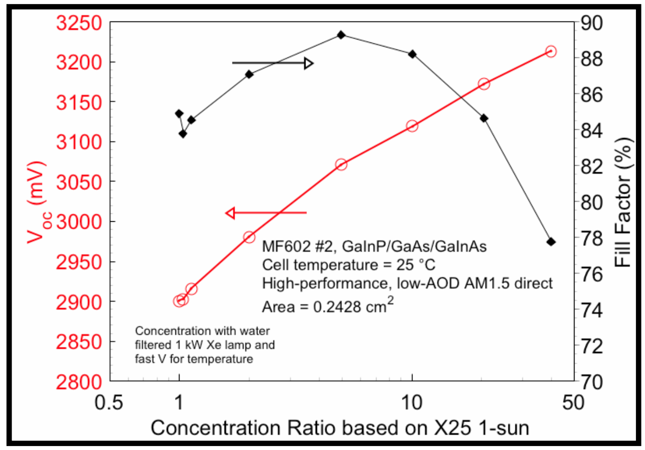

Figure 3. V_{oc} and FF as a function of concentration ratio for a TJ GaInP/GaAs/GaInAs tandem solar cell.

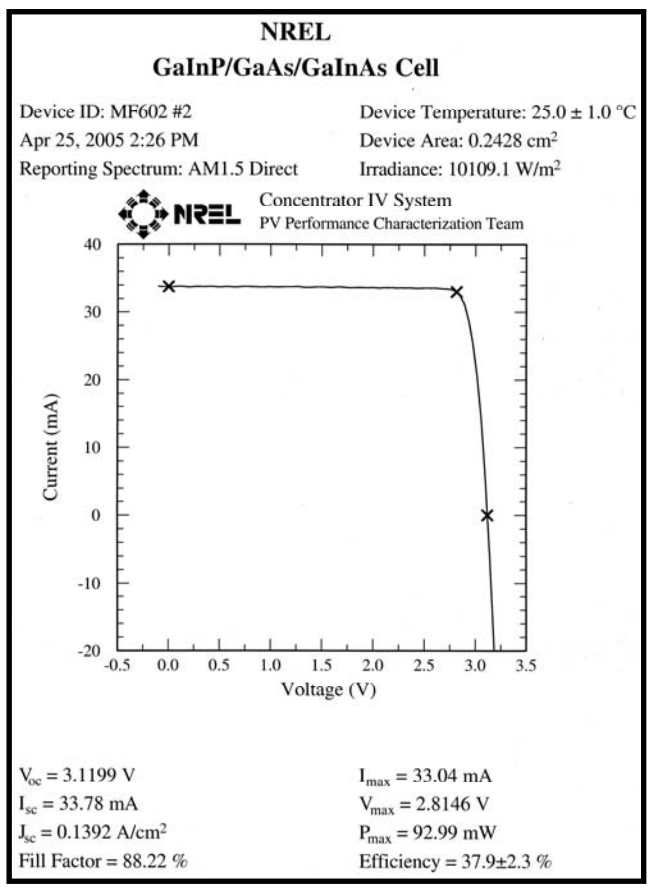

Figure 4. Current-voltage data for a TJ GaInP/GaAs/GaInAs tandem solar cell at peak efficiency.

to a transition from n=2 to n=1 diode behavior, principally in the LMM bottom subcell. The net result of the above trends is that the efficiency peaks at ~10 suns.

Current-voltage data for the tandem cell at peak efficiency are shown in Fig. 4. The efficiency value of 37.9±2.3% represents a new record for solar photovoltaic energy conversion. Continued development of similar tandem cells designed for operation under high concentration ratios is currently underway at NREL.

8. Conclusion

We have described a new approach for ultra-high-efficiency concentrator tandem solar cells based on inverted III-V heteroepitaxial epistructures that combine both LM and LMM component subcells in a monolithic structure. The tandem epistructures are fabricated into handle-mounted, ultra-thin devices, which have many advantages, and potential realistic terrestrial concentrator conversion efficiencies in the 40-45% range. In initial work, we have already demonstrated record-efficiency concentrator tandem cells using our new approach.

A number of research issues remain in order to move the new tandem cell technology from laboratory-scale demonstrations to potential commercial production. A cost-effective, high-yield processing scheme for large-area, handle-mounted, ultra-thin tandem devices must be explored and developed. Also, accurate performance testing under concentration in the laboratory is a difficult issue, particularly for series-connected tandem cells that have near-optimal subcell bandgaps; a multi-source concentrator simulator may need to be developed. The concentrator tandem cell testing problem will only become more complicated as tandem cells with more than three bandgaps become available.

9. Acknowledgements

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10. References

[1] M. W. Wanlass, S. P. Ahrenkiel, R. K. Ahrenkiel, D. S. Albin, J. J. Carapella, A. Duda, J. F. Geisz, Sarah Kurtz, T. Moriarty, R. J. Wehrer, and B. Wernsman, "Lattice-Mismatched Approaches for High-Performance, III-V Photovoltaic Energy Converters," Proc. 31st IEEE PVSC, Lake Buena Vista, FL, 1/3-7/05, IEEE Catalog No. 05CH37608C, ISBN: 0-7803-8708-2.

[2] Presented at the Space Power Workshop, Manhattan Beach, CA, 4/18-21/2005 (manuscript not available).

[3] M. W. Wanlass, "Approaches for Ultra-High Efficiency, Monolithic, Multi-Bandgap, Tandem Solar Photovoltaic Energy Converters," NREL IR # 05-05, patent pending.

[4] M. W. Wanlass and D. S. Albin, "A Rigorous Analysis of Series-Connected, Multi-Bandgap, Tandem Thermophotovoltaic (TPV) Energy Converters," AIP Conf. Proc. 738, 462-470 (2004).