Advances in High-Efficiency Multijunction Terrestrial Concentrator Cells and Receivers

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ABSTRACT

Record concentrator and one-sun solar cell efficiencies have been achieved for 3-junction cells grown and fabricated at Spectrolab under the NREL High-Performance Photovoltaics program. Independent confirmation of efficiency measured at NREL gives 31.3% efficiency for lattice-mismatched $Ga_{0.44}In_{0.56}P/Ga_{0.92}In_{0.08}As/Ge$ one-sun cells (AM1.5G, 25ºC, 4.0 cm^2), 32.0% for lattice-matched 3-junction one-sun cells (AM1.5G, 25ºC, 4.0 cm^2), and 35.2% for lattice-matched concentrator cells (66 suns, AM1.5 Direct, low-AOD spectrum, 25ºC). A wide variety of interconnection, heat sinking and other packaging methods have been experimentally evaluated, resulting in highly robust terrestrial concentrator cell receivers using this type of high-efficiency multijunction solar cell.

1. General Introduction

The quest for ever-higher concentrator solar cell efficiency, while maintaining high reliability under the demanding operating conditions for such cells, remains the central thrust in concentrator cell research. Higher efficiency lowers the area of cells, heat sinking and other receiver components, primary and secondary optics, and support structures that must be purchased for a given concentrator system power output, increasing the cost-effectiveness of concentrator photovoltaics. In order to generate as much economic return as possible on the initial capital outlay for the concentrator hardware, it is desirable to have a highly robust solar cell, enabling a system life of 20 years or more. The specific packaging methods used to mount the cell in a concentrating receiver are particularly critical for high reliability under the high-intensity, high-heat-flux conditions experienced by concentrator cells.

In the NREL High-Performance Photovoltaics (HiPerf PV) program, Spectrolab is pursuing a variety of device architectures not used in conventional concentrator solar cells. Metamorphic multijunction cells, in which active cells are grown lattice-mismatched to the growth substrate, allow a combination of bandgaps that are more optimized for efficient conversion of the solar spectrum than in the lattice-matched case [1-4]. Figure 1 compares the schematic cross section of a metamorphic (MM) 3-junction $Ga_{0.44}In_{0.56}P/Ga_{0.92}In_{0.08}As/Ge$ solar cell with the baseline lattice-matched (LM) 3-junction cell.

Spectrolab is also developing potentially high efficiency concentrator cell designs with subcells formed on different substrates, as in GaInP/GaAs/Si multijunction cells, integrating III-V solar cells grown on a substrate such as GaAs with a subcell formed in a separate silicon substrate. Both mechanically-stacked and wafer-bonded versions of this approach are under investigation. In this paper, we discuss the high efficiency results obtained with the monolithic lattice-matched and metamorphic 3-junction approaches formed on a single substrate.

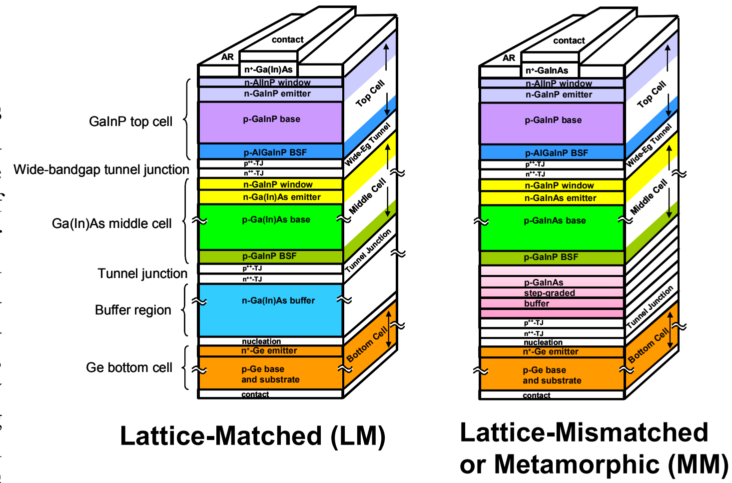

Figure 1. Cross-sections of lattice-matched and metamorphic 3-junction GaInP/GaInAs/Ge solar cells.

2. Lattice-Matched and Mismatched One-Sun Cells

Dual-junction GaInP/GaAs cells[5], and triple-junction GaInP/GaAs/Ge solar cells[6,7] have resulted in remarkably high efficiencies for both space and terrestrial use. However, the bandgap combination of ~1.8-1.9 eV for the GaInP top cell (depending on group-III sublattice disorder) and 1.424 eV for the GaAs subcell is not the optimum pairing for either space or terrestrial solar spectra.

By grading the composition of a GaInAs buffer on a Ge substrate as shown in Fig. 1, the top two subcells can be grown at a new, larger lattice constant, with higher indium composition than when lattice-matched to a GaAs or Ge substrate[1-3]. This allows the GaInP and GaInAs subcells to have lower bandgaps, resulting in higher theoretical conversion efficiencies. For low indium compositions, the smaller open-circuit voltage and fill factor that also come with low bandgap are offset by higher current density due to the longer wavelength photogeneration cutoff. This holds true up to about 14%-In GaInAs middle cell composition in metamorphic GaInP/GaInAs/Ge cells, for the AM0 spectrum in the absence of dislocations[1].

In any lattice-mismatched material system, threading dislocations can drastically increase Shockley-Read-Hall (SRH) minority-carrier recombination in the active device layers: reducing the density of these dislocations has been the main focus of metamorphic concentrator cell development in Spectrolab's NREL HiPerf program. Since most of the benefit of tuning the subcell bandgaps to lower energies can be achieved at smaller indium compositions than 14% in the GaInAs middle cell, and because these lower In compositions mitigate the problem of dislocations propagating into the active cell layers, much of the cell development has focused around lower In compositions such as 8%-In GaInAs.

Figure 2 shows the external quantum efficiency (EQE) of all the subcells in a lattice-matched 3-junction cell, as well as the EQE of the $Ga_{0.44}In_{0.56}P$ top subcell and $Ga_{0.92}In_{0.08}As$ middle subcell of a metamorphic 3-junction cell. These EQE plots are superimposed on the AM0 space, and AM1.5G and AM1.5 Direct, low-AOD[8] terrestrial spectra. This latter low-AOD spectrum is the standard for reporting concentrator cell efficiency in the NREL HiPerf program. The longer wavelength cutoff for both the top GaInP and middle GaInAs metamorphic cells, corresponding to bandgaps of 1.813 eV and 1.305 eV, respectively, results in higher current density in these subcells, and in the metamorphic 3-junction cell as a whole.

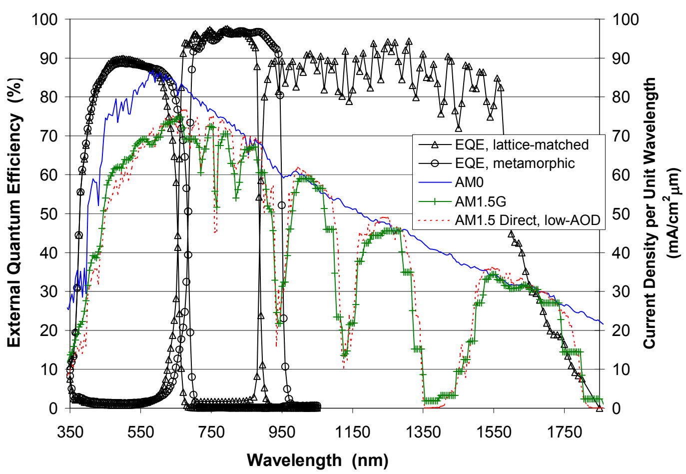

Figure 2. Quantum efficiency of lattice-matched and metamorphic 3-junction cells, with various solar spectra.

Figure 3 plots light I-V measurements for two new record efficiency cells. The lattice-matched 3-junction cell in the chart has an efficiency of 32.0% (AM1.5G, 0.100 W/cm^2, 4.0 cm^2, 25^{o}C), making this the highest independently confirmed solar cell efficiency at one-sun. The metamorphic GaInP/GaInAs/Ge 3-junction cell in Fig. 3 has nearly as high efficiency at 31.3%. This is not only a record efficiency for a metamorphic solar cell, but is also higher than the previous record one-sun efficiency of 31.0% for a cell < 1 cm^2, or 30.3% for a 4.0-cm^2 cell[9]. The higher current and lower voltage of the metamorphic cell design are evident in comparison to the lattice-matched cell in Fig. 3. The record efficiencies were confirmed by I-V measurements at NREL, and these are the data plotted in Fig. 3.

Since the offset voltage between V_{oc} and E_g/q is approximately constant for ideal cells dominated by radiative recombination[7], approximately 130 mV of the

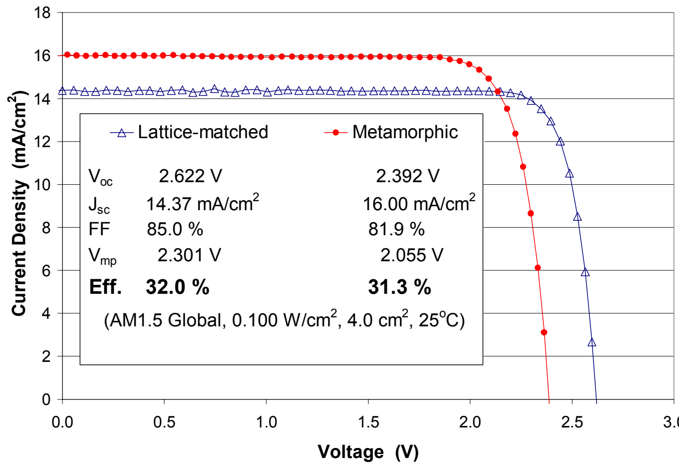

Figure 3. I-V curves of lattice-matched and metamorphic 3-junction cells processed at Spectrolab, with record one-sun efficiency independently measured at NREL.

230 mV difference in V_{oc} between LM and MM cases is accounted for by the ~130 meV difference in the sum of the subcell bandgaps. The relatively small remaining 100 mV portion is due to increased SRH recombination in the two lattice-mismatched subcells. As this voltage difference becomes smaller with further experimentation in metamorphic cell growth, and as we learn the mechanisms controlling the relatively low FF, we expect that the efficiency of the metamorphic cells can reach and surpass that of the best lattice-matched cells.

3. Terrestrial 3-Junction Concentrator Cells

The one-sun solar cells in the last section were fabricated using a mask set with grid patterns optimized for 1 to 1000 suns on the same wafer, in an experimental concentrator cell run. Concentrator 3-junction solar cells from this run have also demonstrated record performance under the concentrated solar spectrum. Figure 4 plots the efficiency, V_{oc}, and FF of a lattice-matched 3-junction cell grown and processed at Spectrolab, and measured at NREL to have an efficiency of 35.2% at 66 suns (AM1.5 Direct, low-AOD, 6.6 W/cm^2, 0.266 cm^2 aperture area, 25^{o}C).

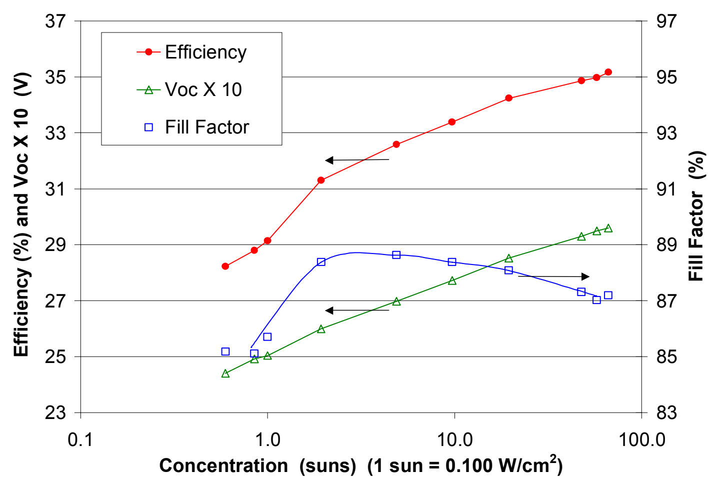

Figure 4. Dependence of record efficiency 3-junction concentrator cell performance on incident intensity.

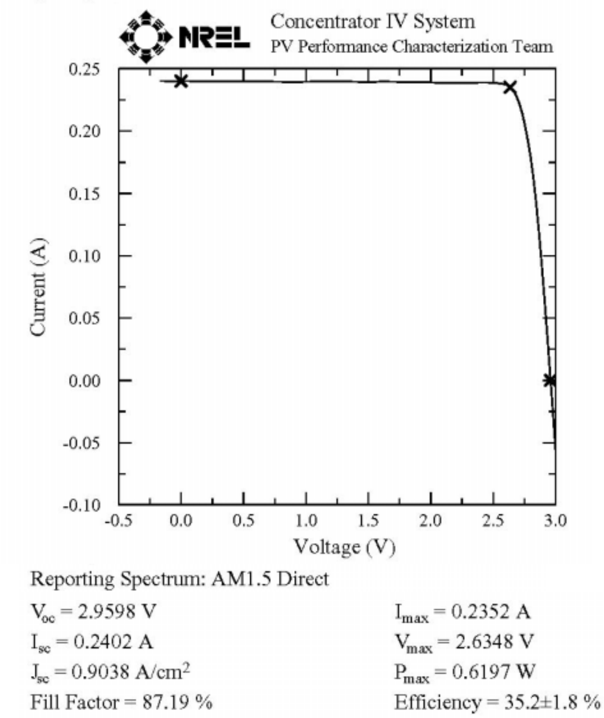

Figure 5. I-V curve of 35.2%-efficient Spectrolab concentrator cell measured at NREL.

The open-circuit voltage of this 3-junction cell is seen to increase by ~250 mV per decade in concentration from the 2.504 V measured at one sun, and the FF for this lightly gridded concentrator cell peaks at only ~3 suns. However, the efficiency has still not peaked by the time it reaches 35.2% at 66 suns incident intensity. This was the highest intensity at which this cell was tested in these steady-state measurements at NREL using an X25 solar simulator. The I-V curve of the 3-junction lattice-matched cell at the 35.2%-efficiency point is plotted in Fig. 5. Measurements of metamorphic concentrator cells, as well as other lattice-matched cells are underway using a pulsed solar simulator, capable of higher concentrations.

4. Terrestrial Concentrator Receivers

In this section, we address the performance and reliability of concentrator cells and receivers under continuous illumination. Short-duration cell efficiency measurements are valuable for determining initial cell performance, but are quite different from long-term, steady-state exposure to high concentration, where heating effects may impact cell performance and reliability. In addressing concentrator cell and receiver reliability, we take note of the following failure mechanisms: (i) cell shunting, (ii) electrical shorts, (iii) cell cracking, and (iv) loss of thermal management.

Cell shunting can be caused by the presence of internal as well as external defects, that can lead to current crowding, which in turn leads to local heat generation. The heated area draws more current, which can eventually lead to thermal runaway conditions. Electrical shorts can occur in the presence of water droplets if the module is not properly insulated. Cell cracking can be caused by repeated thermal cycling, particularly if there is a large thermal expansion mismatch between the cell and the packaging substrate. Loss of thermal management can result from lack of cooling or from the presence of solder voids between the cell and the substrate.

It is clear, therefore, that the above failure mechanisms other than cell shunting are problems to be addressed by the module designer. Conventional wisdom has held that concentrator cell shunting is a problem that concerns primarily the cell design. It is our objective here to determine whether cell shunting is indeed independent of the module design.

In order to do this, we need a standard method of testing concentrator cells and receiver assemblies. We have devised a forward bias injection (FBI) test, where electrical current is injected into a cell until it fails. As the cell is forward biased, bright spots caused by electroluminescence indicate a particular cell area is receiving more current. Generally speaking, such bright spots tend to get brighter with the injection of more current, until the whole cell fails. A more uniformly illuminated cell is an indication of fewer internal shunts. The FBI tests are used in conjunction with outdoor, high concentration tests to assess the performance and reliability of the cells and receivers.

Several test coupons were assembled using different cell sizes (ranging from 4.5 cm^2 to 0.4 cm^2), and different assembly techniques. Examples of the different receivers are shown in Fig. 6. In Fig. 6a, one cell is attached to a thin kovar substrate by conductive epoxy, while the substrate is attached to the heat sink by thermal adhesive. The electrical connection is made by wire bonding the cell busbar to another kovar substrate. In Fig. 6b, one cell is attached directly to the heat sink by thermal adhesive, with the electrical connection being made by soldering metallic interconnects to kovar substrates. In Fig. 6c, one cell is soldered to a metallized ceramic substrate, with the electrical connection being made by soldering metallic interconnects to the traces on the substrate.

(a) (b) (c)

Figure 6. Examples of receiver designs used in this study.

Various assembly processes were used for the different receivers, *e.g.*, cure temperature, time, and weight on top of the cells. Further, some assemblies were produced with almost void-free solder, while others had varying levels of solder voids present between the cell and the substrate.

FBI tests on the different receivers showed a dependence of the onset of cell shunting on the package design and assembly processes. A void-free assembly, for example, had more uniform illumination as the current was being injected into the solar cell, and, as such, was able to carry a higher level of current before the cell shunted. It was also observed that, in general, cell assemblies with a high level of stress induced in the cell by the cell packaging method were susceptible to shunting. Cells that went into high temperature cure without enough weight on top of them bowed during the reflow process and failed at much lower levels of current than did other assemblies. Further, cells that were mounted directly on copper or aluminum were, in general, less robust than cells that were mounted on other substrates that have a coefficient of thermal expansion (CTE) closer to that of the cell.

Based on the above, we defined an appropriate test vehicle to test cell assemblies under high concentration. Cell assemblies with CTE-matched substrates were fabricated with a void-free solder process, and mounted on cooling plates to provide sufficient cooling to the cells during the test. The Spectrolab concentrator cell test set-up is shown in Fig. 7, where the cell assemblies can receive different levels of concentration by changing the relative distance between the cell assembly and the fresnel lens.

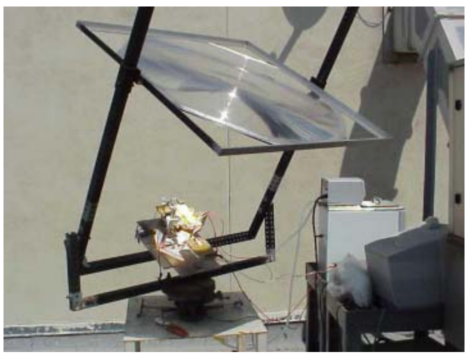

Figure 7. Outdoor concentrator test fixture at Spectrolab.

This setup was used to test several cell assemblies at concentrations up to 1000 suns. It was also used to measure the performance of cells under non-uniform illumination. The details of these tests are discussed in [10].

Additional high concentration tests of Spectrolab's triple-junction cells were obtained at other outdoor facilities. Figure 8 shows I-V curves for a 3-cell string that has been tracking the sun for several months at a concentration of ~450 suns. The high series resistance observed in this figure can be attributed to the series losses in the substrate metallization and the external wiring.

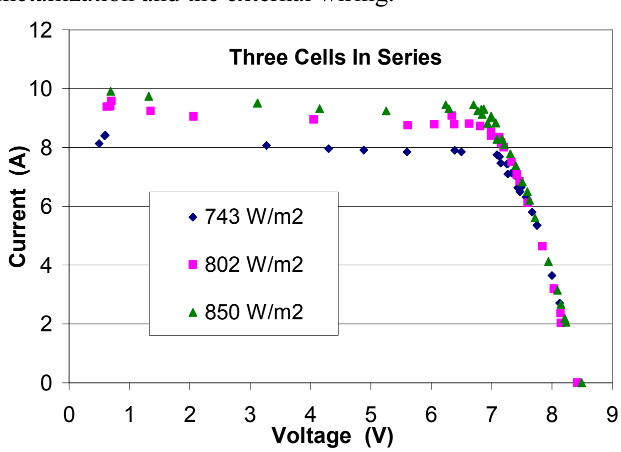

Figure 8. I-V curves from high-concentration outdoor tests of a 3-cell series string.

5. Summary

New performance heights have been reached for multijunction solar cells of an unconventional lattice-mismatched GaInP/GaInAs/Ge design, establishing this type of cell as a contender for the most efficient type of cell. The 31.3% one-sun efficiency measured for such metamorphic cells is greater than the previous efficiency record, and would have been the highest one-sun efficiency yet measured had it not been exceeded by a 32.0% lattice-matched 3-junction cell in the same fabrication run. A new record concentrator cell efficiency of 35.2% under the AM1.5 Direct, low-AOD spectrum has been achieved in this work. Careful consideration of receiver design and the cell package assembly process has resulted in a robust concentrator system, allowing reliable outdoor operation of high-efficiency multijunction concentrator cells, under continuous illumination at high concentration.

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