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Metamorphic Concentrator Solar Cells with Over 40% Conversion Efficiency

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ABSTRACT: Multijunction III-V concentrator cells have attracted much interest for concentrator photovoltaic (PV) systems recently due to their unparalleled conversion efficiencies. As high as these efficiencies are, they can be made even higher if the combination of subcell bandgaps for the multijunction solar cell are chosen from metamorphic semiconductors that are not all lattice-matched to the same growth substrate. Advances in the design of metamorphic subcells to reduce carrier recombination and increase voltage, wide-bandgap tunnel junctions capable of operating at high concentration, metamorphic buffers to transition from the substrate lattice constant to the active subcells, concentrator cell AR coating and grid design, and integration into 3-junction cells current matched under the terrestrial spectrum have resulted in new heights in solar cell performance. A metamorphic $Ga_{0.44}In_{0.56}P$/ $Ga_{0.92}In_{0.08}As$/ Ge 3-junction solar cell from this research has reached a record 40.7% efficiency at 240 suns, under the standard reporting spectrum for terrestrial concentrator cells (AM1.5 direct, low-AOD, 24.0 W/cm^2 25°C), and experimental lattice-matched 3-junction cells have now also achieved over 40% efficiency, with 40.1% measured at 135 suns. This metamorphic 3-junction device is the first solar cell to reach over 40% in efficiency, and has the highest solar conversion efficiency for any type of photovoltaic cell developed to date.

1 INTRODUCTION

In the past decade, terrestrial concentrator multijunction III-V cells have embarked upon a remarkable ascent in solar conversion efficiency. The realization that very high conversion efficiencies can be achieved with advanced multijunction solar cells in practice, not just in theory, has prompted a resurgence of research in multijunction cells and commercial interest in concentrator III-V photovoltaics. This paper presents recent advances in multijunction cell research that have led to experimental metamorphic (MM), or lattice-mismatched, solar cells with 40.7% efficiency under the concentrated terrestrial spectrum. This is the first solar cell to reach over 40% efficiency, and is the highest solar conversion efficiency yet achieved for any type of photovoltaic device. Experimental lattice-matched (LM) cells have now also broken the 40% milestone, with 40.1% efficiency demonstrated for a LM 3-junction cell. Both of these cell efficiency results have been independently verified by cell measurements at the National Renewable Energy Laboratory (NREL). Many of the high efficiency device structures developed in the experiments leading to these record performance cells have now been incorporated in production III-V multijunction cells, increasing the average efficiency of these mass-produced solar cells as well, while other experimental device improvements will be implemented in production in the coming months and years. This paper discusses the science behind the 40.7% metamorphic and 40.1% lattice-matched cells, the opportunity to reach new levels of PV system cost-effectiveness with production III-V concentrator cells that make use of these advances, and possibilities for the next generations of terrestrial concentrator cells with efficiencies of 45%, or even 50%.

METAMORPHIC SOLAR CELLS

Perhaps the essential distinguishing feature of III-V multijunction cells is the very wide range of subcell and device structure bandgaps that can be grown with very high crystal quality, and correspondingly high minority-

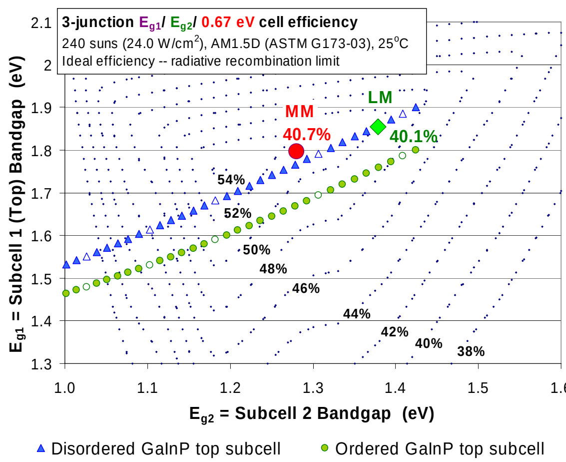


Figure 1. Ideal iso-efficiency contours for 3-junction terrestrial concentrator cells with variable top and middle subcell bandgaps, based on radiative recombination and the terrestrial solar spectrum at 240 suns. Subcell 1 and 2 bandgap pairs of GaInP and GaInAs at the same lattice constant are shown for both disordered and ordered GaInP. The measured efficiencies and bandgap combinations for the record 40.7% MM and 40.1% LM cells are plotted on the chart, showing the theoretical advantage of the metamorphic design, now realized in practice.

carrier recombination lifetimes. This is true for lattice-matched multijunction cells, but the flexibility in bandgap selection takes on a whole new dimension when metamorphic semiconductors are used, providing freedom from the constraint that all subcells must have the same crystal lattice constant. The area of metamorphic solar cell materials has attracted interest from many photovoltaic research groups around the globe [1-7].

The theoretical benefits of flexibility in subcell bandgap selection are made apparent in Fig. 1, which plots iso-efficiency contours for 3-junction terrestrial concentrator cells as a function of top (subcell 1) bandgap Eg1 and middle (subcell 2) bandgap Eg2.

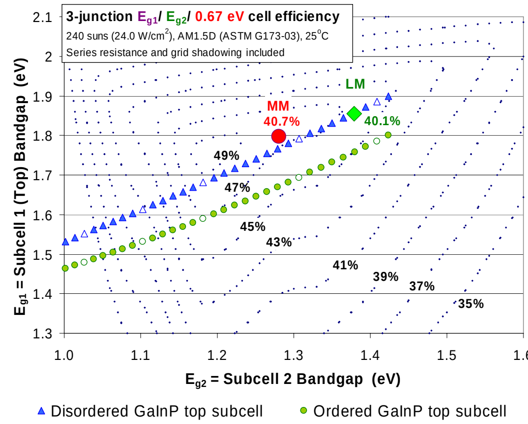
Figure 1 plots contours of ideal efficiency based on the diode characteristics of subcells limited only by the fundamental mechanism of radiative recombination, and on the shape of the terrestrial solar spectrum. The cell model is discussed in greater detail in [7]. Efficiencies up to 54% can be seen to be possible in principle at this concentration for 3-junction cells in this radiative recombination limit, increasing to over 58% for 4-junction terrestrial concentrator cells [7].

The bandgap combinations that are possible with GaInP/ GaInAs/ Ge 3-junction solar cells, where the GaInP and GaInAs subcells have the same lattice constant but can both be lattice-mismatched to the Ge substrate, are shown in Fig. 1. The cases with a disordered group-III sublattice in the GaInP subcell, giving higher bandgap at the same GaInP composition, and with an ordered (low Eg) group-III sublattice in the GaInP subcell, are both plotted. Metamorphic cells can be seen to bring the cell design closer to the region of Eg1, Eg2 space that has the highest theoretical efficiencies. The lower bandgaps of MM subcells can use a larger part of the solar spectrum, that is wasted as excess photogenerated current in the Ge bottom cell in most lattice-matched 3-junction cells. In the past, recombination at dislocations in MM materials have often thwarted this promise of higher theoretical efficiency. However, for the recent metamorphic 40.7%-efficient and lattice-matched 40.1%-efficient cell results, plotted in Fig. 1, the density and activity of dislocations has been controlled sufficiently to show the efficiency advantage of the MM design, not just theoretically but now also experimentally.

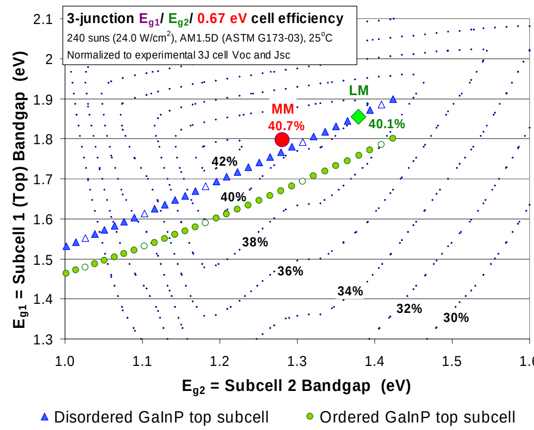
Figures 2a and 2b take this analysis a bit farther. The efficiency contours in Fig. 2a take into account the shadowing and specific resistance associated with the metal grid pattern used on the 40.7% record cell. The fill factor calculated for the 3-junction cell with the bandgap combination of the MM 40.7% cell is 87.5% with series resistance included, essentially identical to that measured experimentally for the 40.7% cell at 240 suns.

In Fig. 2b, additional real-life effects are included by using empirical values for the active-area external quantum efficiency (EQE), and for the decrease in 3-junction cell Voc from Shockley-Read-Hall (SRH) recombination in addition to radiative recombination. The record 40.7%-efficiency 3-junction MM cell has an average active-area external quantum efficiency of 0.925, and actual Voc that is 233 mV lower than the ideal Voc in the radiative limit. This is equivalent to 78 mV per subcell on average, though since the GaInAs middle subcell Voc is often close to the radiative limit, the difference actual Voc and ideal radiative Voc is more heavily distributed in the top and bottom subcells. With the addition of these last real-life effects, the calculated contours in Fig. 2b show a good estimate of the efficiencies that can be achieved in practical, state-of-the-art, 3-junction cells as a function of bandgap. It should be noted, however, that unlike Fig. 1, these efficiencies are not fundamental limits, and can be made higher by finding ways to reduce the non-fundamental EQE and Voc losses included in Fig. 2b.

Schematic diagrams of LM and MM cells are shown in Fig. 3, showing the step-graded metamorphic buffer used in the MM case to transition from the lattice constant of the substrate to that of the upper subcells. The lattice constants and strain in the various MM 3-junction cell layers are imaged in the high-resolution X-ray diffraction (HRXRD) reciprocal space map (RSM) shown in Fig. 4. The buffer can be seen to be nearly 100% relaxed, with very little residual strain to drive the formation of dislocations in the active upper subcells.



(a)



(b)

Figure 2. Iso-efficiency contour plots for 3-junction cells including the effects of (a) grid resistance and shadowing using the metal grid design of the record 40.7%-efficient cell; and (b) additionally including empirically determined average quantum efficiency of 0.925, and 3-junction cell V_{oc} 233 mV lower than the ideal voltage based on radiative recombination alone, giving an experimentally-grounded prediction of practical, state-of-the-art 3J cell efficiencies, as a function of subcell Eg.

The shift in the quantum efficiency of the 3 subcells in GaInP/ GaInAs/ Ge 3-junction cells, as a result of the higher indium composition and lower bandgap of the metamorphic GaInP and GaInAs subcells, is shown in Fig. 5. In this way the MM cells are able to capture some of the current density that would otherwise be wasted in the Ge subcell. The quantum efficiencies are overlaid on the AM0, and terrestrial AM1.5G and AM1.5D, low-AOD solar spectra, to show the current densities available in the response range of each subcell.

HIGH-EFFICIENCY MULTIJUNCTION CELLS

Bandgap engineering of subcells in 3-junction solar cells, made possible by metamorphic semiconductor materials, has now resulted in higher measured efficiencies for metamorphic cells than in even the best

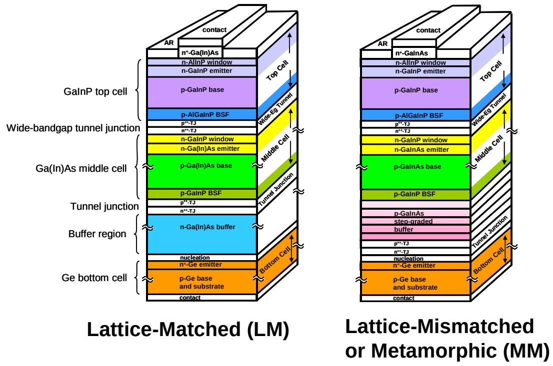


Figure 3. Schematic cross-sectional diagrams of lattice-matched (LM) and metamorphic (MM) GaInP/GaInAs/Ge 3-junction cell configurations, corresponding to the LM 40.1% and MM 40.7%-efficient concentrator cells.

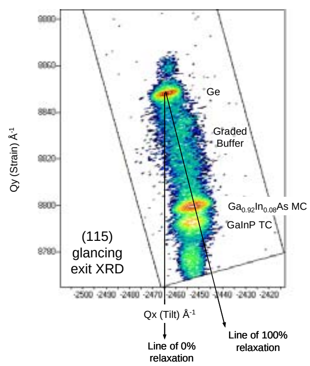


Figure 4. High-resolution X-ray diffraction reciprocal space map of a metamorphic 3-junction cell structure, showing a metamorphic buffer with almost no residual strain, and a GaInP top cell that is pseudomorphic with respect to the $Ga_{0.92}In_{0.08}As$ middle cell.

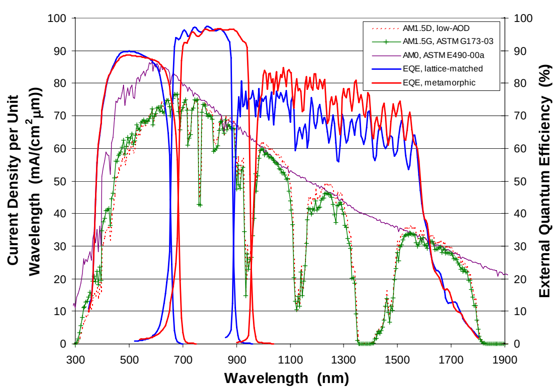


Figure 5. External quantum efficiency for the GaInP, GaInAs, and Ge subcells of LM and MM 3-junction cells, showing extension of the lower-Eg, metamorphic GaInP and GaInAs responses to longer wavelengths, allowing them to use more of the solar spectrum.

lattice-matched cells. Experiments on step-graded buffers, used to transition from the substrate to the subcell lattice constant, have been used to control the classic problem of dislocations in the active cell regions due to the lattice mismatch. The bandgap-voltage offset (E_g/q) - V_{oc} is a key indicator of the quality and suppression of SRH recombination in semiconductors of variable bandgap, where lower offset values are desired, since it is a measure of the separation between electron and hole quasi-Fermi levels and the conduction and valence band edges [5-7]. Metamorphic 8%-In GaInAs single-junction cells were built and tested with a bandgap-voltage offset of 0.42 V at one sun, essentially the same as GaAs control cells, reflecting the long minority-carrier lifetimes that can be achieved in metamorphic materials.

An extensive experimental campaign was carried out on GaInP/GaInAs/Ge terrestrial concentrator cells, using a variety of metamorphic and lattice-matched 3-junction cell configurations, wide-bandgap tunnel junctions and other high-efficiency semiconductor device structures, current matching conditions, cell sizes, grid patterns, and fabrication processes, resulting in new understanding of the limiting mechanisms of terrestrial multijunction cells, and new heights in performance. Figure 6 plots the measured illuminated I-V curve for the record efficiency 40.7% metamorphic GaInP/ GaInAs/ Ge 3-junction cell at 240 suns, under the standard spectrum for concentrator solar cells (AM1.5D, low-AOD, 24.0 W/cm^2, 25°C). This is the first solar cell to reach over 40% efficiency, and is the highest solar conversion efficiency yet achieved for any type of photovoltaic device. A lattice-matched 3-junction cell has now also achieved over 40% efficiency, with 40.1% measured at 135 suns (AM1.5D, low-AOD, 13.5 W/cm^2, 25°C). These efficiencies have been independently verified by measurements at the National Renewable Energy Laboratory (NREL). Light I-V characteristics of both the record MM and LM devices are compared in Fig. 7.

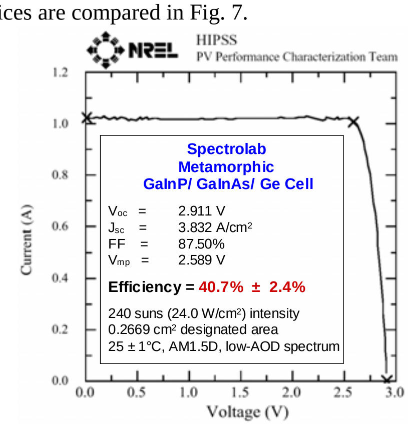


Figure 6. Illuminated I-V curve for the record 40.7% metamorphic 3-junction cell, independently verified at NREL. This is the first photovoltaic cell of any type to reach over 40% solar conversion efficiency.

The highest cell efficiencies from a number of photovoltaic technologies by year since 1975 are plotted in Fig. 8, showing the most recent 40.7%-efficient cell result. It is interesting to note that III-V multijunction concentrator cells are not only the highest efficiency technology, but also have the highest rate of increase. These high III-V cell efficiencies have translated to concentrator PV module efficiencies over 30%, more than double the ~15% module efficiencies that are more typical of flat-plate silicon modules. This high efficiency is extremely leveraging for PV system economics [8], as it reduces all area-related costs of the module. Production multijunction concentrator cells with efficiency in the 40% range could cause the market growth for concentrator PV to explode, with multi-GW/year production levels.

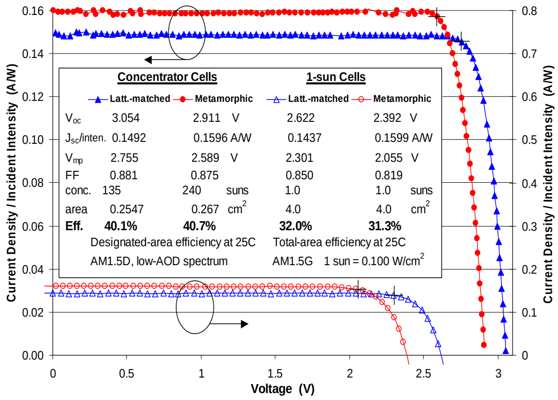


Figure 7. Comparison of the light I-V characteristics of the 40.1% lattice-matched and 40.7% metamorphic 3-junction concentrator cells, and earlier record one-sun cells. The higher current and lower voltage of the metamorphic design is evident.

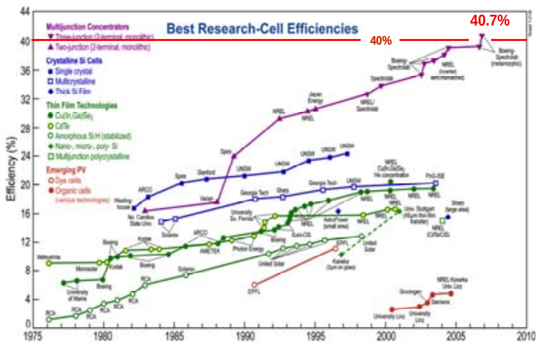


Chart courtesy of Bob McConnell, NREL

Figure 8. Plot of record cell efficiencies for a range of photovoltaic technologies, showing the recent advance to 40.7% efficiency for III-V multijunction cells.

In Fig. 9, the measured efficiency, Voc, and fill factor are plotted as a function of incident intensity, or concentration ratio, for the record 40.7% MM and 40.1% LM cells, as well as for an additional MM cell with good performance at high intensities. It is interesting to note that the efficiencies of both the record MM and LM cells track very closely at the same concentration, but the measurements were able to be extended to a higher concentration for the MM cell. Fill factors for both types of cell are quite high at about 88% in the 100-200 sun range. The open-circuit voltage Voc increases at rates of approximately 210 mV/decade and 190 mV/decade for the MM and LM record cells respectively, in the 100-200 suns range. Thus the MM subcells increase in voltage somewhat more rapidly with excess carrier concentration than in the LM case, as one would expect if defects in the MM materials are becoming less active at mediating recombination at higher injection levels. Subtracting off the 59 mV/decade increase for the Ge subcell, which has a diode ideality factor n very close to unity, gives an average n for the upper two subcells of 1.26 in the MM case and 1.10 in the LM case in the same concentration range, with decreasing n as the incident intensity increases.

SUMMARY

Multijunction GaInP/ GaInAs/ Ge solar cells have been demonstrated with 40.7% efficiency using metamorphic semiconductor technology,and 40.1% for lattice-matched

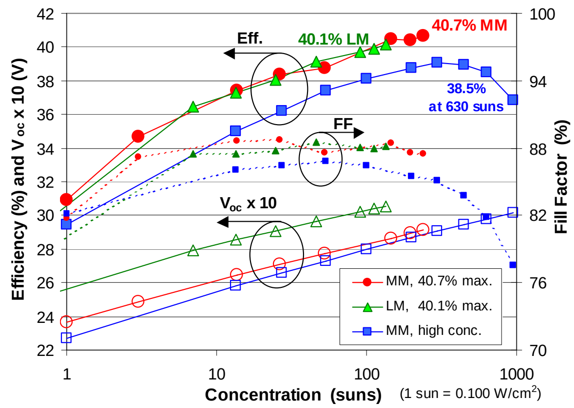


Figure 9. Efficiency, Voc, and FF of record performance 40.7% metamorphic and 40.1% lattice-matched 3-junction cells as a function of incident intensity. An additional cell is shown which maintains an efficiency of 38.5% over 600 suns, and 36.9% over 950 suns.

cells. These are the first solar cells to reach over the milestone efficiency of 40%, and have the highest solar conversion efficiencies of any type of photovoltaic device to date. These very high experimental cell efficiencies have begun to be translated to production solar cells as well. The recent realization of very high-efficiency III-V multijunction cells has positioned concentrator PV technology such that it may well have a game-changing effect on the economics of PV electricity generation in the near future. New multijunction cell configurations offer the potential to increase cell efficiencies still further, to 45%, and perhaps even to 50% efficiency.

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