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Research Article

Advances in High-Efficiency III-V Multijunction Solar Cells

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The high efficiency of multijunction concentrator cells has the potential to revolutionize the cost structure of photovoltaic electricity generation. Advances in the design of metamorphic subcells to reduce carrier recombination and increase voltage, wide-band-gap tunnel junctions capable of operating at high concentration, metamorphic buffers to transition from the substrate lattice constant to that of the epitaxial subcells, concentrator cell AR coating and grid design, and integration into 3-junction cells with current-matched subcells 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. Solar cells with more junctions offer the potential for still higher efficiencies to be reached. Four-junction cells limited by radiative recombination can reach over 58% in principle, and practical 4-junction cell efficiencies over 46% are possible with the right combination of band gaps, taking into account series resistance and gridline shadowing. Many of the optimum band gaps for maximum energy conversion can be accessed with metamorphic semiconductor materials. The lower current in cells with 4 or more junctions, resulting in lower I^2R resistive power loss, is a particularly significant advantage in concentrator PV systems. Prototype 4-junction terrestrial concentrator cells have been grown by metal-organic vapor-phase epitaxy, with preliminary measured efficiency of 35.7% under the AM1.5 direct terrestrial solar spectrum at 256 suns.

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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 discusses 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 [1, 2]. 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 also broken the 40% milestone, with 40.1% efficiency demonstrated for an 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 photovoltaic (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%.

2. METAMORPHIC SOLAR CELLS

Perhaps the essential distinguishing feature of III-V multijunction cells is the very wide range of subcell and device

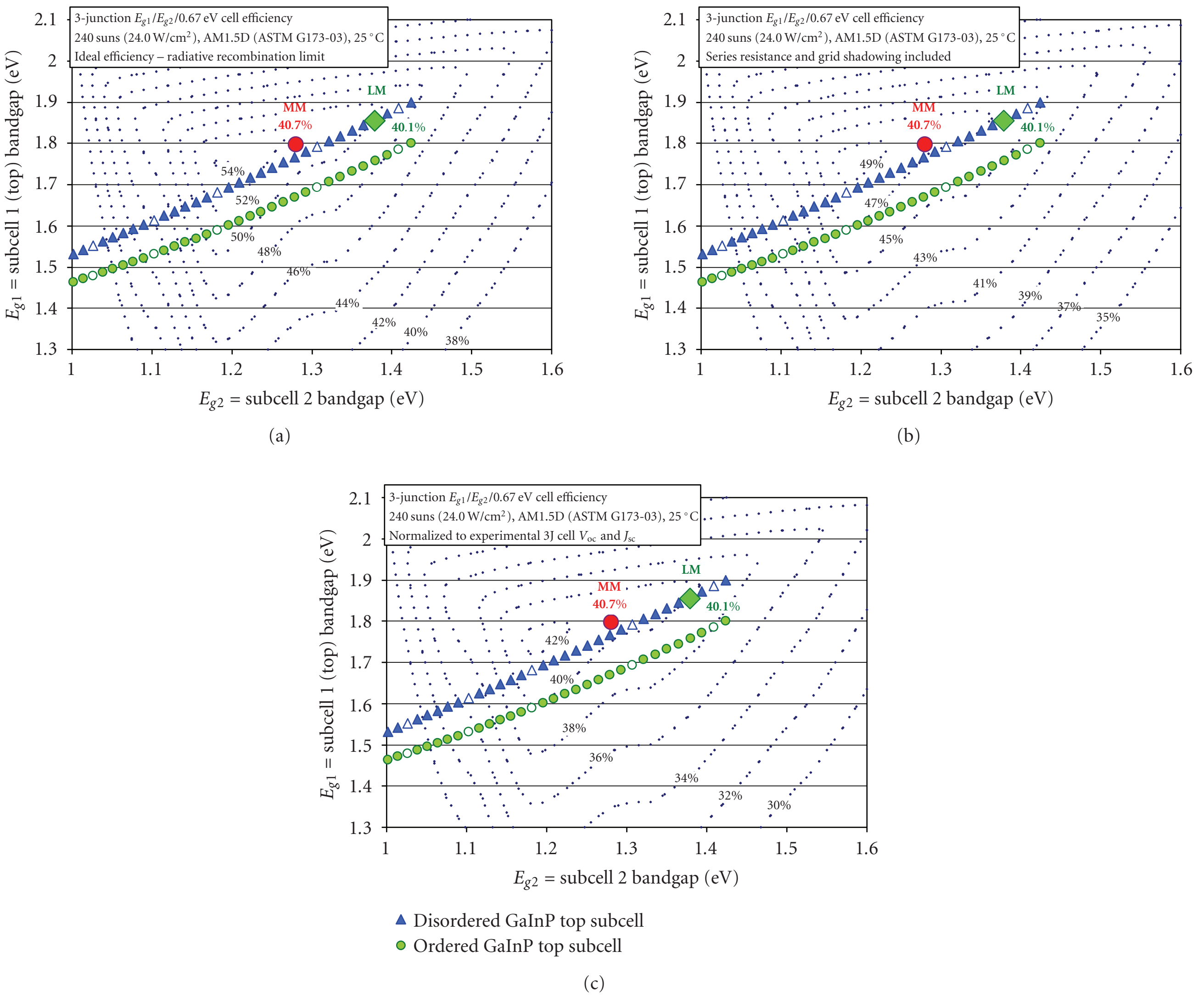


Figure 1: Calculated iso-efficiency contours for 3-junction terrestrial concentrator cells with variable top and middle subcell band gaps for the terrestrial solar spectrum at 240 suns: (a) theoretical efficiency based on radiative recombination [1]; (b) including the effects of grid resistance and shadowing using the metal grid design of the record 40.7%-efficient cell; and (c) 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 E_g. Subcell 1 and 2 band gap pairs of GaInP and GaInAs at the same lattice constant are shown for both disordered and ordered GaInP. The measured efficiencies and band gap combinations for the record 40.7% MM and 40.1% LM cells are plotted, at 240 and 135 suns, respectively, showing the theoretical advantage of the metamorphic design, now realized in practice.

structure band gaps that can be grown with high crystal quality, and correspondingly high minority-carrier recombination lifetimes. This is true for lattice-matched multijunction cells, but the flexibility in band gap 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 photovoltaic research groups around the globe [1–11].

The theoretical benefits of flexibility in subcell band gap selection are made apparent in Figure 1(a), which plots iso-efficiency contours for 3-junction terrestrial concentrator cells as a function of top (subcell 1) band gap E_{g1} and middle (subcell 2) band gap E_{g2} [1]. Figure 1(a) 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 [10]. Efficiencies up to 54% can be seen to be possible in principle at this concentration for 3-junction cells in the radiative recombination limit, increasing to over 58% for 4-junction terrestrial concentrator cells [10].

In 3-junction GaInP/GaInAs/Ge metamorphic solar cells, the GaInP and GaInAs subcells can be grown on a metamorphic buffer such that these two subcells are lattice-matched to each other, but are both lattice-mismatched to

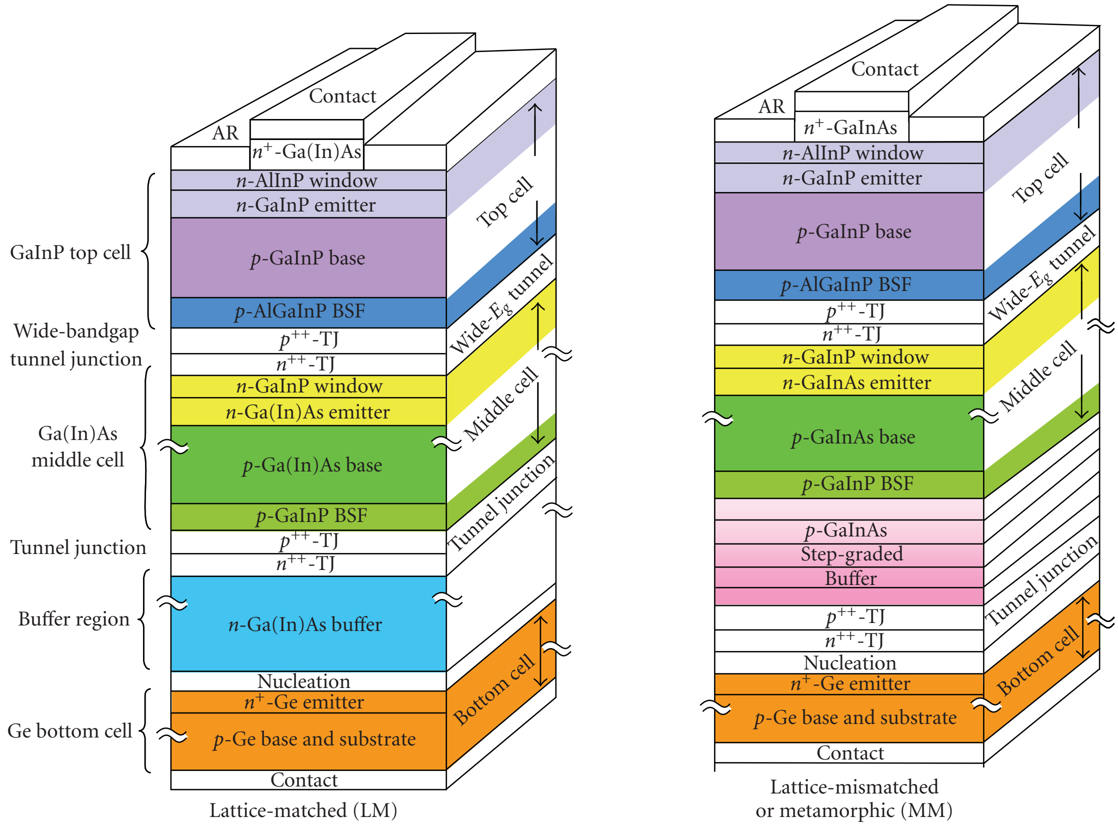


FIGURE 2: Schematic cross-sectional diagrams of lattice-matched (LM) and metamorphic (MM) GaInP/GaInAs/Ge 3-junction cell configurations, corresponding to the LM 40.1% and MM 40.7%-efficient concentrator cells.

the Ge growth substrate and subcell. The band gap combinations that are possible with GaInP and GaInAs subcells at same lattice constant, but with varying lattice mismatch to the Ge substrate, are shown in Figure 1(a). The cases with a disordered group-III sublattice in the GaInP subcell, giving higher band gap at the same GaInP composition, and with an ordered (low E_g) 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 E_{g1}, E_{g2} space that has the highest theoretical efficiencies. The lower band gaps 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 Figure 1, the density and activity of dislocations have been controlled sufficiently to show the efficiency advantage of the MM design, not just theoretically but now also experimentally.

Figures 1(b) and 1(c) take this analysis a bit farther. The efficiency contours in Figure 1(b) take into account the shadowing and specific series 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 band gap 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 Figure 1(c), 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 V_{oc} 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 V_{oc} that is 233 mV lower than the ideal V_{oc} in the radiative limit. This is equivalent to 78 mV per subcell on average, though since the GaInAs middle subcell V_{oc} is often close to the radiative limit, the difference between actual V_{oc} and ideal radiative V_{oc} is more heavily distributed in the top and bottom subcells. With the addition of these last real-life effects, the calculated contours in Figure 1(c) show a good estimate of the efficiencies that can be achieved in practical, state-of-the-art, 3-junction cells as a function of band gap. The measured efficiencies of the plotted 40.7% MM and 40.1% LM record cells correspond to the efficiency contours in Figure 1(c), but are also plotted in Figures 1(a) and 1(b) for reference. It should be noted that unlike Figure 1(a), the present, state-of-the-art, practical efficiencies of the contours in Figure 1(c) are not fundamental limits, and can be made higher by finding ways to reduce the nonfundamental EQE and V_{oc} losses that have been included in Figure 1(c).

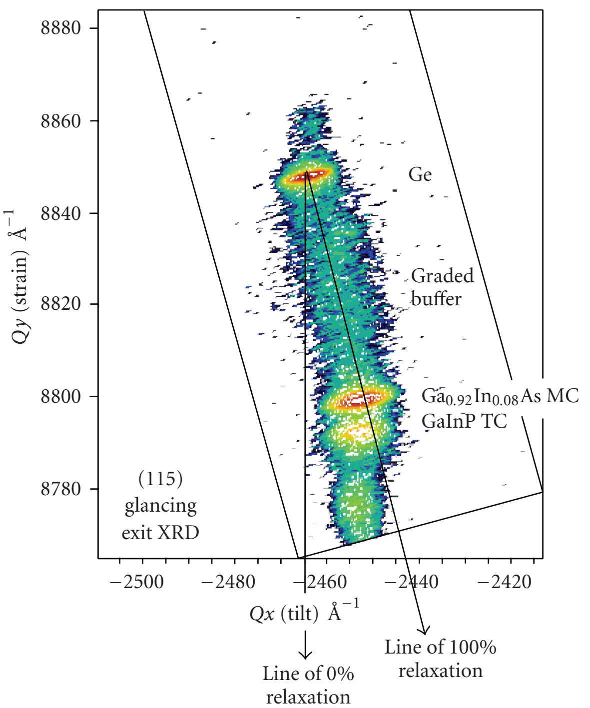


Figure 3: High-resolution X-ray diffraction reciprocal space map of a metamorphic 3-junction cell structure, showing a metamorphic buffer with almost no residual strain, and a GaInP top cell that is pseudomorphic with respect to the $Ga_{0.92}In_{0.08}As$ middle cell.

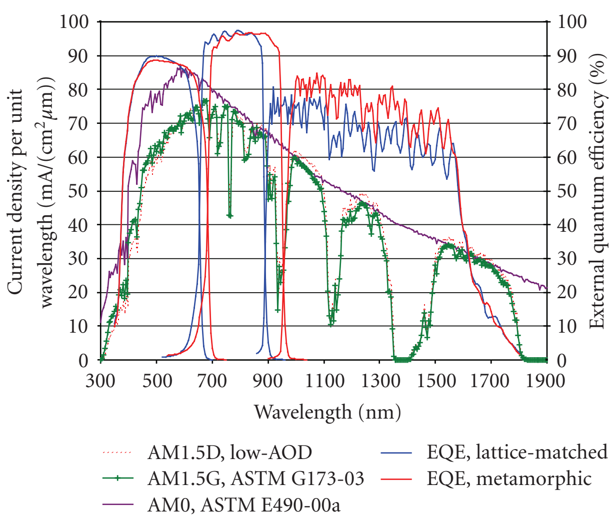


Figure 4: External quantum efficiency for GaInP, GaInAs, and Ge subcells of LM and MM 3-junction cells, showing extension of the lower-E_g MM GaInP and GaInAs responses to longer wavelengths, allowing them to use more of the solar spectrum [1].

Schematic diagrams of LM and MM cells are shown in Figure 2, 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 Figure 3. 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.

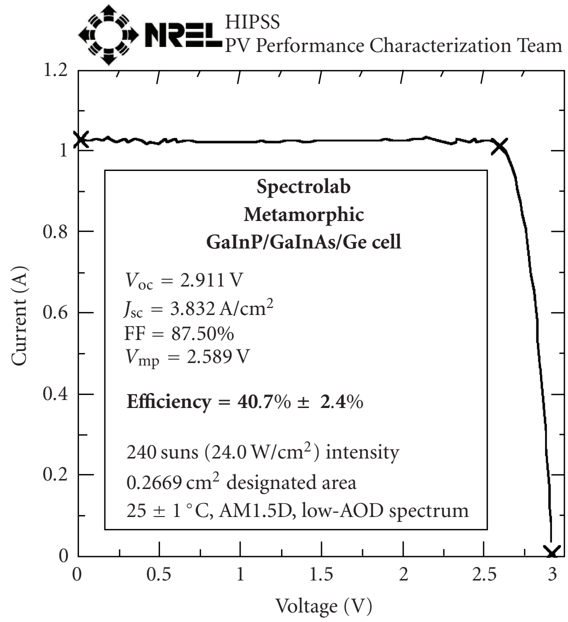
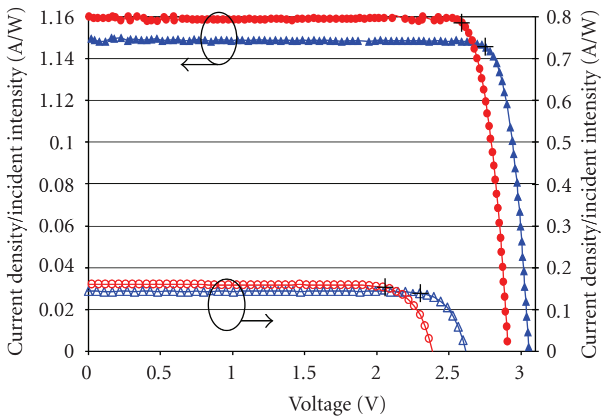


Figure 5: Illuminated I-V curve for the record 40.7% metamorphic 3-junction cell, independently verified at NREL. This is the first photovoltaic cell of any type to reach over 40% solar conversion efficiency.

The 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 band gap of the metamorphic GaInP and GaInAs subcells, is shown in Figure 4 [1]. 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.

3. HIGH-EFFICIENCY MULTIJUNCTION CELLS

Band gap 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 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 band gap-voltage offset $(E_g/q) - V_{oc}$ is a key indicator of the quality and suppression of SRH recombination in semiconductors of variable band gap, 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 [8–10]. Metamorphic 8%-In GaInAs single-junction cells were built and tested with a band gap-voltage offset



	Concentrator cells		1-sun cells	
	Latt.-matched	Metamorphic	Latt.-matched	Metamorphic
V_{oc}	3.054	2.911 V	2.622	2.392 V
J_{sc}/inten.	0.1492	0.1596 A/W	0.1437	0.1599 A/W
V_{mp}	2.755	2.589 V	2.301	2.055 V
FF	0.881	0.875	0.850	0.819
Conc.	135	240 suns	1.0	1.0 suns
Area	0.2547	0.267 cm^2	4.0	4.0 cm^2
Eff.	**40.1%**	**40.7%**	**32.0%**	**31.3%**
	Designated area efficiency at 25 °C AM1.5D, low-AOD spectrum		Total area efficiency at 25 °C AM1.5G 1 sun = 0.100 W/cm^2	

Figure 6: 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 [1]. The higher current and lower voltage of the metamorphic design is evident.

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-band-gap 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 5 plots the measured illuminated I-V curve for the record efficiency 40.7% metamorphic GaInP/GaInAs/Ge 3-junction cell at 240 suns [1], 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 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 Figure 6 [1].

The highest cell efficiencies from a number of photovoltaic technologies by year since 1975 are plotted in Figure 7, showing the most recent 40.7%-efficient cell result. It is interesting to note that III-V multijunction concentrator cells not only are 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 [12], 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.

In Figure 8, the measured efficiency, V_{oc}, 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 V_{oc} 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. From the slopes of V_{oc} versus concentration (current density) we can extract values of the diode ideality factor n. Subtracting off the 59 mV/decade increase for the Ge subcell, which has diode ideality factor 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.

4. FOUR-JUNCTION SOLAR CELLS

A 4-junction (Al)GaInP/ AlGa(In)As/ Ga(In)As/ Ge terrestrial concentrator solar cell [10] is shown in Figure 9, where the parentheses indicate optional elements in the subcell composition. This type of cell divides the photon flux available in the terrestrial solar spectrum above the band gap of the GaInAs subcell 3 into 3 pieces, rather than 2 pieces in the case of a 3-junction cell. As a result, the current density of a 4-junction cell is roughly 2/3 that of a corresponding 3-junction cell, and the I^2R resistive power loss is approximately $(2/3)^2 = 4/9$, or less than half that of a 3-junction cell. Figure 9 shows a lattice-matched 4-junction cell, with all the subcells at the lattice constant of the Ge substrate, but lattice-mismatched versions of the 4-junction cell are also possible, giving greater flexibility in bandgap selection.

Iso-efficiency contours for 4-junction terrestrial concentrator cells, under the AM1.5D (ASTM G173-03) solar spectrum at 500 suns (50.0 W/cm^2), are plotted in Figure 10 as a function of the band gaps of subcells 2 and 3. Ideal 4-junction cell efficiency is plotted in Figure 10(a), and practical cell efficiency, consistent with the measured 3J cell efficiency, in Figure 10(b). The band gap of subcell 1 is held at 1.9 eV, corresponding to GaInP at the Ge lattice constant with a disordered group-III sublattice, and subcell 4 (the bottom

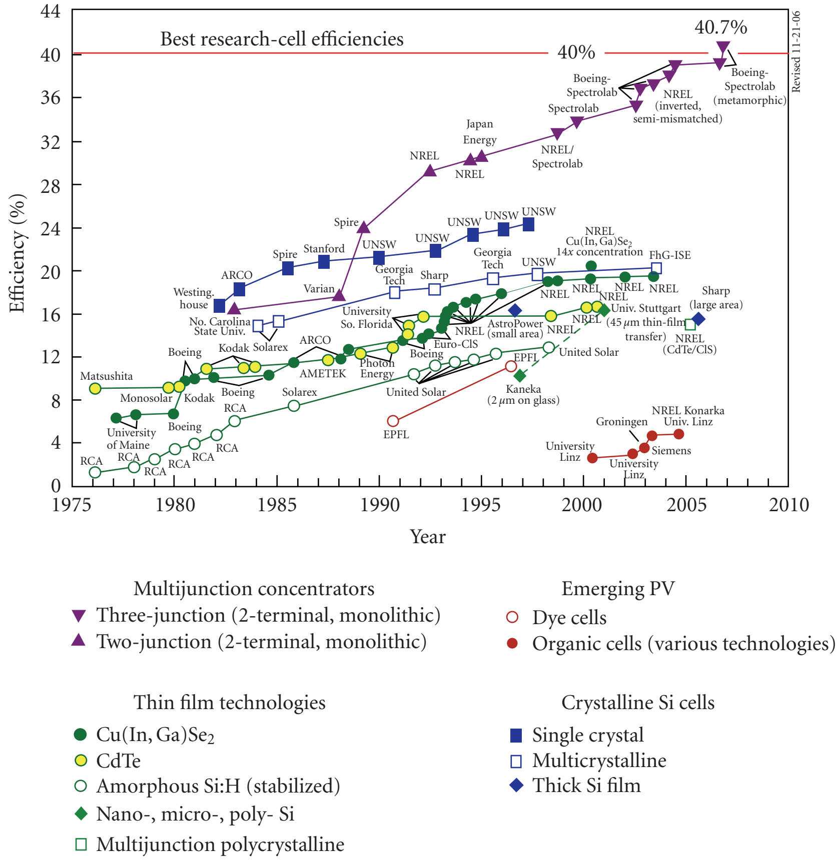


FIGURE 7: Plot of record cell efficiencies for a range of photovoltaic technologies, showing the recent advance to 40.7% efficiency for III-V multijunction cells. Chart courtesy of Bob McConnell, NREL.

subcell) is fixed at the 0.67-eV band gap of Ge, for this analysis [10].

The diamond in the plots indicates the 1.62/1.38 eV band gap combination of the AlGaInAs subcell 2 and GaInAs subcell 3 of a 4-junction cell described later in the paper (see the quantum efficiency measurements in Figure 11). Ideal efficiencies of over 58%, and practical cell efficiencies of 47% are possible for 4-junction terrestrial concentrator cells with a band gap combination of 1.90/1.43/1.04/0.67 eV. These band gaps are accessible with metamorphic materials and the use of transparent graded buffer layers, for example, in inverted metamorphic cell designs [6, 8, 10, 11]. It is worth noting that these practical 4J cell efficiencies are about 5 absolute efficiency points over those for 3-junction cells. Four-junction cells benefit from reduced resistive power losses as described above, and for this band gap combination, also benefit from more efficient use of the terrestrial solar spectrum.

Four-junction cells designed for the terrestrial solar spectrum and the high current densities of concentrator operation have been grown by metal-organic vapor-phase epitaxy (MOVPE), processed into devices, and tested. The external quantum efficiency of one such 4J cell is plotted in Figure 11 versus photon energy. The band gaps of each subcell can be determined from the quantum efficiency data, and the extracted values are listed in the legend. By convoluting with the terrestrial AM1.5D (ASTM G173-03) spectrum, the current density of each subcell can also be determined. The current densities are 9.24, 9.24, 9.58, and 21.8 mA/cm2 for subcells 1, 2, 3, and 4, respectively, such that the subcells are very close to being current matched for this 4J cell.

Illuminated light I-V curves are shown in Figure 12 for a 4-junction (Al)GaInP/ AlGa(In)As/ Ga(In)As/ Ge solar cell measured at 256 suns [10], and for a similar solar cell with only the upper 3 junctions active (inactive Ge). The open-circuit voltage of the 4-junction cell is 4.364 V, compared to 3.960 V for the cell with an inactive subcell 4, indicating the Ge bottom cell accounts for about 400 mV of the V_{oc} at this concentration. Independently confirmed measurements of the 40.1% lattice-matched and 40.7% metamorphic 3-junction cells are also shown for comparison. Preliminary measured efficiency for this as yet nonoptimized 4J cell is 35.7% at 256 suns.

5. SUMMARY

Multijunction GaInP/GaInAs/Ge solar cells have been demonstrated with 40.7% efficiency using metamorphic semiconductor technology, and 40.1% for lattice-matched cells [1]. These are the first solar cells to reach over the milestone efficiency of 40%, and have the highest solar conversion

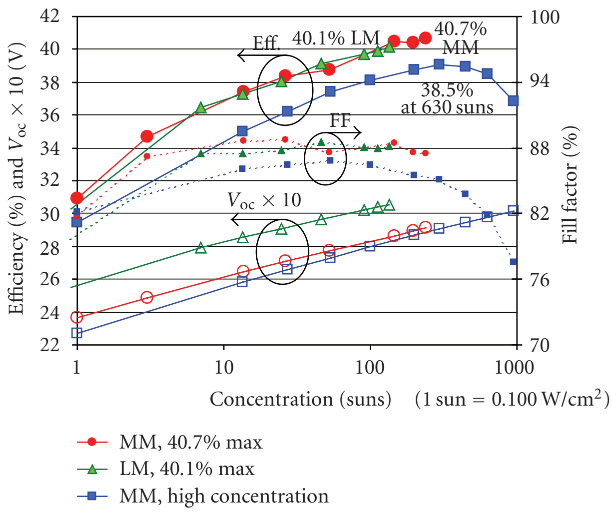


FIGURE 8: Efficiency, V_{oc}, and FF of record performance 40.7% metamorphic and 40.1% lattice-matched 3-junction cells as a function of incident intensity. An additional cell is shown which maintains an efficiency of 38.5% over 600 suns, and 36.9% over 950 suns.

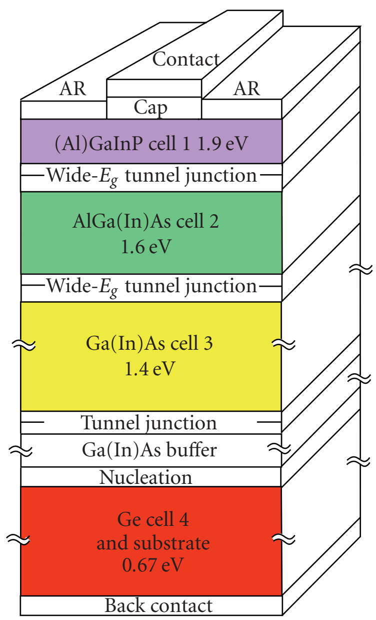


FIGURE 9: A 4-junction (Al)GaInP/ AlGa(In)As/ Ga(In)As/Ge terrestrial concentrator solar cell cross-section.

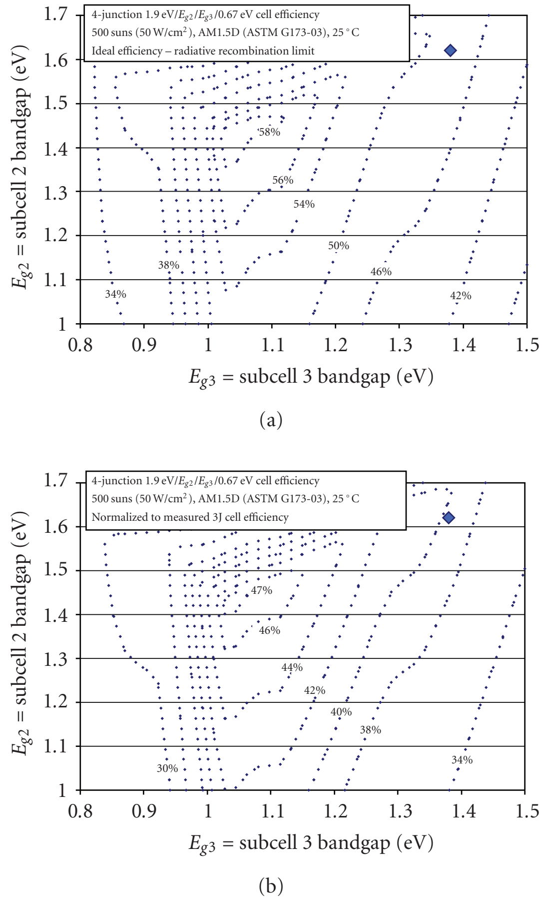


FIGURE 10: Contour plots of (a) ideal efficiency and (b) efficiency normalized to experiment, for 4-junction solar cells, with variable subcell 3 and subcell 2 band gaps.

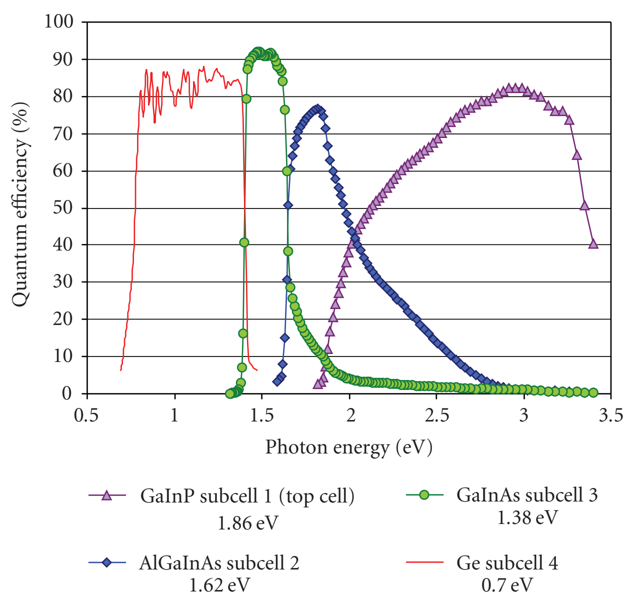


FIGURE 11: External quantum efficiency of a 4-junction (Al)GaInP/ AlGa(In)As/ Ga(In)As/ Ge terrestrial concentration cell.

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 dependence of 3- and 4-junction terrestrial concentrator cell efficiency on the band gaps of subcells 1, 2, and 3 is calculated, and presented in contour plots of both ideal efficiency and practical cell efficiency. Ideal cell efficiencies are over 58%, and practical efficiencies of 47% are achievable for 4-junction concentrator cells [10]. The low resistive

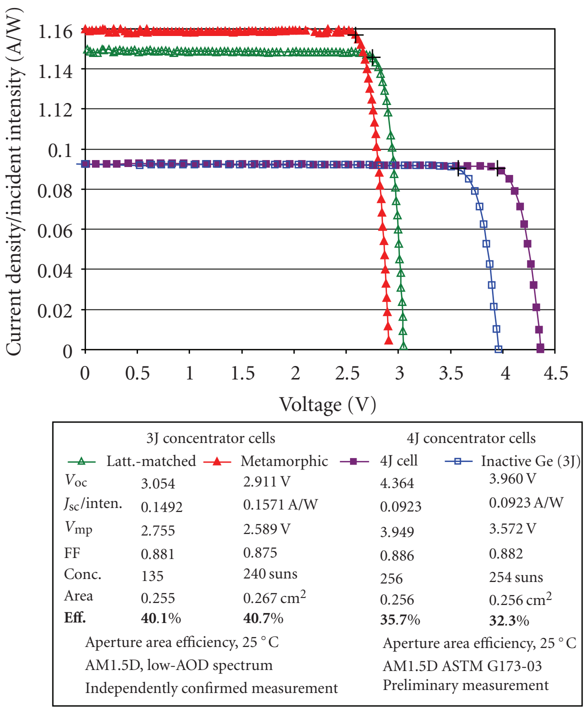


FIGURE 12: Illuminated I-V characteristics of an unoptimized 4-junction terrestrial concentrator cell with 35.7% efficiency, and V_{oc} over 4.3 volts. I-V curves for the record 40.7%-efficient metamorphic and 40.1% lattice-matched 3-junction cells are also shown.

power loss that results from the high-voltage, low-current design of cells with 4 or more junctions is a powerful advantage in concentrator applications. New 4-junction terrestrial concentrator cell architectures have been demonstrated, with 35.7% measured efficiency [10]. 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. Terrestrial concentrator cells with 3, 4, or more junctions, coupled with advances in metamorphic materials that have resulted in record solar cell efficiency of 40.7% today, offer the promise to increase efficiency and lower the cost of terrestrial photovoltaic concentrator systems still further, to 45%, and perhaps even to 50% efficiency.

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