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High-Efficiency GaInP/GaAs Tandem Solar Cells

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GaInP/GaAs tandem solar cells have achieved efficiencies between 25.7–30.2%, depending on illumination conditions. The efficiencies are the highest confirmed two-terminal values measured for any solar cell within each standard illumination category. The monolithic, series-connected design of the tandem cells allows them to be substituted for silicon or gallium arsenide cells in photovoltaic panel systems with minimal design changes. The advantages of using GaInP/GaAs tandem solar cells in space and terrestrial applications are discussed primarily in terms of the reduction in balance-of-system costs that accrues when using a higher efficiency cell. The new efficiency values represent a significant improvement over previous efficiencies for this materials system, and we identify grid design, back interface passivation, and top interface passivation as the three key factors leading to this improvement. In producing the high-efficiency cells, we have addressed nondestructive diagnostics and materials growth reproducibility as well as peak cell performance.

Nomenclature

AM = air mass, a relative measure of the amount of air through which the sun's light passes before reaching a solar cell, it alters both the intensity and the spectral energy distribution of sunlight, $(\cos\theta)^{-1}$

AM0 = air mass 0, a solar spectrum representing sunlight just outside the Earth's atmosphere, used as a standard measurement condition for space solar cells

AM1.5D = air mass 1.5 direct, a solar spectrum representing light coming directly at an angle of 48 deg from a point overhead, used as a standard measurement condition for solar cells that use additional optics to concentrate the light onto the cells

AM1.5G = air mass 1.5 global, a solar spectrum representing light coming at an angle of 48 deg from a point overhead plus the diffuse reflected light from an unclouded sky, used as a standard measurement condition for solar cells designed for use on the Earth's surface without additional optics

BSF = back surface field, describes a material layer that repels minority carriers from the back surface of a solar cell with an electric potential change produced either by an increase in doping or, more typically, an increase in bandgap

FF = fill factor, the ratio of the maximum power produced by a solar cell to the product of the J_{sc} and the V_{oc}

III–Vs = group of semiconductors consisting of elements from column III of the periodic table alloyed to elements from column V of the periodic table

J_{sc} = short-circuit current density, the current density produced by a solar cell under illumination at the zero-voltage point in the current–voltage curve

V_{oc} = open-circuit voltage, the voltage across a solar cell under illumination at the point in the current–voltage curve where no current is flowing

θ = angle between a point directly overhead and the path of the sun's light

$\times$ = sunlight intensity concentration ratio, for example, 140× means sunlight that is 140 times as intense as unconcentrated sunlight

Introduction

FOR the past few years, III–V multijunction solar cells have held the records for highest energy-conversion efficiency under all solar illumination conditions, and they are unlikely to lose this leadership position in the foreseeable future. Although they are more expensive to make than many other types of solar cells, their high efficiency not only leads to fewer cells needed in each application, but also to less of all the accompanying hardware and labor that goes into making a complete power system. For example, the combination of high efficiency and excellent radiation resistance makes these cells attractive for space applications. GaAs single-junction cells on germanium substrates are already commercially available for space applications, and there are no major technical or economic impediments to developing GaAs-based multijunction cells on germanium substrates. A recent comparison[1] of GaAs and silicon single-junction cells indicates that a six-fold higher cost of GaAs cells is more than compensated by the savings in panel area and weight, and this difference would be even more favorable if multijunction III–V cells were used. A similar study[2] also found that multijunction III–V cells are the lowest-cost photovoltaic power system once launch weight and attitude control costs are included.

For terrestrial applications, concentrator III–V solar cells are demonstrating excellent efficiencies at 400× or more, where only 25 cm^2 of solar cell material is needed for 1 m^2 of panel aperture area. With the combination of the large savings in cell material costs under high concentration and the high efficiency of these cells, III–V multijunction concentrator sys-

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tems may prove to have lower[3] production costs (around $2.00/W) for utility applications and stand-alone systems than flat-plate polycrystalline or amorphous thin-film technologies. A second study[4] comparing advanced silicon concentrator cells with single-junction and multijunction GaAs-based cells on germanium substrates reached similar conclusions.

This article describes in more detail the advantages offered by a specific III–V multijunction solar cell technology, the tandem solar cell consisting of a $Ga_{0.52}In_{0.48}P$ (hereafter GaInP) top cell and a GaAs bottom cell. These advantages center primarily on the very high efficiency these cells can reach under a variety of illumination conditions. A specific device structure that achieved new record efficiencies is discussed in some detail. Finally, we present highlights of the materials growth and processing changes that led to the improved efficiencies as well as to greater reproducibility.

Advantages of the GaInP/GaAs Technology

Table 1 compares the latest efficiency values for GaInP/GaAs tandem solar cells with cell efficiencies for other technologies. The only other monolithic technology that approaches the efficiency of GaInP/GaAs is a similar device in which $Al_{0.37}Ga_{0.63}As$ replaces GaInP as the top-cell material. High efficiencies in the AlGaAs/GaAs tandem depend heavily on proprietary techniques for growing high-quality AlGaAs, a compound that is notoriously sensitive to part-per-billion oxygen and water contamination. As discussed next, our device uses aluminum alloys only in the device window layer, and is therefore much less sensitive to growth system conditions. GaInP/GaAs tandems can also be grown on germanium substrates, a change that allows substantial cost and weight reduction with only minor efficiency loss. The mechanically stacked three-junction and concentrator cells in Table 1 yield comparable efficiencies, but are physically bulky and more expensive to process and package. The GaAs/GaSb efficiencies are difficult to compare in detail with our results because all reported efficiency measurements for the GaAs/GaSb cells are four-terminal measurements (in which the power is drawn off the component cells at two different currents and two different voltages) or module measurements (which include losses from concentrating optics). Another confounding factor in comparing results is that most III–V device efficiencies increase significantly with concentration. (The concentrator tandem GaInP cell reported at 140–180× in Table 1, for example, had an unconcentrated AM1.5D efficiency of 26.4%.)

InP-based technologies are being pursued both because InP has a higher radiation than GaAs, and because modeling shows that InGaAs/InP combinations should improve more rapidly with concentration[15] than the GaAs-based combinations and eventually surpass the latter in efficiency. The main reason for the latter effect is that the improvements in V_{oc} and FF that come with higher concentration represent greater fractional increases for the lower bandgap combinations. As Table 1 shows, however, InP cells have not surpassed GaAs-based technologies in efficiency despite the theoretical advantages. Two primary factors hindering higher efficiencies are the lack of a passivating material for InP, forcing cell designs that incorporate high grid coverage,[16] and the lack of antireflection coatings that span the broader wavelength range. Another drawback of the InGaAs/InP technology relative to the GaInP/GaAs tandem is the higher cost of the InP substrates, although, as with GaAs-based cells, there may be ways of reusing substrates or otherwise reducing substrate costs.

Also shown in Table 1 are a few single-junction cell record efficiencies. None of the designs used to achieve record efficiencies in these materials have come into commercial production, and so some representative commercially grown cells are also listed. Because the manufacturing process needed for the GaInP/GaAs technology is only slightly more complex than for GaAs, the commercial-to-record-efficiency ratio for GaInP/GaAs is likely to be similar to the favorable result seen for GaAs. In fact, because cell costs for the GaInP/GaAs tandem should be within a few percent of GaAs cells once the manufacturing process development is complete, there are probably only a few applications where GaAs cells would offer a long-term advantage over GaInP/GaAs tandems. Two commercial solar cell manufacturers have stated their intentions to develop the tandems as a new product,[17] and other research groups have begun to report excellent results with GaInP/GaAs tandem cells.[18,19]

Commercially designed silicon cells are unquestionably cheaper to make per unit area than GaInP/GaAs cells. Moderately priced thin-film polycrystalline modules have also become available on the market. However, the cost differences may reverse sign at the systems level, particularly for space applications,[1] because the lower efficiency of commercial silicon cells requires more balance-of-system materials and labor per unit output power. For thin-film polycrystalline cells such as $CuInGaSe_2$, the reduction in efficiency is so great that panel weight and costs overshadow even very large differences in cell cost. The two- to three-fold increase in panel size may become untenable as a result of increased drag for some missions in low Earth orbit, regardless of panel cost considerations.

The high efficiency of GaInP/GaAs tandem cells loses some of its balance-of-system leverage in terrestrial applications; however, the tandems may still be the most cost-effective cell in a significant number of circumstances. The primary example is concentrator systems designed for 300–1000× concentration, wherein cell cost is reduced substantially by reducing cell

Table 1 State-of-the-art, two-terminal cell efficiencies for several photovoltaic technologies[a]

Technology	AM0	AM1.5G	AM1.5D
GaInP/GaAs	25.7	29.5	30.2 (Ref. 6) (140–180×) 29.1 (425×)
AlGaAs/GaAs	23.0 (Ref. 7)	27.6 (Ref. 7)	
InGaAs/InP	22.0 (Ref. 8)		≈30[d] (50×) (Ref. 9)
AlGaAs/GaAs on InGaAsP[b]	25.2 (Ref. 10)		
GaAs/GaSb[b]	≈30[c] (100×) (Ref. 11)		≈31[d] (100×) (Ref. 12)
GaAs		25.1	27.5 (205×)
GaAs (commercial, germanium substrate)	18 (Ref. 1)	24.3	
Si	19 (Ref. 13)	23.1	26.5 (140×)
Si (commercial)	14 (Ref. 1)	17	
$CuInGaSe_2$		17.1 (Ref. 14)	

[a]AM1.5G and AM1.5D values are from Green and Emery[5] unless otherwise indicated. Efficiency measurements have a relative uncertainty of about 2%, so that cell efficiency of 30% would have an absolute uncertainty of ±0.6%.
[b]Mechanical stack.
[c]Extrapolated from module measurements.
[d]Extrapolated from three- or four-terminal measurements.

area. The extra bulk in tracking systems and lenses, however, limits application to moderate-size or utility-scale systems. Concentrator modules are also best used in climates with relatively few overcast days because, unlike flat-plate modules, concentrators cannot easily collect sunlight scattered by the atmosphere or clouds. Tandems may be cost-effective for a few flat-plate applications where the area available on the product or system is limited to the point where only a higher efficiency cell will prove acceptable. For most other terrestrial applications, GaInP/GaAs cells will not be economically competitive with silicon in the foreseeable future and may be underbid by polycrystalline thin-film cells made from a variety of materials.

Cell Description and Performance

The GaInP/GaAs cells discussed here are grown[20] by atmospheric-pressure organometallic vapor phase epitaxy. The cells are processed with unannealed, electroplated gold front and back contacts and a two-layer antireflection coating of ZnS and MgF_2. The cell area is 0.25 cm^2. The cell structure[21] consists of a GaInP top cell connected in series with a low-resistivity, grown-in tunnel junction to a GaAs bottom cell, as shown in Fig. 1. The GaInP layers are all lattice-matched to GaAs. Because of spontaneous ordering on the Ga–In sublattice, the band gap of the GaInP varies with growth conditions[22] from about 1.8 to 1.95 eV at constant composition. This variation is exploited in the top cell to produce a BSF layer of higher bandgap GaInP. Figure 2 shows the current–voltage curve for the best cell produced to date for the AM0 solar spectrum, as measured by NREL's Photovoltaic Performance Group using a technique similar to that of Glatfelder and Burdick.[23] The cell has an energy-conversion efficiency of 25.7% at one-sun AM0. NASA Lewis Research Center independently obtained a similar AM0 efficiency (25.4%) for this device. A different cell, optimized for the AM1.5G spectrum, achieved a one-sun AM1.5G efficiency of 29.5%, with J_{sc} = 14.0 mA/cm^2, V_{oc} = 2.385 V, and FF = 88.5%. The structure of the AM1.5G cell differs from the AM0 cell only in that the top-cell base layer is 0.6 μm instead of 0.5 μm. Concentrator cells[6] differ slightly in size, design, and processing.

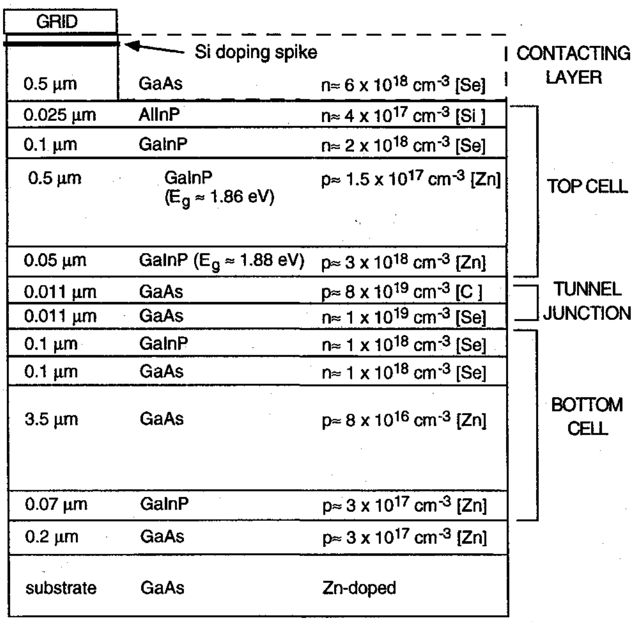

Fig. 1 Solar cell structure for AM0 standard solar spectrum. The BSF layers are indicated for each subcell; these layers determine the back interface passivation.

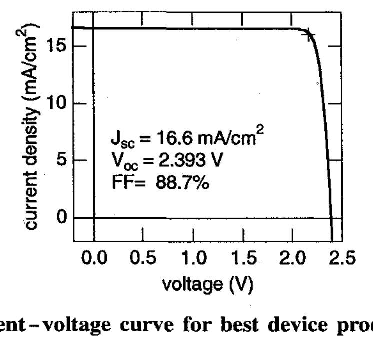

Fig. 2 Current–voltage curve for best device produced to date for the AM0 spectrum.

One complication introduced by the tandem cell structure is that the same amount of photogenerated current should be collected in each subcell for maximum efficiency. This is achieved in practice by a trivial adjustment of the thickness of the top cell to allow more or less light to pass through to the bottom cell. Because this balance depends on the number of uv and visible photons relative to the number of near-infrared photons in the light illuminating the cell, the optimum top-cell thickness depends on the solar spectrum under which it will be used. This design feature makes the GaInP/GaAs tandem suitable for everything from AM0 cells optimized for end-of-life (EOL) with a top-cell thickness of 0.45–0.55 μm to AM1.5D concentrator cells with a top-cell thickness[20,24] of 1.2–1.5 μm. This level of thickness control is easily attained[25] in commercially available multiwafer epitaxial growth systems. Even so, attaining respectable efficiencies does not require such fine tuning. For example, the record AM0 cell reported above has an AM1.5G efficiency of 28.5%.

One criticism frequently directed at series-connected tandem solar cells is that the current-matching condition at operation might lead to lower power output under conditions where the light spectrum or cell spectral response changes with time. We have used radiation testing and modeling to show, however, that this concern is not justified for most anticipated space and terrestrial operating environments. Part of the reason for the robust efficiency performance of the device is that current losses from operation under slight mismatch conditions are partially offset[26] by FF increases. For terrestrial applications, modeling[26,27] shows that the GaInP/GaAs tandem outperforms single-junction GaAs cells even though shifting atmospheric conditions lead to periods of tandem cell operation with slight current mismatch. Radiation testing of tandem cells for space environments shows that most degradation occurs in the GaAs bottom cell.[28] Tandem cells designed for optimum EOL efficiency start out limited by the top-cell current and gradually reach current-matched conditions over time, with power vs radiation fluence curves comparable to or better than those for single-junction cells. We recently measured[29] a 19.6% EOL efficiency for a GaInP/GaAs tandem cell exposed to 10^{15} electrons/cm^2 using 1-MeV electrons. This EOL value is 82% of its beginning-of-life efficiency, several percent higher than ratios observed[30–33] for GaAs single-junction cells.

Critical Processing and Growth Considerations

In achieving record efficiencies, this work has identified three key factors in the GaInP/GaAs tandem cell technology: 1) grid design, 2) back interface passivation, and 3) top interface passivation. Relative contributions from these three factors to the AM1.5G efficiency improvement over previous GaInP/GaAs cell designs[34] are given in Table 2.

Optimizing the grid design for this cell reduced the front surface contacting grid coverage from 4.9 to 1.9% of the device area without a loss in FF, yielding a significant increase in current density. Grid coverage minimization is a relatively straightforward calculation based on contact resistance, sheet resistance of the upper (n-type) layer of the top cell, and grid metal characteristics. The low grid coverage is possible because the emitter is adequately passivated and can be made thick enough to bring the sheet resistance down to 420 Ω/square. The tandem cell also operates at high-voltage and low-

Table 2 Breakdown of improvements from the previous best GaInP/GaAs tandem solar cell for the AM1.5G spectrum

Device parameter	Old	New	Increase, %	Grid design	Passivation Back	Passivation Front
J_{sc}, mA/cm^2	13.6	14.0	2.9	++[a]	——	+[a]
V_{oc}, V	2.295	2.385	3.9	——	++	——
FF	0.875	0.885	1.1	——	++	+
Efficiency, %	27.3	29.5	8.1	++	++	+

[a]++ and + indicate major and minor contributing factors to the increase, respectively.

current density relative to single-junction and low-bandgap multijunction cells; this lower current load allows the use of fewer grid lines.

The second key factor in this technology is the passivation of the back interfaces in both cells. BSF layers are used to reduce the recombination of minority carriers at these interfaces. When the layers do not function optimally, the concentration of minority carriers in the base is reduced, in turn increasing the dark current in the device and partially canceling out the photogenerated current. A nondestructive indicator of a BSF problem, therefore, is a decrease in V_{oc}, the voltage where the dark current becomes equal in magnitude to the photogenerated current. Very high recombination rates can also remove enough photogenerated carriers to reduce the cell J_{sc}, although in mild cases only the V_{oc} is significantly affected. FF also decreases with increasing dark current, although the relationship[35] is considerably more complex.

Our improvements in back interface passivation have led us to two main conclusions. First, the bottom-cell BSF layer, a thin layer of GaInP, is effective only if doped to a hole carrier concentration of at least 2×10^{17} holes/cm^3. This level corresponds to the doping needed to prevent the BSF layer from being totally depleted. Second, the top-cell BSF layer, a thin layer of higher bandgap GaInP, is found to be sensitive to dopant diffusion and memory effects during growth.[20] (Memory effects occur when dopant atom compounds adsorb onto the walls of the growth system and desorb after the dopant gas flow has been stopped, so that dopant atoms appear in layers where they were not intended to be.) Because the tunnel junction layers have very high doping levels, most of the damaging dopant effects originate there. The BSF layer passivation is improved by modifying the tunnel-junction dopant scheme to use less selenium to reduce the selenium memory effect and to replace zinc with carbon to reduce *p*-type dopant diffusion. Selenium flow reduction is accompanied by arsine flow reduction to maintain high dopant incorporation and high conductivity in the tunnel junction. Because dopant diffusion and memory effects can vary substantially from run-to-run, depending on defect densities in substrates, ambient temperature in the growth system, and other parameters not readily controlled, the tunnel-junction change also significantly enhances yield and reproducibility.

The third key factor is maintaining the quality of the top-cell front interface passivation layer, the $Al_{0.53}In_{0.47}P$ (abbreviated AlInP) window. Although not a primary factor in the efficiency improvement discussed here, the AlInP window is often a source of reproducibility problems, resulting in unpredictable losses of about 10–20% in the top-cell J_{sc}. The problem is easily identified in the device internal quantum efficiency (QE) as a reduction in the high-energy response of the top cell, illustrated in Fig. 3. Two different solutions to this problem have been identified: 1) substituting disilane for hydrogen selenide as the dopant in the AlInP window layer, and 2) using a point-of-use phosphine purifier. The exact degradation mechanism is unclear, but it is most likely related to removal of trace levels of oxygen from the source gases and to the smaller dopant ionization energy for Si relative to Se in AlInP. We have had successful results with three different phosphine purifiers, all of which are based on reactive materials that chemically remove contaminants and are placed downstream of the mass flow controllers in the growth system. The combination of disilane and phosphine purifier use has led to consistently good high-energy quantum efficiencies.

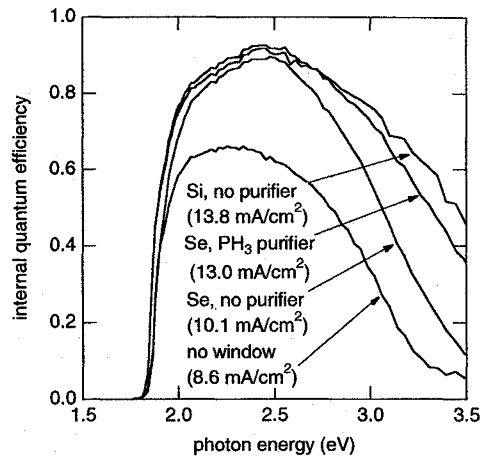

Fig. 3 Internal QE for four GaInP single-junction cells with different window layer variations. Numbers in parentheses are J_{sc} values derived by integrating the QE curve with the AM1.5G spectrum. The sample labeled no window was grown with a window layer that was removed by etching after processing of the cells. Tandem cells with good front interface passivation are consistently produced by using a point-of-use phosphine purifier and disilane as a dopant.

Summary

Tandem GaInP/GaAs photovoltaic cells have been grown with record efficiencies between 25.7–30.2%, depending on illumination conditions. The efficiency increases add to the system-level economic leverage of these cells relative to less costly but also less efficient solar cells. For space applications, GaInP/GaAs tandem cells should be economically competitive with all existing technologies once a manufacturing capability is developed. For terrestrial applications, concentrator systems should be able to effectively use GaInP/GaAs cells. Much of the groundwork in materials growth and device processing has already been done in developing these record cells. We have identified preferred dopant schemes for optimum performance and yield. In addition, we have correlated device performance parameters with specific layers in the tandem structure, allowing faster diagnosis of materials growth problems.

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