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

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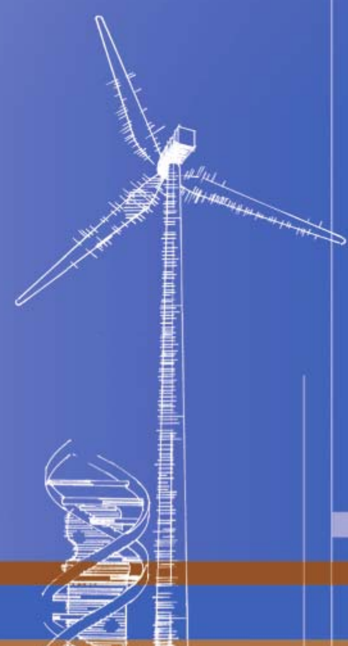

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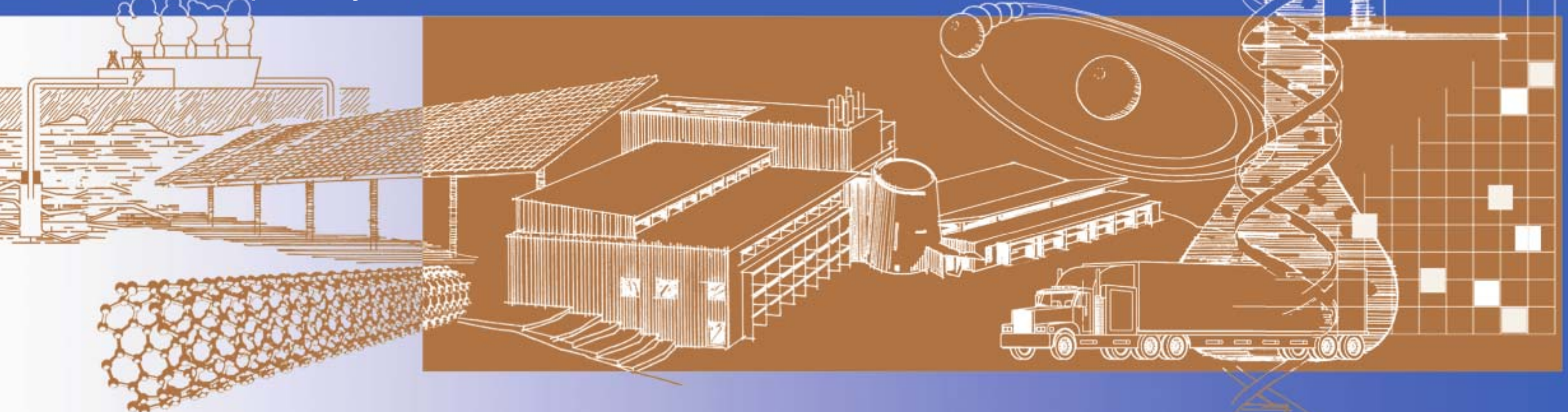

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Enhanced-Depletion-Width GaInNAs Solar Cells Grown by Molecular-Beam Epitaxy

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ABSTRACT

The 3-junction, $GaInP_2$/GaAs/Ge solar cell is a non-optimized structure due to excess light falling on 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, 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 current to keep the overall 4-junction structure current matched. If the currents generated from the GaInNAs subcell are increased, the possibility exists for practical efficiencies of greater than 40% from this structure

1. Objectives

Our objective is to increase the current from the GaInNAs junction by employing a p–i–n structure with a wide, intrinsic base layer. We will accomplish this by using molecular-beam epitaxy (MBE), a growth technique that has far fewer background impurities than metalorganic chemical-vapor deposition (MOCVD).

2. Technical Approach

The built-in field across the depleted layer sweeps minority carriers toward the junction, increasing the current from the cell. Without the use of the built-in field, the diffusion lengths in GaInNAs are not long enough to generate sufficient current in a 4-junction structure. Figure 1 shows modeled internal quantum efficiency (IQE) values for a GaInNAs cell with different thicknesses of the intrinsic base layer, or depletion layer, assuming there is no collection outside the depletion region. Clearly, the IQE is expected to improve dramatically with wider depletion widths. We estimate that an IQE>0.9 is necessary for GaInNAs to achieve current matching in a 4-junction structure, indicating that collection lengths (depletion widths, plus any contributions from diffusion) of approximately 2 m must be realized. Unfortunately, GaInNAs grown by MOCVD typically shows background carrier concentrations near 10^{17} cm^{-3} [4], with corresponding depletion widths of ~0.2 m. This is most likely due to the residual carbon impurities in the layers stemming from the carbon-containing precursors used in MOCVD, as well as some contribution from gallium vacancies. A positron annihilation spectroscopy report [5] shows that gallium vacancies are far more likely to form in MOCVD-grown GaInNAs than in material grown by MBE. Hydrogen stabilizes the vacancy-nitrogen complex [6], and there is abundant active hydrogen available in MOCVD growth. MBE, however, can be a hydrogen- and carbon-free growth technique, minimizing impurities and the formation of gallium vacancies.

3. Results and Accomplishments

Using these lower impurity and vacancy concentrations,

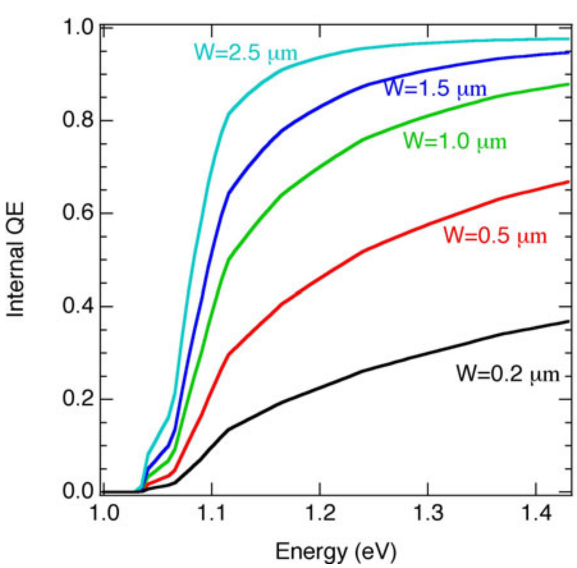

Figure 1. Calculations for GaInNAs with a bandgap of 1.05 eV, showing an increase in IQE with increasing depletion width, W.

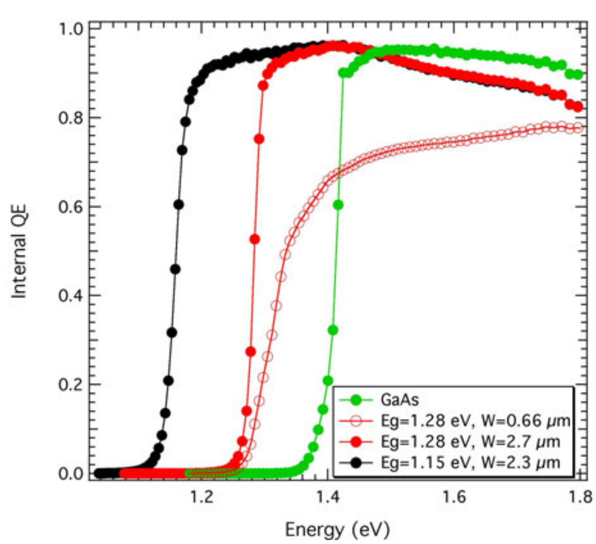

Figure 2. Comparison of IQEs for similar samples with different bandgaps and wide and short depletion widths.

we have succeeded in growing GaInNAs solar cells with depletion widths greater than 3   m by MBE. These cells, most with bandgaps near 1.3 eV, show greatly enhanced short-circuit currents and IQEs compared to reports in the literature. In addition, recent cells with E_g~1.15 eV show no degradation in depletion width or IQE compared to samples with higher bandgaps. Figure 2 shows the IQE 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 IQE from a cell with E_g~1.15 eV. The falloff of the IQE at high energies is due to the rather basic cell structure used in these experiments. The cell consists of an unintentionally doped GaInNAs base layer and a Si-doped GaAs emitter (n~1.5×10^{18} cm^{-3}). A highly Si-doped GaAs contact layer caps the structure. This structure does not employ a back-surface field, and has no window layer and no way to remove the contact layer after processing. This leads to recombination of carriers with higher energies at the front surface. *The IQEs 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 shows maximum IQEs below 0.7 [7]. Indeed, the best GaInNAs solar cells previously reported anywhere have had near band-edge IQEs below 0.75.

Figure 3 shows the dependence of the IQE (measured at an energy of E_g+0.2 eV) on the depletion width as measured by capacitance-voltage profiling. The data compare favorably to a simple model that assumes there is no collection from the GaAs emitter and that the diffusion length of carriers in the GaInNAs base is negligible. The data points that are higher than the model may indicate a contribution from diffusion. The data points on the right side of the plot (wide depletion-width samples) may be limited by the thickness of the base layer, and cells with thicker bases may show even higher IQEs.

The bandgaps of these cells need to be pushed toward 1 eV without significant degradation of the depletion width. 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, it is encouraging that early results from cells with lower bandgaps (in the range of 1.15 eV) do not show significant degradation (see Fig. 2). Another potential problem with using a p–i–n structure is possible carrier recombination in the depletion region, lowering the open-circuit voltage (V_{oc}), and perhaps the IQE [8] of the cell. GaInNAs already suffers from lower-than-expected V_{oc}'s, presumably due to some unidentified defect. Additional decreases in the V_{oc} would reduce the usefulness of GaInNAs in a 4-junction structure, whether or not the current is increased. Promisingly, the V_{oc}'s for our cells do not show any measurable decrease with increasing depletion width. The V_{oc} for one of our typical GaInNAs cells with a bandgap of ~1.3 eV is ~0.7 V. There is the possibility that this voltage will increase with an optimized cell structure.

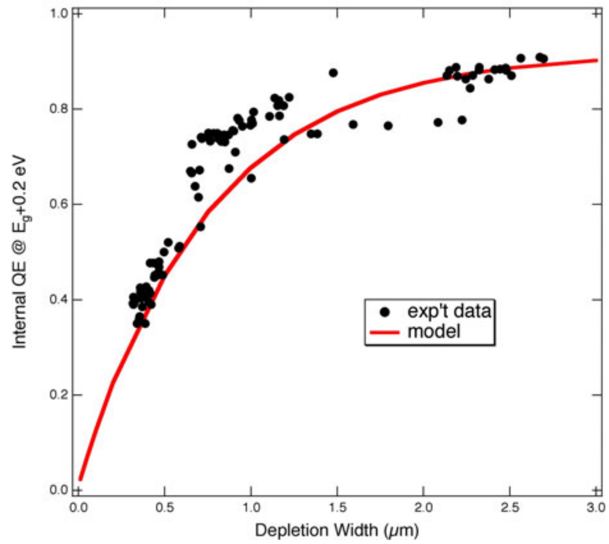

Figure 3. Compilation of internal QE values (taken at E_g+0.2 eV) vs. depletion width. The data resemble the expected values from a simple model that assumes no contribution from diffusion or the emitter, and an 8% shadow loss.

4. Conclusions

High-quality GaInNAs has been sought for use in 4-junction solar cells for many years. Although the voltages in this material are still lower than they should be, we show here that the currents are greatly increased with the use of an MBE-grown p–i–n structure with a wide depletion region. These increased currents allow the use of GaInNAs in multijunction structures without the GaInNAs subcell limiting the current of the device.

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14. ABSTRACT *(Maximum 200 Words)*
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15. SUBJECT TERMS
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