

# High Voltage Quantum Well Waveguide Solar Cells

**Roger E. Welsler,\* Gopal G. Pethuraja, and Ashok K. Sood**

Magnolia Solar, Inc.

54 Cummings Park, Suite 316, Woburn, MA 01801

251 Fuller Road, CESTM-B250, Albany, NY 12203

**Oleg A. Laboutin, Mark Chaplin, Van Un, and Wayne Johnson**

Kopin Corporation

200 John Hancock Road, Taunton, MA 02780

**Adam W. Sood, David J. Poxson, Jaehee Cho, and E. Fred Schubert**

Rensselaer Polytechnic Institute (RPI)

110 Eighth Street, Troy, NY 12180

**Pradeep Haldar**

College of Nanoscale Science and Engineering (CNSE)

257 Fuller Road, Albany, NY 12203

**Jennifer L. Harvey**

New York State Energy Research and Development Authority (NYSERDA)

17 Columbia Circle, Albany, NY 12203

## ABSTRACT

Photon absorption, and thus current generation, is hindered in conventional thin-film solar cell designs, including quantum well structures, by the limited path length of incident light passing vertically through the device structure. Optical scattering into lateral waveguide structures provides a physical mechanism to dramatically increase photocurrent generation through in-plane light trapping. However, the insertion of wells of high refractive index material with lower energy gap into the device structure often results in lower voltage operation, and hence lower photovoltaic power conversion efficiency. In this work, we demonstrate that the voltage output of an InGaAs quantum well waveguide photovoltaic device can be increased by employing a novel III-V material structure with an extended wide band gap emitter heterojunction. Analysis of the light IV characteristics from small area test devices reveals that non-radiative recombination components of the underlying dark diode current have been reduced, exposing the limiting radiative recombination component and providing a pathway for realizing solar-electric conversion efficiency of 30% or more in single-junction cells.

## INTRODUCTION

Quantum well solar cells seek to harness a wide spectrum of photons at high voltages in a single-junction device by embedding narrow energy-gap wells within a wide energy-gap matrix. By avoiding the limitations of current matching inherent in multi-junction devices, quantum well waveguide solar cells have the potential to deliver ultra-high efficiency over a wide range of operating conditions. Since their

\*E-mail: [rwelsler@magnoliasolar.com](mailto:rwelsler@magnoliasolar.com)

initial suggestion by researchers at Imperial College and Philips Research Laboratories, quantum well solar cells have been demonstrated in a variety of different material systems, and the basic concept has been extended to include quantum dots [1-7]. Clear improvements in lower energy spectral response have been experimentally confirmed in both quantum well and quantum dot solar cells. However, photon absorption, and thus current generation, is hindered in conventional quantum structured solar cells by the limited path length of incident light passing vertically through the device. Moreover, the insertion of narrow energy-gap material into the device structure often results in lower voltage operation, and hence lower photovoltaic power conversion efficiency.

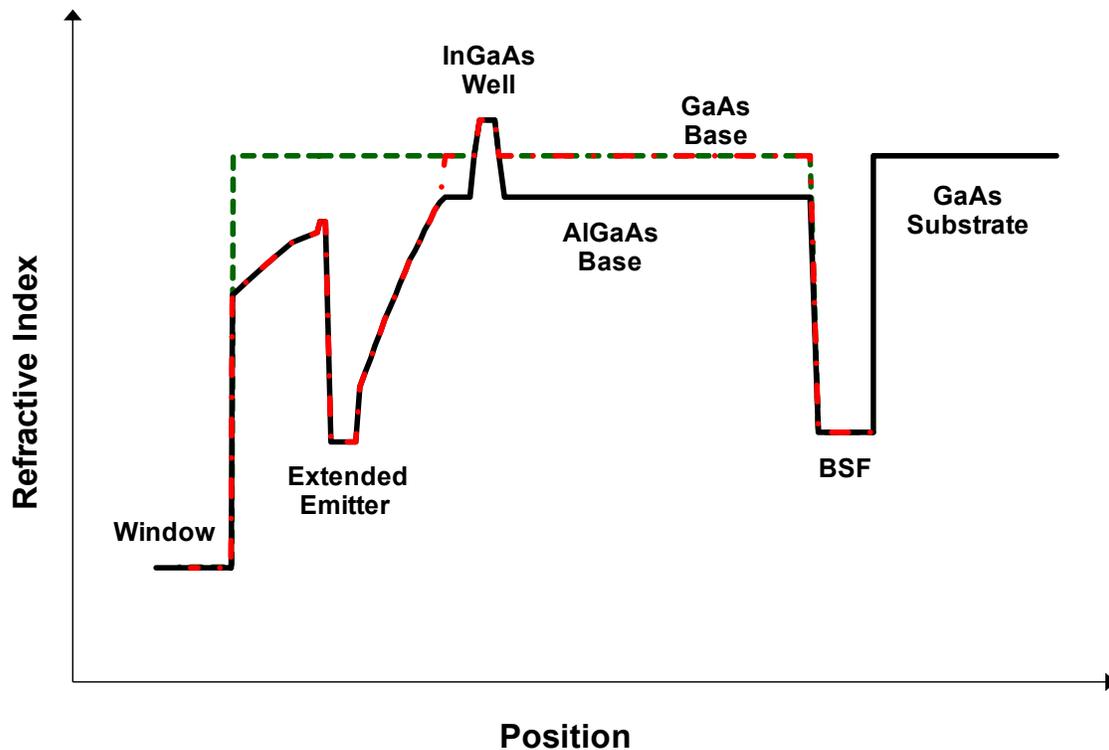
Optical scattering into laterally propagating waveguide modes provides a physical mechanism to dramatically increase photocurrent generation in quantum well solar cells via in-plane light trapping. The refractive index contrast in a typical quantum well solar cell provides lateral optical confinement and naturally forms a slab waveguide structure. Coupling of normally incident light into lateral optical propagation paths has been reported to lead to increases in the short circuit current of InP/InGaAs quantum well waveguide solar cells coated with nanoparticles [4]. However, maintaining high open circuit voltage remains a universal challenge for all quantum well and quantum dot solar cell devices.

Recently, InGaAs quantum well solar cells with a novel material structure have achieved record high open circuit voltages [8-9]. Unwanted space charge recombination has been minimized by employing an extended region of wide energy gap material within the depletion region adjacent to the emitter, and by using InGaAs quantum wells with a step-graded compositional profile. In this paper, we review and summarize our latest experimental efforts to enhance the open circuit voltage of InGaAs quantum well waveguide solar cell structures. Analysis indicates that these high-voltage InGaAs quantum well devices are operating in a regime of suppressed radiative recombination. Projections based upon this analysis suggests that advanced quantum well solar cell structures which both minimize the underlying diode dark currents and increase the optical path length have the potential to deliver solar electric conversion efficiencies exceeding 30% over a wide range of spectral conditions.

## EXPERIMENT

In this work, we have grown and tested several different types of InGaAs quantum well structures on semi-insulating GaAs substrates. In a conventional homojunction structure, an InGaAs well is embedded within a GaAs matrix, resulting in a refractive index profile such as that shown with the dashed green line in Figure 1. To reduce the diode dark current below that obtained in conventional structures, wider energy-gap InGaP and AlGaAs material has been employed in the emitter and inserted into the depletion region adjacent to the emitter, forming an extended wide band gap emitter heterojunction structure. The dashed-dot red line in Figure 1 illustrates this second type of quantum well structure. To further enhance the refractive index contrast around the InGaAs well, a third structure employs an AlGaAs base layer, as summarized with the solid black line in Figure 1.

All of the InGaAs quantum well solar cell structures studied in this work have been synthesized via metal-organic chemical vapor deposition (MOCVD) at Kopin Corporation. Single InGaAs quantum wells with a target thickness of 33 nm are located within the built-in field of the junction depletion region. A step-graded InGaAs compositional profile is employed to form a series of smaller energy steps (~ 35 meV) that photogenerated carriers can overcome to escape from the potential well [10]. The effective energy gap of the InGaAs well is a function of both the well compositional profile and thickness, and can be quantified by photoluminescence (PL) emissions. As-grown samples have been characterized by PL measurements generated with excitation from both 532 nm and 785 nm laser sources.

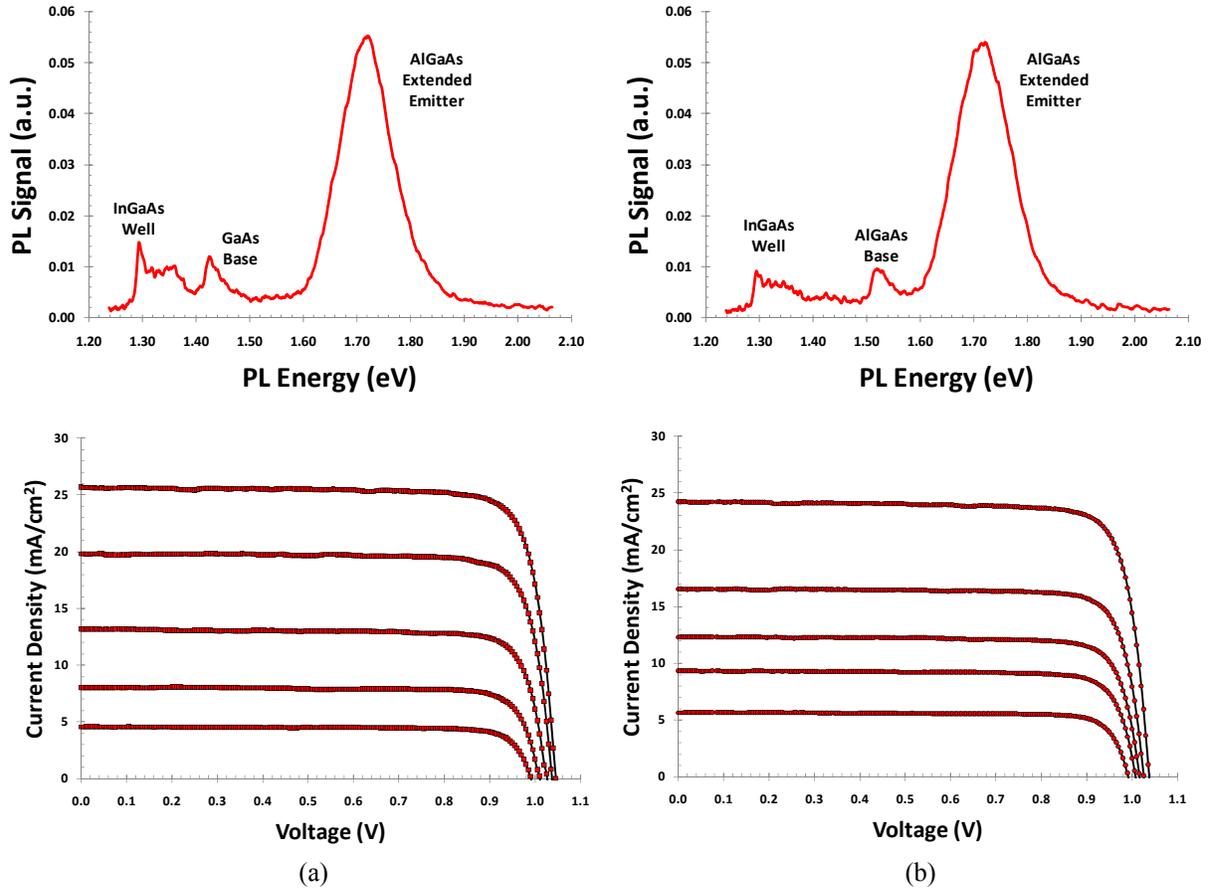


**Figure 1:** Approximate refractive index versus position profile for three different InGaAs quantum well waveguide solar cell structures studied in this work.

Small, simple mesa test devices have been fabricated with standard wet etch chemistry and photolithography to define devices with junction area as small as  $75 \mu\text{m} \times 75 \mu\text{m}$ . A variety of tests have been made on these devices, including dark current versus voltage, capacitance versus voltage, and illuminated current versus voltage measurements. For light I-V measurements, the photocurrent is generated by illumination with an un-calibrated halogen lamp through a probe station microscope that can be varied in intensity. A test structure consisting of a device with a junction area of  $200 \mu\text{m} \times 340 \mu\text{m}$  and an open aperture of  $120 \mu\text{m} \times 260 \mu\text{m}$  has been used to measure the illuminated current versus voltage characteristics of all three structures. In addition, the extended heterojunction structure with a GaAs base has been re-grown and fabricated into a larger, nearly  $500 \mu\text{m} \times 500 \mu\text{m}$  device. Specifically, the larger device has a junction area of  $0.2236 \text{ mm}^2$ , and an aperture area that is nearly 98.4% of the junction area. While the results obtained from the smaller devices are consistent with the larger devices, the larger relative aperture size of the  $500 \mu\text{m} \times 500 \mu\text{m}$  device enables us to characterize the illuminated I-V performance at slightly higher current densities.

## RESULTS

The photoluminescence spectra and light IV characteristics from the two InGaAs quantum well solar cell structures employing an extended wide energy-gap emitter are shown in Figure 2. In both structures, the PL emission from the step-graded InGaAs well peaks near 1.30 eV, while the extended AlGaAs emitter material luminescence peaks around 1.72 eV. The base layer emissions differ, as expected, with a peak near 1.42 eV for the GaAs base structure and 1.52 eV for the AlGaAs base.

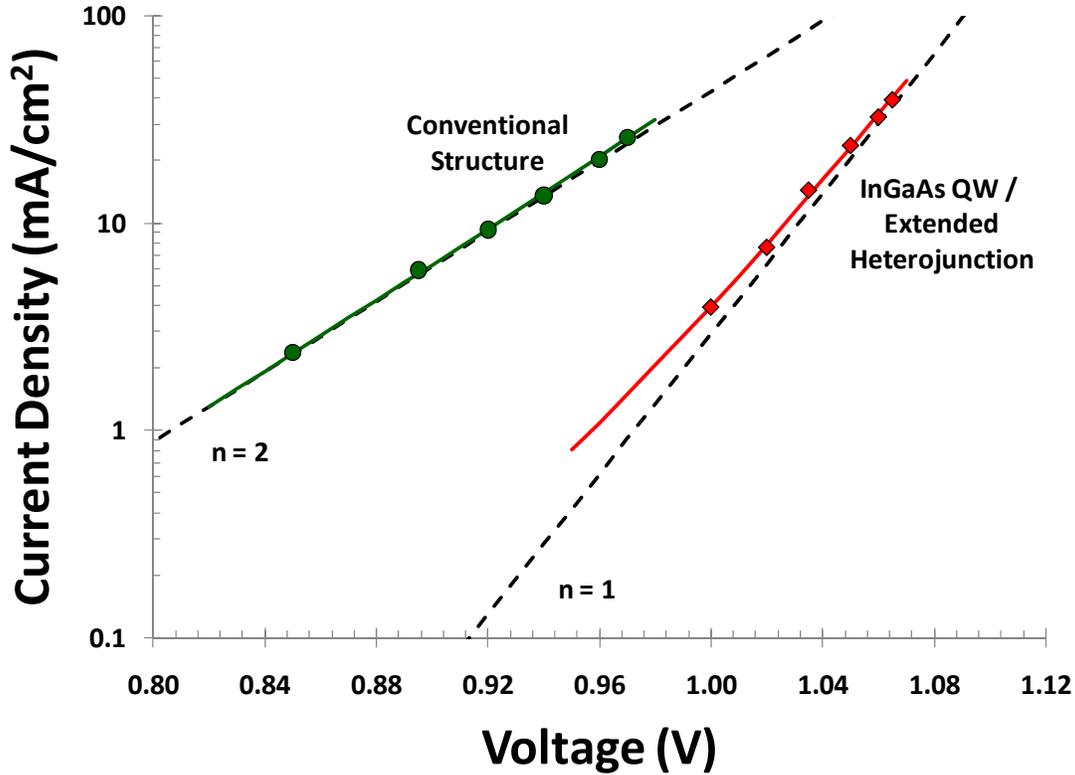


**Figure 2:** Photoluminescence spectra and light IV measurements made at varying levels of white light intensity on a small area test device from quantum well solar cell structures consisting of a step-graded InGaAs well within a (a) GaAs or (b) AlGaAs base layer and employing an extended wide band gap AlGaAs/InGaP emitter heterojunction.

Overall, the illuminated current-voltage characteristics of the two emitter heterojunction structures are quite similar. Small area test devices on both structures exhibit fill factors near 83%, short circuit current density ( $J_{sc}$ ) on the order of  $25 \text{ mA/cm}^2$  at maximum halogen lamp intensity, and open circuit voltage ( $V_{oc}$ ) approaching 1.05 V. These open circuit voltage values are higher than the  $V_{oc} \sim 0.97 \text{ V}$  obtained on the control structure without the extended heterojunction, and comparable to the  $V_{oc}$  of state-of-the-art bulk GaAs single-junction cells [11-12], despite the addition of a narrower energy gap InGaAs well.

## DISCUSSION

To further quantify the voltage characteristics of the InGaAs quantum well waveguide solar cells, the short circuit current at varying white light intensities have been analyzed as a function of open circuit voltage. The  $J_{sc}$ - $V_{oc}$  curve that results from characterizing and plotting the short circuit current as a function of open circuit voltage provides an effective measurement of the underlying dark diode current, unencumbered by the effects of series resistance [13]. Figure 3 compares the diode current of a conventional structure to that of the InGaAs quantum well structure with a GaAs base layer and an extended heterojunction fabricated into a  $0.2236 \text{ mm}^2$  device. A dramatic reduction in the  $n=2$  space charge recombination is observed, allowing the  $n=1$  saturation current density ( $J_{01}$ ) to be extracted from a



**Figure 3:**  $J_{sc}$ - $V_{oc}$  curves derived from illuminated I-V measurements on two different quantum well structures and employing a two-diode fit to model of the underlying dark currents. The InGaAs quantum well structure with an extended heterojunction employs a GaAs base layer and is fabricated into a  $0.2236 \text{ mm}^2$  device.

two-diode fit of the short circuit current versus open circuit voltage data. The diode fit assumes the underlying dark current can be described as the sum of two diodes at room temperature ( $25 \text{ }^\circ\text{C}$ ), one with an ideality factor of one ( $n=1$ ) and the other with an ideality factor of two ( $n=2$ ). Diode fits suggest that the  $n=1$  saturation current density of the diode current can be reasonably fit as  $J_{o1} = 4.5 \times 10^{-17} \text{ mA/cm}^2$  for both InGaAs quantum well solar cells employing an extended heterojunction.

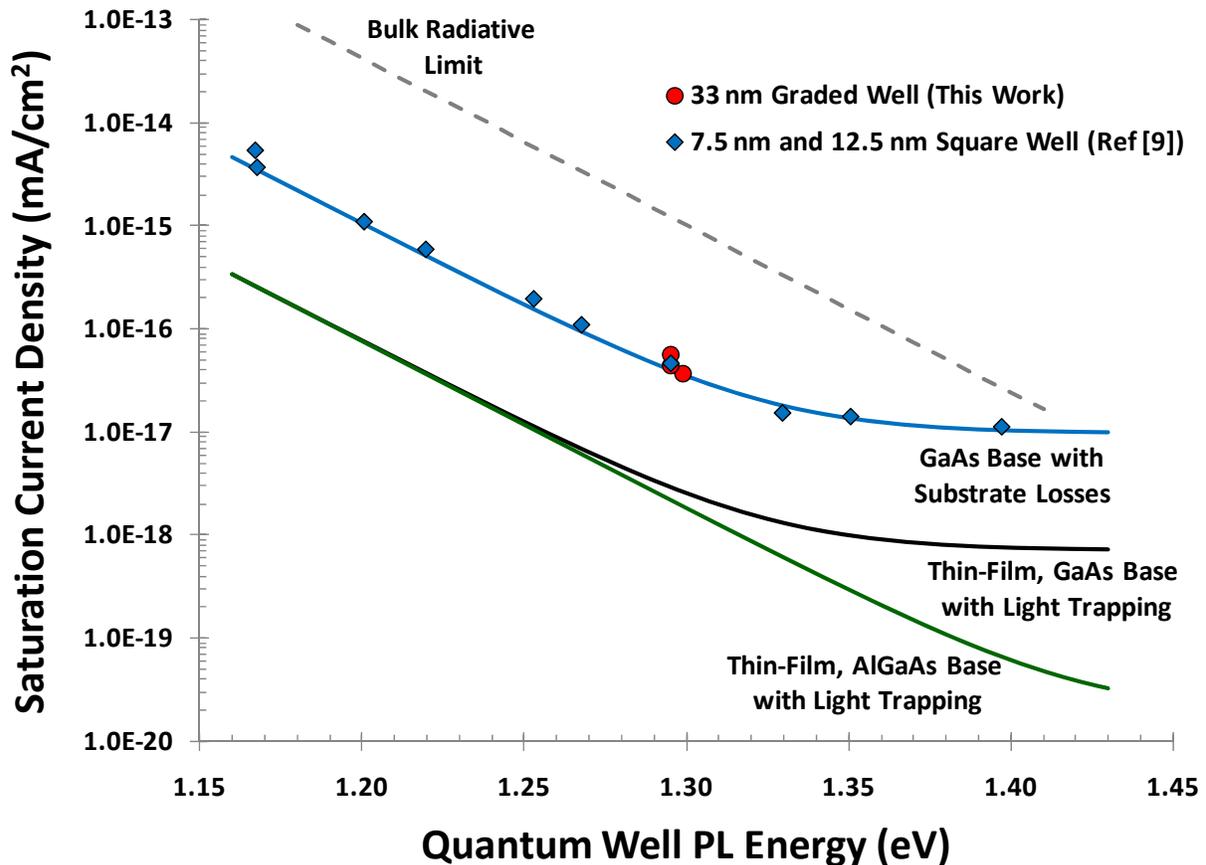
While Shockley injection typically limits the  $n=1$  component of bulk III-V diodes, radiative recombination within the InGaAs quantum well could also play a role [14]. Indeed, the observed lack of sensitivity of the voltage characteristics to the addition of aluminum to the base layer may suggest that radiative limits have been reached at 1-sun bias levels in quantum well solar cells employing an extended heterojunction structure. The concept of detailed balance is a well established means of computing the expected radiative current that should limit the performance of photonic devices. As noted by Henry [15], the  $n=1$  saturation current density ( $J_{o1}$ ) in the radiative limit should equal the thermal radiation current ( $J_{th}$ ), such that:

$$J_{th} = \left( \frac{q(n_{cell}^2 + 1)kTE_g^2}{4\pi^2\hbar^3c^2} \right) \exp\left(-E_g/kT\right) \quad (1)$$

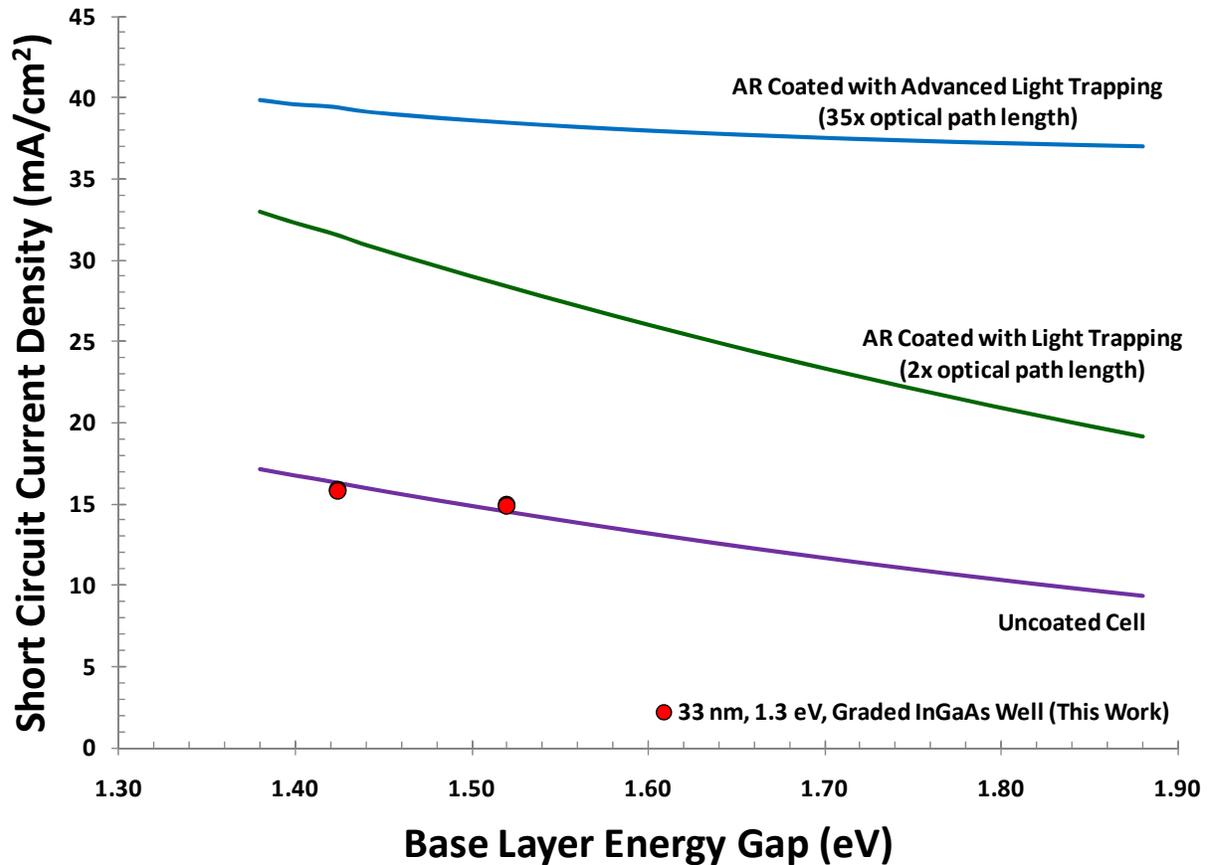
where  $E_g$  corresponds to the peak energy of the photons emitted at temperature  $T$ . An absorbing bottom substrate is assumed in Equation (1), with photons escaping via the top surface into a media with a refractive index ( $n_{top}$ ) of one (e.g. air). Following Henry [15], we also assume in Equation (1) that the refractive index of the cell ( $n_{cell}$ ) and the bottom substrate ( $n_{bottom}$ ) are both equal to that of GaAs ( $n_{GaAs} \sim$

3.5). Assuming an effective energy gap of 1.3 eV for the InGaAs well, Equation (1) implies  $J_{01} = 1 \times 10^{-15}$  mA/cm<sup>2</sup>, which is nearly an order and a half *higher* in magnitude than the value inferred from measurements on InGaAs quantum wells with an extended heterojunction structure. This analysis suggests that our InGaAs quantum well structures are actually operating in a regime of suppressed radiative recombination.

A number of different physical mechanisms can lead to a suppression in radiative current relative to that predicted by Equation (1), including the finite volume of the InGaAs well, photon recycling, and perturbations in the diode quasi-Fermi level [16-17]. While work is on-going to clarify the role of each of these mechanisms in our devices [9], photon recycling is an intriguing phenomenon that can potentially be leveraged to further reduce the dark current and hence increase the operation voltage of InGaAs quantum well solar cells operating in the radiative limit. Radiative emissions can be suppressed in structures which support the re-absorption of emitted photons by reflecting emitted photons back into the absorber region of the device. In the devices characterized in this work, such photon recycling is expected to be negligible due to basic geometrical considerations associated with fabricating test structures with limited lateral dimensions on a relatively thick substrate (~ 625 μm). However, photon recycling effects could be greatly enhanced by removing the GaAs substrate and fabricating devices with



**Figure 4:** Plot of  $n=1$  saturation current density as a function of InGaAs well energy. The dashed line represents the results of traditional detailed balance calculations [15] assuming optically thick cells and an absorbing substrate. The solid lines represent a modified model under development [19] that better match recent experimental results on InGaAs quantum wells employing extended wide band gap emitters and projecting the impact of photon recycling.



**Figure 5:** Projected short circuit current versus base layer energy gap for both coated and uncoated devices employing a 33 nm, 1.3 eV InGaAs quantum well with a 0.5  $\mu\text{m}$  thick, higher energy gap base layer. The calculations assume illumination with a 5800 K blackbody, while the solid shapes represent a 0.6 fraction of the measured data at maximum intensity, taken here as an approximation of an 5800 K (AM0) spectrum.

a thin-film architecture. Back reflections and photon recycling could be further enhanced by the use of an omni-directional back reflector incorporating a low index film between the substrate and the back metal [18]. Indeed, a lossless bottom mirror which reflects back all downward emitted photons for re-absorption in the well could potentially reduce the radiative current by over an order of magnitude [16]. Figure 4 illustrates the potential reduction in dark current that could be realized by fabricating InGaAs quantum well solar cells with an extended heterojunction in a thin-film format which promotes efficient light trapping [19].

Enhanced light trapping, in addition to providing an avenue to further suppress radiative recombination, can be leveraged to dramatically increase the short circuit current of thin film solar cells. Photon absorption, and thus current generation, is hindered in conventional thin film solar cell designs, including quantum well structures, by the limited path length of incident light passing vertically through the device structure. Figure 5 illustrates the projected short circuit current of InGaAs waveguide solar cells employing a single 33 nm well with an absorption edge at 950 nm ( $\sim 1.3$  eV) embedded within a 0.5  $\mu\text{m}$  higher energy gap base layer. The calculations summarized in Figure 5 employ realistic estimates of the absorption coefficient and assume the solar spectrum can be approximated by that of a 5800K blackbody. Under these conditions, the short circuit current of uncoated cells is expected to decrease slightly with

increasing base layer energy gap, in line with our measured results. Applying a standard two-layer antireflection (AR) coating to the front surface and employing a simple reflector at the back surface to double the optical path length is expected to nearly double the short circuit current. Short circuit currents approaching  $40 \text{ mA/cm}^2$  are projected for devices with 1.3 eV wells that employ more advanced light trapping structures to leverage the waveguide properties of the quantum well structure and further increase the optical path length. Even higher short circuit currents would be expected from light trapping structures employing lower energy gap wells. We note that AM0 (and AM1.5) efficiencies in excess of 30% can be achieved in devices that can combine  $J_{01}$  values on the order of  $1 \times 10^{-18} \text{ mA/cm}^2$  with  $J_{sc}$  values above  $40 \text{ mA/cm}^2$  (or  $32 \text{ mA/cm}^2$ ).

## CONCLUSIONS

Record high open circuit voltages have been demonstrated in InGaAs quantum well waveguide solar cell structures. Higher open circuit voltages result from the use of a novel structure incorporating a wide band gap barrier layer within a heterojunction depletion region to suppress non-radiative recombination. A dramatic reduction in the  $n=2$  space charge recombination is observed, allowing the  $n=1$  saturation current density to be extracted from a simple two-diode fit of the short circuit current versus open circuit voltage data. Analysis suggests that these high-voltage InGaAs quantum well devices are operating in a regime of suppressed radiative recombination. The application of advanced light trapping structures provides a means to both further suppress the radiative dark current and enhance the optical path length within the absorbing layers. The resulting increases to the operating voltage and short circuit current are projected to result in solar-electric conversion efficiencies exceeding 30%.

## ACKNOWLEDGMENTS

The authors would like to thank the New York State Energy Research and Development Authority (NYSERDA) and the National Aeronautics and Space Administration (NASA) and for supporting this work via contracts # ERDA1-0000021389 and NNX11CE59P.

## REFERENCES

- [1] W. J. Barnham and G. Duggan, "A New Approach to High-Efficiency Multi-Band-GaP Solar Cells," *J. Appl. Phys.*, vol. 67, pp. 3490-3493, April 1990.
- [2] D. B. Bushnell, T. N. D. Tibbits, K. W. J. Barnham, J. P. Connolly, M. Mazzer, N. J. Ekins-Daukes, J. S. Roberts, G. Hill, and R. Airey, "Effect of Well Number on the Performance of Quantum-Well Solar Cells," *J. Appl. Phys.*, vol. 97, no. 124908, June 2005.
- [3] A. Alemu, J. A. H. Coaquira, and A. Freundlich, "Dependence of Device Performance on Carrier Escape Sequence in Multi-Quantum-Well p-i-n Solar Cells," *J. Appl. Phys.*, vol. 99, no. 084506, May 2006.
- [4] D. Derkacs, W. V. Chen, P. M. Matheu, S. H. Lim, P. K. L. Yu, and E. T. Yu, "Nanoparticle-Induced Light Scattering for Improved Performance of Quantum-Well Solar Cells," *Appl. Phys. Lett.*, vol. 93, no. 091107, September 2008.
- [5] A. Luque, A. Marti, N. Lopez, E. Antolin, E. Canovas, C. Stanley, C. Farmer, L.J. Caballero, L. Cuadra, and J.L. Balenzategui, "Experimental Analysis of the Quasi-Fermi Level Split in Quantum Dot Intermediate-Band Solar Cells," *Appl. Phys. Lett.*, vol. 87, no. 083505, August 2005.

- [6] R. B. Laghumavarapu, A. Moscho, A. Khoshakhlagh, M. El-Emawy, L.F. Lester, and D.L. Huffaker, "GaSb/GaAs Type II Quantum Dot Solar Cells for Enhanced Infrared Spectral Response," *Appl. Phys. Lett.*, vol. 90, no. 173125, April 2007.
- [7] S. M. Hubbard, C. G. Bailey, R. Aguinaldo, S. Polly, D. V. Forbes, and R. P. Raffaele, "Characterization of Quantum Dot Enhanced Solar Cells for Concentrator Photovoltaics," *Proceedings of the 34th IEEE Photovoltaic Specialists Conference*, June 2009.
- [8] R. E. Welser, O. A. Laboutin, M. Chaplin, and V. Un, "Reducing Non-Radiative and Radiative Recombination in InGaAs Quantum Well Solar Cells," *Proceedings of the 37<sup>th</sup> IEEE Photovoltaic Specialists Conference*, no. 761, June 2011.
- [9] R. Welser, O. Laboutin, and W. Johnson, "Probing the Radiative Limits of III-V Quantum Wells," accepted to *ECS Transactions - Boston, MA, Volume 16, State-of-the-Art Program on Compound Semiconductors 53 (SOTAPOCS 53)*, MS #E8-2094, September 2011.
- [10] Y. Okada and N. Shiotsuka, "Fabrication of Potentially Modulated Multi-Quantum Well Solar Cells," *Proceedings of the 31<sup>st</sup> IEEE Photovoltaic Specialists Conference*, p. 591-594, December 2005.
- [11] S. R. Kurtz, J. M. Olson, and A. Kibbler, "High Efficiency GaAs Solar Cells Using GaInP Window Layers," *Proceedings of the 21<sup>st</sup> IEEE Photovoltaic Specialists Conference*, pp. 138-140, May 1990.
- [12] A. W. Bett, F. Dimroth, G. Stollwerck, and O. V. Sulima, "III-V Compounds for Solar Cell Applications," *Appl. Phys. A*, vol. 69, pp. 119-129, June 1999.
- [13] A.G. Aberle, S. R. Wenham, and M. A. Green, "A New Method for Accurate Measurements of the Limped Series Resistance of Solar Cells," *Proceedings of the 23<sup>rd</sup> IEEE Photovoltaic Specialists Conference*, pp. 133-139, May 1993.
- [14] D.C. Johnson, I.M. Ballard, K.W.J. Barnham, J.P. Connolly, M. Mazzer, A. Bessière, C. Calder, G. Hill, and J.S. Roberts, "Observation of Photon Recycling in Strain-Balanced Quantum Well Solar Cells," *Appl. Phys. Lett.*, vol. 90, no. 213505, May 2007.
- [15] C.H. Henry, "Limiting Efficiencies of Ideal Single and Multiple Energy-gap Terrestrial Solar Cells," *J. Appl. Phys.*, vol. 51, pp. 4494-4500, August 1980.
- [16] A. Marti, J. L. Balenzategui, and R. F. Reyna, "Photon Recycling and Shockley's Diode Equation," *J. Appl. Phys.*, vol. 82, pp. 4067-4075, October 1997.
- [17] J. Nelson, J. Barnes, N. Ekins-Daukes, B. Kluitinger, E. Tsui, K. Barnham, C.T. Foxon, T. Cheng, and J.S. Roberts, "Observation of Suppressed Radiative Recombination in Single Quantum Well P-I-N Photodiodes," *J. Appl. Phys.*, vol. 82, pp. 6240-6246, December 1997.
- [18] J.-Q. Xi, M. Ojha, W. Cho, J. L. Plawsky, W. N. Gill, T. Gessmann, and E. F. Schubert, "Omnidirectional Reflector Using Nanoporous SiO<sub>2</sub> as a Low-Refractive-Index Material," *Optics Letters*, vol. 30, pp. 1518-1520, June 2005.
- [19] R. E. Welser, submitted to the 2012 SPIE-Photonic West, Tracking #: PW12O-OE102-59.