February 2005 • NREL/CP-520-37479

Conference Paper

Enhanced-Depletion-Width GaInNAs Solar Cells Grown by Molecular-Beam Epitaxy

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Prepared for the 31st IEEE Photovoltaics Specialists
Conference and Exhibition
Lake Buena Vista, Florida
January 3–7, 2005

National Renewable Energy Laboratory
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ENHANCED-DEPLETION-WIDTH GaInNAs SOLAR CELLS GROWN BY MOLECULAR-BEAM EPITAXY

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ABSTRACT

GaInNAs, potentially useful in a 4-junction $GaInP_2/GaAs/GaInNAs/Ge$ solar cell, suffers from very low minority-carrier collection lengths. To date, the currents available from GaInNAs solar cells are not high enough to increase the efficiency of a 3-junction device by adding this fourth junction. Here, we grow p-i-n GaInNAs solar cells by MBE with wide, intrinsic base layers and internal QE's near 1.0. If similar 1.0-eV GaInNAs junctions can be successfully integrated into the 3-junction structure, the resulting 4-junction cell would have a higher efficiency.

INTRODUCTION

The 3-junction, $GaInP_2/GaAs/Ge$ solar cell is a non-optimized structure due to excess light absorbed by the Ge junction. Because of this, a fourth junction inserted between the GaAs and Ge subcells could use the excess light and provide an increase in device efficiency [1]. Unfortunately, the leading candidate material, $Ga_{1-3x}In_{3x}N_xAs_{1-x}$, hereafter GaInNAs, suffers from very low minority-carrier diffusion lengths compared to its parent compound, GaAs [2],[3]. These low diffusion lengths do not allow for the collection of adequate photocurrent to increase the efficiency of a 4-junction device to more than that of a 3-junction structure. If the photocurrents generated from the GaInNAs subcell are increased, practical conversion efficiencies from this structure may exceed 40%.

Defects in the GaInNAs layer lead to short lifetimes for minority carriers. This means that diffusion lengths in this material are not long enough to generate significant photocurrent. One way to accomplish an increase of current from the GaInNAs junction is to employ a p–i–n structure with a wide, intrinsic base layer. The built-in field across this depleted layer sweeps minority carriers toward the junction, increasing the current generated by the cell. Figure 1 shows modeled internal quantum efficiency (QE) values for 1.05 eV bandgap GaInNAs solar cells with different thicknesses of the intrinsic base layer, or depletion layer. The model assumes that there is no collection from the GaAs emitter and no contribution due to diffusion in the GaInNAs base and that all carriers in the depleted layer are collected. Clearly, the QE is expected to improve dramatically with wider depletion widths. We estimate that photocarrier collection (drift plus any potential contribution from diffusion) from a region greater than 2 μm is necessary for a GaInNAs cell with a bandgap near 1 eV to provide an increased efficiency over the 3-junction device [4].

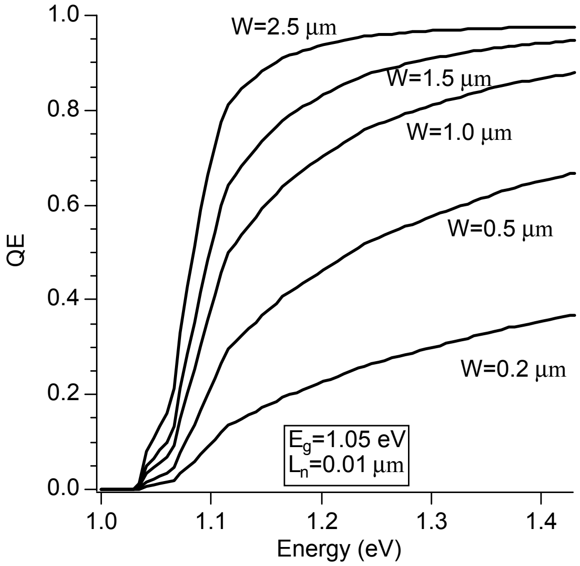

Figure 1. Calculations for GaInNAs solar cells with bandgaps of ~ 1.05 eV, showing an increase of the internal quantum efficiency with increasing depletion width, W, for a base thickness of 3 μm.

Growth of GaInNAs by MBE

Collection of sufficient photocarriers from outside the depletion region in GaInNAs is not assured because diffusion lengths are low. To make use of field-aided collection in the depletion region, a p-i-n structure requires a thick base layer with a very low background acceptor concentration. Unfortunately, GaInNAs grown by metalorganic chemical-vapor deposition (MOCVD) typically shows background carrier concentrations near 10^{17} cm^{-3} [5], with corresponding depletion widths of ~0.2 μm. Carbon acceptors incorporated from the organic precursors used in MOCVD account for much of this high background level. The rest is likely due to gallium vacancies that are stabilized in GaInNAs by the abundant atomic hydrogen available during growth [6]. A positron annihilation spectroscopy report [7] shows that gallium vacancies are more likely to form in MOCVD-grown GaInNAs than in material grown by molecular-beam epitaxy (MBE) due to the lack of hydrogen present during MBE growth. Also, MBE uses carbon-free sources, thus minimizing background impurities in addition to gallium vacancies. As a result, material grown by MBE has the potential for much lower background acceptor concentrations resulting in depletion widths of several microns.

EXPERMINENTAL DETAILS

GaInNAs solar cells were grown by solid-source MBE using elemental sources of Ga, In, and As, with active nitrogen provided by an Oxford HD25 rf-plasma source. The growth temperature for the nitride layers was ~530°C and no post-growth annealing was performed. GaAs cells were grown for comparison at a temperature of ~580°C. For these experiments, the solar cells consist of an unintentionally doped GaInNAs, 3 µm thick base layer and a Si-doped GaAs emitter (n~1.5x10^{18} cm^{-3}). A highly Si-doped GaAs contact layer caps the structure. This structure is somewhat non-optimized in that it does not employ a back-surface field, has no window layer, and no way to selectively remove the contact layer after processing.

The QE, current-voltage (IV), and capacitance-voltage (CV) measurements were completed using standard techniques. The internal QE was calculated from the measured external QE and reflectivity. The QE data presented below were corrected for grid shadowing to facilitate the comparison of devices with different grid designs. The IV curves yielded the short-circuit current (J_{sc}) and open-circuit voltage (V_{oc}), and the CV data provided the depletion width.

RESULTS AND DISCUSSION

Quantum Efficiency

Utilizing the lower impurity and vacancy concentrations possible using MBE growth, we succeeded in growing GaInNAs solar cells with depletion widths greater than 2 µm. These cells, with bandgaps down to 1.15 eV, show greatly enhanced short-circuit currents and QEs compared to reports in the literature. Figure 2 shows the QE measurements of several GaInNAs solar cells, displaying the difference between wide and narrow depletion widths at E_g~1.28 eV, as well as the QE from a cell with E_g~1.15 eV. The QE for a comparable GaAs cell is included for reference. The QEs for the samples with the wide depletion widths are, to our knowledge, the best reported for a GaInNAs sample. A report by Li *et al* on GaInNAs samples with similar bandgaps, but grown by MOCVD, shows maximum QEs below 0.7 [8]. Indeed, the best GaInNAs solar cells reported anywhere have had near band-edge QEs of approximately 0.8 [9].

Figure 3 shows the dependence of the QE (measured at an energy of E_g+0.2 eV) on the depletion width. The data compares favorably to a simple model that assumes light is filtered by, but not collected by, the GaAs emitter and that the diffusion length of carriers in the GaInNAs base is negligible. The collection of photocarriers in the emitter is neglected because the emitter is not passivated, and most of the photocarriers recombine at the front surface. There are many data points that lie significantly above the model's predictions, possibly indicating some collection from diffusion in addition to the collection due to the drift of carriers in the field. The contribution of this non-zero diffusion length to the QE may be negligible when the depletion width is increased to more than 2 µm.

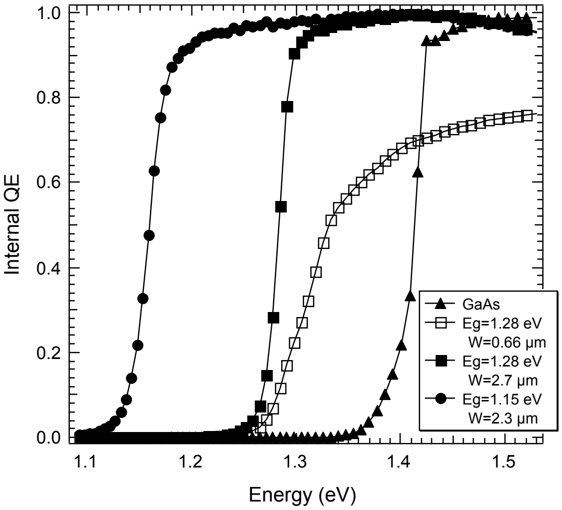

Figure 2. Comparison of QEs for similar samples with wide and short depletion widths. The data are corrected for the measured grid coverage to facilitate the comparison of devices with different grid designs.

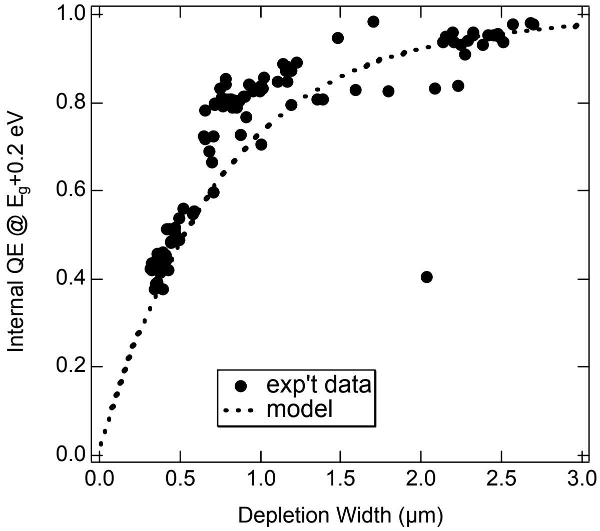

Figure 3. Compilation of QE values (measured at E_g+0.2 eV) vs. depletion width. The data resemble the expected values from a simple model that assumes no contribution from diffusion or the emitter. The data are corrected for estimated grid coverage to facilitate the comparison of devices with different grid designs.

Concentrator Measurements

The possibility exists that using a wide, intrinsically doped layer in a solar cell device will adversely effect the associated series resistance, especially under concentrator operation. To evaluate this issue, we measured the IV curves as a function of concentration for a 1.28-eV junction with a fully depleted base of width 3 μm and doping p=2x10^{14}/cm^3. The IV curves were measured using a pulsed solar simulator, [10] with the sample nominally at 25°C. Figure 4 shows the resulting V_{oc}, the ideality factor *n* as deduced from the slope of the V_{oc} curve, and the fill factor (FF) vs. J_{sc}. In the application with $GaInP_2$ and GaAs top and middle cells, the desired one-sun current would be on the order of 14 mA/cm^2, i.e. a 500-sun current of 7 A/cm^2 as indicated by the vertical dotted line in the figure. At this concentration, Fig. 4c shows that FF is barely below its one-sun value, indicating that series resistance is not a significant factor at this concentration.

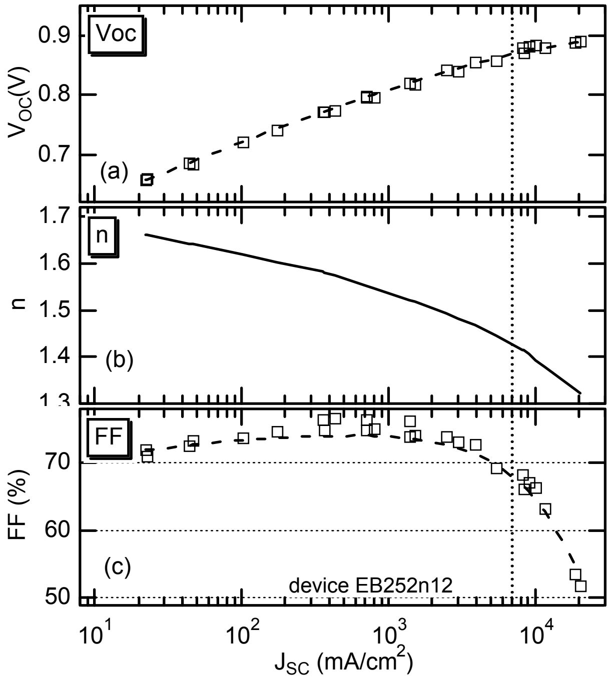

Figure 4. (a) V_{oc}, (b) ideality factor, n, and (c) FF of a wide-depletion-width, 1.28-eV GaInNAs cell as a function of concentration. The dashed line in (c) is a fit to a series-resistance model, with fit value Rs=1.1x10^{-2} Ωcm2.

To be more quantitative, we fit the FF data by calculating FF for the standard diode equation with ideality factor *n*, including series resistance R_S as the fit parameter, and scaled to the measured FF value at one sun. A very good fit is obtained with R_S=1.1x10^{-2} Ωcm^2, as shown by the dashed line in Fig. 4c. This value for R_S represents the sum of all the series resistances in the device, including not only the base resistance of interest but also resistances through the emitter, the grid fingers, and the grid-semiconductor contact. Separate measurements of these parameters indicate that together they total 2x10^{-3} Ωcm^2, so R_S due to the base alone is R_S=9x10^{-3} Ωcm^2. At the 500-sun current of 7 A/cm^2, the voltage drop across the base due to this R_S is 0.063 V. In other words, the wide-depletion-width device of Fig. 4 does not suffer significantly from series resistance across the base for concentrations at least as high as 500 suns.

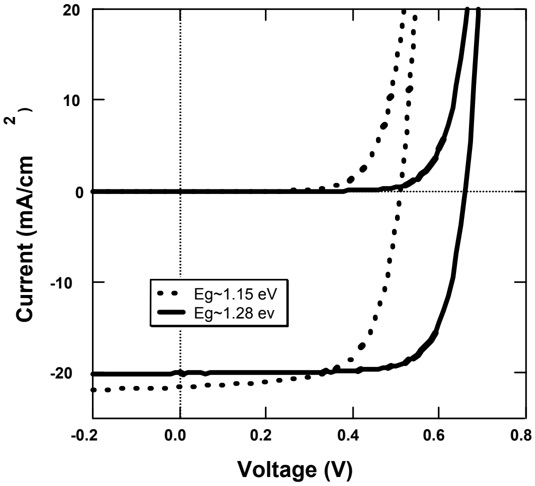

Figure 5. Light and dark IV curves for the wide-depletion-width GaInNAs cells from Fig.2.

Open-Circuit Voltage

Figure 5 shows light and dark IV curves for the wide-depletion-width GaInNAs layers in Fig. 2. The measurements were performed without a GaAs filter. The difference between the bandgap and the V_{oc} (E_g-V_{oc}) for these cells is ~0.62 V. Typically, E_g-V_{oc} is about 0.4–0.5 V for GaAs and $GaInP_2$, while GaInNAs cells are usually much closer to 0.6 V, presumably due to some unidentified defect [11]. One concern with using a p–i–n structure is possible carrier recombination in the depletion region, lowering the V_{oc}, and perhaps the QE [12] of the cell. Additional decreases in the V_{oc} would reduce the usefulness of GaInNAs in a 4-junction structure, whether or not the current is increased [4]. Promisingly, the V_{oc}'s for our cells degrade by less than 5% for depletion widths of several microns.

W would like to know what V_{oc} we can expect from a 1.0-eV GaInNAs solar cell. For one-sun applications, we could expect ~0.4 V, based on E_g-V_{oc}~0.6. Using the data in Fig. 4 and assuming the same value for E_g–V_{oc}, we estimate that a 1.0-eV junction would show V_{oc}~0.6 V at 500 suns illumination. There is the possibility that these voltages will increase with an optimized cell structure.

It is important to note that the bandgaps of the samples in this study are only as low as 1.15 eV, much higher (that

Table 1. Photocurrent collected from GaInNAs layers for photons with energies below the GaAs band edge.

E_g (eV)	AM0 (mA/cm^2)	Low AOD (mA/cm^2)
1.28	3.15	2.16
1.15	6.64	5.67

is, much less nitrogen) than necessary for use in a current-matched 4–junction structure. Table I shows the photocurrent collected from the GaInNAs junction (below the GaAs band edge) for two different spectra. Clearly, the bandgaps of these cells need to be pushed toward 1 eV, without significant degradation of the depletion width, to provide an increase in device efficiency for the 4-junction structure. It is possible that the addition of more nitrogen to these cells will adversely affect the background carrier concentrations, and hence the depletion widths. However, we are encouraged by the excellent QEs obtained for the bandgaps studied thus far.

CONCLUSIONS

High-quality GaInNAs has been sought for use in 4-junction solar cells for several years. Although the photovoltages in this material are still lower than they ideally should be, we show here that the photocurrents are greatly increased with the use of an MBE-grown p–i–n structure with a wide depletion region. Series resistance across the low-doped base does not significantly degrade concentrator performance up to at least 500 suns. With extension to lower bandgaps, these increased quantum efficiencies may provide the current needed for a higher-efficiency 4-junction $GaInP_2$/GaAs/GaInNAs/Ge device.

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REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

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1. **REPORT DATE** *(DD-MM-YYYY)* February 2005	2. **REPORT TYPE** Conference Paper	3. **DATES COVERED** *(From - To)* 3-7 January 2005

4. **TITLE AND SUBTITLE** Enhanced-Depletion-Width GaInNAs Solar Cells Grown by Molecular-Beam Epitaxy	5a. **CONTRACT NUMBER** DE-AC36-99-GO10337
	5b. **GRANT NUMBER**
	5c. **PROGRAM ELEMENT NUMBER**
6. **AUTHOR(S)** A.J. Ptak, D.J. Friedman, S. Kurtz, and J. Kiehl	5d. **PROJECT NUMBER** NREL/CP-520-37479
	5e. **TASK NUMBER** PVA54401
	5f. **WORK UNIT NUMBER**
7. **PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)** National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401-3393	8. **PERFORMING ORGANIZATION REPORT NUMBER** NREL/CP-520-37479
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14. **ABSTRACT** *(Maximum 200 Words)*

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15. **SUBJECT TERMS**
PV; enhanced depletion; solar cell; quantum efficiency; concentrator measurements; open-circuit voltage; bandgap; molecular-beam epitaxy;

16. **SECURITY CLASSIFICATION OF:**			17. **LIMITATION OF ABSTRACT**	18. **NUMBER OF PAGES**	19a. **NAME OF RESPONSIBLE PERSON**
a. **REPORT** Unclassified	b. **ABSTRACT** Unclassified	c. **THIS PAGE** Unclassified	UL		19b. **TELEPHONE NUMBER** (*Include area code*)

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