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# High-Voltage, Low-Current GaInP/GaInP/GaAs/GaInNAs/Ge Solar Cells

R. R. King, P. C. Colter, D. E. Joslin, K. M. Edmondson, D. D. Krut, N. H. Karam, and Sarah Kurtz[†]

Spectrolab, Inc., 12500 Gladstone Ave., Sylmar, CA 91342
[†]National Renewable Energy Laboratory, 1617 Cole Blvd., Golden, CO 80401

## ABSTRACT

Four-junction GaInP/GaAs/GaInNAs/Ge solar cells are a widely-pursued route toward AM0 efficiencies of 35% and above, and terrestrial efficiencies of up to 40%. Extensive research into the new material system of GaInNAs has so far yielded subcells with AM0 current densities far below the ~17 mA/cm$^2$ needed to current match the other subcells in the stack. A new multijunction structure, a 5-junction GaInP/GaInP/GaAs/GaInNAs/Ge cell, divides the solar spectrum more finely in order to relax this current matching requirement, by using an optically thin, high-bandgap GaInP top subcell, with an additional thick, low-bandgap GaInP subcell beneath it, in combination with a GaInNAs subcell. In this way, the 5-junction cell design allows the practical use of GaInNAs subcells to increase the efficiency of multijunction cells. Light I-V and external quantum efficiency measurements of the component subcells of such 5-junction cells are discussed. Experimental results are presented for the first time on GaInP/GaInP/GaAs/GaInNAs/Ge cells with the top four junctions active, with measured $V_{oc}$ of 3.90 V.

## INTRODUCTION

Recently, many research groups have studied the GaInNAs material system with the goal of using this new semiconductor in a 4-junction GaInP/GaAs/GaInNAs/Ge solar cell[1-4]. The ability to achieve a bandgap of ~1 eV in GaInNAs with a composition that is lattice-matched to GaAs is shared by only a few other semiconductor materials. The ~1 eV bandgap allows an ideal GaInNAs subcell to be current-matched to the other three subcells, while the matched lattice constant allows the epitaxial GaInP, GaAs, and GaInNAs subcells in a monolithic GaInP/GaAs/GaInNAs/Ge cell structure to be grown with virtually no misfit dislocations. Over 35% conversion efficiency under the AM0 space solar spectrum is possible in theory for a 4-junction GaInP/GaAs/GaInNAs/Ge cell.

In practice, GaInNAs has not yet demonstrated its full potential as a semiconductor material suitable for a high-efficiency solar cell. P-type GaInNAs has so far exhibited a very low minority electron diffusion length $L_n$ , due to both low lifetime and low electron mobility. Only ~11 mA/cm$^2$ short-circuit density $J_{sc}$ has been achieved in GaInNAs cells to date, while approximately 17 mA/cm$^2$ is required for current matching to high-efficiency GaInP and GaAs subcells[3,5,6]. Additionally, the available photon flux below the GaAs bandgap is barely enough to allow

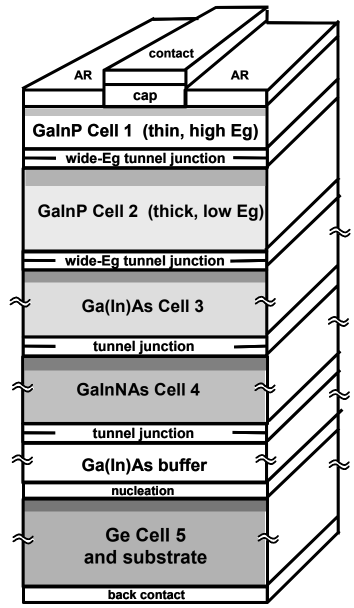


Fig. 1. Cross-sectional diagram of a monolithic, 5-junction GaInP/GaInP/GaAs/GaInNAs/Ge solar cell, which divides the photon flux above the GaAs bandgap among three subcells.

current-matched GaInNAs and Ge cells under the most ideal current collection conditions, so lowering the GaInNAs bandgap further to increase the current would begin to limit the Ge subcell current. Thus, the low material quality and current collection efficiency of the GaInNAs cell, combined with the dearth of photons in the AM0 spectrum between the energies of the GaAs and GaInNAs bandgaps, pose serious obstacles to realization of the 35% efficiency potential of the 4-junction GaInP/GaAs/GaInNAs/Ge solar cell. Similar problems limit the practical efficiency of such cells under the AM1.5D or AM1.5G terrestrial spectra.

## APPROACH

One solution to this problem relies on device design, rather than on improvement of the GaInNAs semiconductor material. Dividing the solar photon flux among 5 or 6 subcells reduces the current density in each subcell compared to the 4-junction cell case, and so lowers the current density needed in any given subcell to current match the other subcells. A 5-junction GaInP/GaInP/GaAs/GaInNAs/Ge cell can be grown with an extremely thin GaInP subcell 1 (top subcell) that transmits some light through to a thick GaInP subcell 2 in order to current match these two cells[7], as shown in cross-section in Fig. 1. It is helpful to design the 5-junction cell to make use of the substantial change in bandgap that GaInP exhibits due to group-III sublattice ordering, by growing a high-bandgap (~1.90 eV), thin subcell 1 with a high amount of sublattice disorder, and a low-bandgap (~1.77 eV), thick subcell 2 with an ordered sublattice, even at the same GaInP composition in the two subcells.

In such a 5-junction cell, a poor current producer like a GaInNAs subcell need only have a current density of ~11 $mA/cm^2$ for current matching, much closer to what has been achieved in practice than the 17 $mA/cm^2$ needed for a 4-junction GaInP/GaAs/GaInNAs/Ge cell. Because of this ability to current match to the lower current density that has been achieved in the GaInNAs cell, the calculated efficiency of the lattice-matched 5-junction cell is much higher, up to 33% under the AM0 spectrum, than the 4-junction GaInP/GaAs/GaInNAs/Ge cell. Several related cell structures incorporating a lattice-mismatched GaInAs subcell are discussed theoretically in [8].

One set of possible bandgaps for the 5-junction cell is plotted in Fig. 2, and compared to the current density per unit photon energy in the AM0 space and AM1.5G terrestrial spectra. The current density available to each subcell is the integrated area for a given spectrum above the subcell bandgap, less the photogenerated current density in the subcells above it. Fig. 2 gives a visual representation of how the available current above the GaAs cell 3 bandgap is divided among three subcells rather than two, resulting in ~33% reduction in the overall current of the 5J cell that the GaInNAs subcell must match. Because the 1.90-eV bandgap of the thin, disordered GaInP cell 1 is so close to the 1.77-eV bandgap of the thick, ordered GaInP cell 2 in this example, cell 1 must be grown to be very thin in order to boost the current of cell 2. Additionally, a small amount of arsenic may be added to form a GaInPAs cell 2 to lower its bandgap and increase its current.

The low current density of the 5-junction cell has the added benefit of decreasing the resistive power losses in the cell. The fractional power losses (power loss divided by the cell power output) due to resistive mechanisms such as contact, top layer, and finger resistance are proportional to $J_{mp}/V_{mp}$ , where $J_{mp}$ and $V_{mp}$ are the current density and voltage at the maximum power point [9]. To first order, assume that $J_{mp}$ in a 4-junction (4J) GaInP/GaInP/GaAs/Ge cell is 2/3 that of conventional GaInP/GaAs/Ge 3-junction (3J) cell, and that the efficiency and power output $J_{mp}V_{mp}$ remain approximately the same for the two cell types. Then fractional power losses due to resistance are lower in the 4J cell by the square of the ratio between the two cell currents, $(J_{mp,4J}/J_{mp,3J})^2$, or by a factor of 4/9. In a 5J cell with the same $J_{mp}$ as the 4J cell, but a higher $V_{mp}$ and efficiency due to the addition of the GaInNAs cell 4, the fractional power losses are even lower. The resistive power losses are comparable to grid shadowing losses in most well-optimized solar cells, and can be the dominant type of grid-related power loss, as in concentrator solar cells with prismatic covers to eliminate grid shadowing.

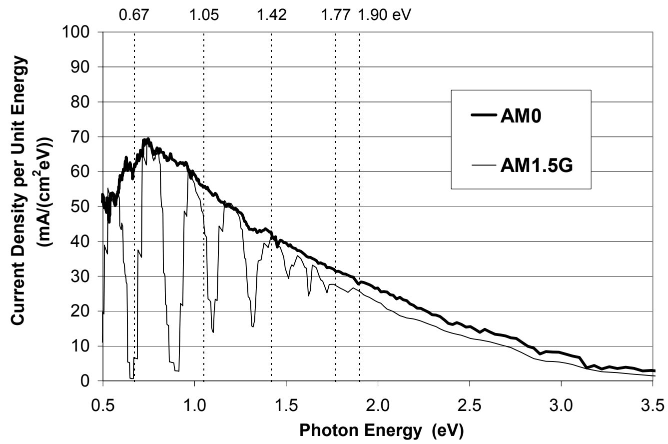


Fig. 2. Comparison of the AM0 and AM1.5G spectra, plotted as current density per unit photon energy, with the subcell bandgaps in a GaInP/GaInP/GaAs/GaInNAs/Ge 5-junction cell.

To explore the 5-junction GaInP/GaInP/GaAs/GaInNAs/Ge cell concept experimentally, cell structures in which only a single subcell is active were grown and fabricated. Multijunction cells incorporating the top three or the top four subcells were also built, to provide the first demonstrations of the thin GaInP cell 1/ thick GaInP cell 2 combination, and of a 4-junction GaInP/GaInP/GaAs/GaInNAs cell. All of these cells were grown on Ge substrates, for which the Ge cell was inactive. The external quantum efficiency (EQE) of each subcell was measured, and light I-V characteristics were measured under an XT-10 solar simulator spectrally balanced to simulate the AM0 spectrum for conventional 3-junction GaInP/GaAs/Ge cells.

## RESULTS AND DISCUSSION

The external quantum efficiencies of the four uppermost individual subcells for a 5-junction GaInP/GaInP/1%-In GaInAs/GaInNAs/Ge solar cell are plotted in Fig. 3. The EQEs are measured on cells with no anti-reflection (AR) coating, and are corrected to show the estimated quantum efficiency with AR coating, by multiplying by a factor of $(1 - R_{AR})/(1 - R_{no\ AR}) = 1.32$. Cells 1, 2, and 3 are measured on structures in which only the cell under test is active, and the other cells are made inactive by isotype doping. The GaInNAs cell 4 is measured on a GaInP/GaInP/GaAs/GaInNAs/Ge cell in which the 4 upper subcells are active. Fig. 3 shows how the response of each subcell moves to progressively longer wavelength ranges from cell 1 to cell 4: roughly 350-650 nm for the thin, disordered GaInP cell 1; 450-700 nm for the thick, ordered GaInP cell 2; 625-900 nm for the 1%-In GaInAs cell 3; and 800-1150 nm for the GaInNAs cell 4. The long-wavelength end of these ranges correspond closely to the bandgaps for each subcell base material extracted from the measured EQE, and listed in Table 1: approximately 1.90 eV for the thin, disordered GaInP cell 1; 1.77 eV for the thick, ordered GaInP cell 2; 1.38 eV for the 1%-In GaInAs cell 3; and 1.08 eV for the GaInNAs cell 4.

Table 1. Solar cell parameters for the 4 top individual subcells in a GaInP/GaInP/1%-In GaInAs/GaInNAs/Ge 5-junction cell, as well as for 3- and 4-junction cells composed of the top 3 and 4 junctions, respectively.

| Cell Configuration | Jsc from EQE, corr. with AR ($mA/cm^2$) | Sum of Jsc from EQE, through this subcell ($mA/cm^2$) | Jsc from light I-V, corr. with AR ($mA/cm^2$) | Bandgap From EQE (eV) | Voc (V) | Sum of Voc through this subcell (V) | FF (%) | Eff. (%) |
|---|---|---|---|---|---|---|---|---|
| Thin GaInP cell 1 | 10.01 | 10.01 | 10.43 | 1.902 | 1.426 | 1.426 | 80.2 | 8.81 |
| Thick GaInP cell 2 | 6.90 | 16.91 | 7.66 | 1.770 | 1.359 | 2.785 | 84.6 | 6.51 |
| 1%-In GaInAs cell 3 | 14.08 | 30.99 | 15.44 | 1.374 | 1.024 | 3.809 | 79.0 | 9.24 |
| GaInNAs cell 4 | 8.30 | 39.29 | — | 1.077 | — | — | — | — |
| 3-junction: cells 1, 2, & 3 | — | — | 8.58 | — | 3.699 | — | 87.1 | 20.43 |
| 4-junction: cells 1,2,3,&4 | — | — | 9.33 | — | 3.903 | — | 72.6 | 19.55 |

The current densities calculated by integrating the EQE of each subcell over the AM0 spectrum are also shown in Table 1. As can be seen from these values and from the EQE curves in Fig. 3, the thick GaInP cell 2 and the GaInNAs cell 4 are the subcells with the lowest current, limiting the current through the multijunction stack. The low current of cell 2 can be elevated by increasing the amount of light transmitted by the thin GaInP cell 1, for example by: further thinning of cell 1; raising the bandgap of cell 1 by increasing disorder in the group-III sublattice; or by alloying with Al to form a higher-bandgap AlGaInP top cell. Additionally, the low current of cell 2 can be increased by lowering the cell 2 bandgap, for instance: by alloying with As to form a GaInPAs cell 2 with the same lattice constant as the other subcells in the stack; by using a higher indium composition in cell 2 resulting in a lattice-mismatched, lower-bandgap GaInP cell 2; or by a combination of the two methods. The GaInNAs cell is still quite unoptimized with respect to anneal conditions, bandgap, thickness, and the amount of light transmitted by the GaInAs cell 3. So a range of options exist to increase the GaInNAs cell 4 current.

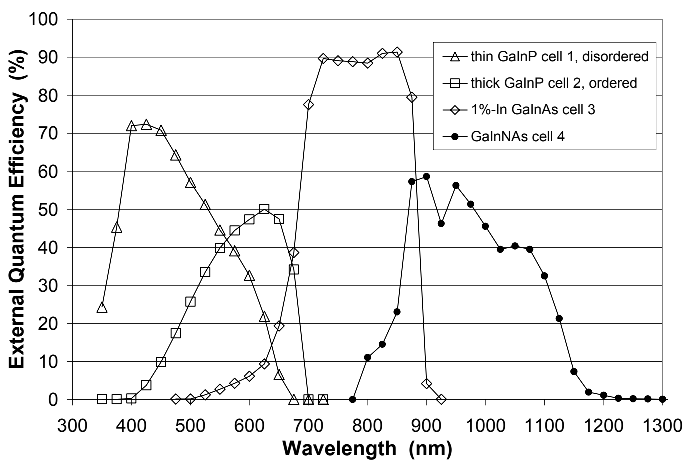


Fig. 3. External quantum efficiency for the upper four component subcells of a 5-junction GaInP/GaInP/ 1%-In GaInAs/GaInNAs/Ge solar cell, measured on cells with no anti-reflection (AR) coating, and corrected to show the estimated quantum efficiency with AR coating.

Fig. 4 shows the illuminated I-V curves for the top 3 subcells: the thin GaInP cell 1; thick GaInP cell 2; and 1%-In GaInAs cell 3. In these structures, all subcells other than the subcell under test are inactive, isotype subcells. Also shown are the I-V curves of the 3-junction cell that results from integrating the top 3 subcells, and a 4-junction GaInP/GaInP/GaAs/GaInNAs/Ge cell with only the Ge cell inactive. The light I-V measurements were made on cells with no AR coating, but as for the EQE data, the current densities have been corrected by a factor of $(1 - R_{AR})/(1 - R_{no\ AR}) = 1.32$, in order to show the expected current densities with AR coating.

Comparing cells 1 and 2, the low current density of thick GaInP cell 2 due to insufficient transmission of the thin GaInP cell 1 is clear. Cell 2 also has a lower $V_{oc}$ than cell 1, primarily due to the high degree of sublattice ordering and correspondingly low bandgap of cell 2, compared to the high bandgap of the mostly disordered GaInP cell 1. The current density of the 1%-In GaInAs cell 3 is clearly in excess of what is needed, and some of this current could be passed to the GaInNAs cell 4 by making cell 3 thinner, or increasing its bandgap by adding phosphorus to grow a GaInPAs cell 3.

The highest Voc yet achieved for the cells in this study is 3.90 V for the 4-junction GaInP/GaInP/ GaAs/GaInNAs/Ge solar cell shown in Table 1 and Fig. 4, in which only the Ge subcell is inactive. However, the low fill factor (FF) of the GaInNAs subcell 4 degrades the FF of the 4-junction cell to ~73%. As described above, the active GaInNAs solar cell in this stack benefits from the

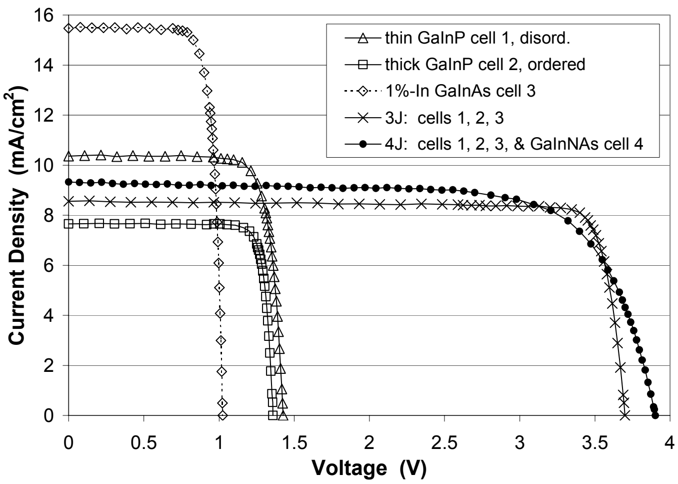


Fig. 4. Light I-V curves for the 3 top individual subcells of a GaInP/GaInP/1%-In GaInAs/GaInNAs/Ge 5-junction solar cell, for the 3-junction cell formed by the combination of these subcells, and a 4-junction GaInP/GaInP/GaAs/GaInNAs cell on an inactive Ge substrate.

reduced current needed to match the other subcells, by virtue of dividing the photon flux above ~1.77 eV energy between the top two GaInP subcells. The Jsc is higher than for the 3-junction cells, indicating that the GaInNAs subcell 4 does not limit the current of the other subcells.

## SUMMARY

Component subcells for a new type of 5-junction solar cell, incorporating a 1.08-eV GaInNAs cell 4 and a thin, high-bandgap GaInP cell 1 as well as a thick, low-bandgap GaInP cell 2, have been built and tested. The bandgaps of the two GaInP subcells were varied at the same semiconductor composition to achieve a high ~1.90 eV bandgap for top cell (cell 1) and low ~1.77 eV bandgap for cell 2, by controlling the GaInP group-III sublattice disorder. Through a combination of bandgap control and thinning of the GaInP cell 1, the concept of dividing the available photon flux with energy above ~1.77 eV between the top two GaInP cells was demonstrated, although cell 2 current still needs to be increased significantly to bring the present 0.69 $J_{sc}$ ratio between cell 1 and cell 2 close to unity. The lower current density of the full multijunction cell that results from even division between the two GaInP subcells benefits the efficiency of a 5-junction cell, allowing even a low current producer like the GaInNAs cell 4 to be current matched. Series resistance losses are also significantly reduced by the low current density. A 4-junction cell with a thin GaInP cell 1, thick GaInP cell 2, GaAs cell 3, and GaInNAs cell 4, grown on an inactive n-type Ge substrate, is demonstrated for the first time, and measured to have an open-circuit voltage of 3.90 V. The $J_{sc}$ is limited by the GaInP cell 2 and GaInNAs cell 4, but the currents in these cells can be increased by device optimization. With the inclusion of an active Ge cell 5 in a 5-junction solar cell grown on a p-type Ge substrate, a $V_{oc}$ of over 4.0 V is expected.


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