Next Generation Photovoltaic Devices Leveraging Restricted Angular Emissions

R. E. Welser*, A. K. Sood*, P. S. Wijewarnasuriya** and N. K. Dhar***

* Magnolia Optical Technologies, Inc., Woburn, MA, USA, rwelser@magnoliaoptical.com
** Army Research Laboratory, Adelphi, MD, USA
*** Night Vision & Electronics Sensors Directorate, Fort Belvoir, VA, USA

ABSTRACT

In this paper, we review the theoretical impact of restricted angular emissions on solar cell performance, and discuss how nanostructured III-V absorber layers in combination with advanced optical structures might be employed to realize practical restricted emission cells for next-generation photovoltaic applications.

Keywords: photovoltaics, III-V devices, GaAs, quantum well solar cell

1 INTRODUCTION

Thin-film III-V devices are an attractive technology for photovoltaic energy-harvesting devices, capable of supplying portable and mobile power in both terrestrial and space environments. Single-junction III-V technologies can provide high performance levels over a wide range of operating conditions and minimize costs relative to multi-junction space power cells by limiting the required volume of epitaxial material.

The most efficient single-junction thin-film III-V cells reported to date have employed high-performance back reflector structures. The back reflector effectively restricts the angular profile of the radiative emissions from the III-V cell, which can enhance the voltage output of cells operating at or near the radiative limit. In this paper, we will discuss strategies for further restricting radiative emissions and achieving single-junction III-V thin-film cells with efficiencies approaching 40%. In particular, the use of nanostructured layers in the absorber layer provides a pathway for realizing advanced photovoltaic device concepts with higher conversion efficiency.

Over the past several decades, nanostructured III-V quantum well and quantum dot solar cells have been investigated as a means of implementing advanced device concepts to improve solar cell efficiency. Previous work in the field of quantum well solar cells has also shown that the radiative emissions from strained InGaAs wells are not necessarily isotropic, but instead can exhibit a partially restricted emission profile. Detailed balance calculations suggest that restricted radiative emissions can have a significant impact on the open circuit voltage and efficiency. In this paper, we review the impact restricted angular emissions can theoretically have on solar cell performance, and discuss how advanced nanostructured absorber layers in combination with high-performance back reflector structures can be employed to realize next-generation photovoltaic devices leveraging restricted angular emissions.

2 RESTRICTED ANGULAR EMISSIONS

III-V nanostructures have been investigated as a means of implementing advanced device designs that leverage processes employing optical up-conversion via an intermediate band [1], hot carrier extraction [2], and/or restricted luminescent emissions [3]. All of these advanced device concepts require, in one way or another, the inhibition of radiative recombination from the nanostructured materials. Detailed balance calculations suggest that restricted radiative emissions in particular can have a significant impact on the open circuit voltage and efficiency of lower energy-gap cells [3-4]. Figure 1 is a plot of limiting theoretical efficiency versus energy gap under a 6000K blackbody spectrum, assuming detailed balance and four different radiative emission angles.

The theoretical calculations used in Figures 1 and 4 are based upon a generalized expression of the radiative dark current (J_{rad}) often used to estimate ideal solar cell performance, traditionally known as the Shockley-Queisser (S-Q) limit [5]:

$$J_{rad} = 2F_{dc}\frac{qE_g{}^2kT}{h^3c^2}\exp\left(\frac{-E_g}{kT}\right)\exp\left(\frac{eV}{kT}\right) \qquad (1)$$

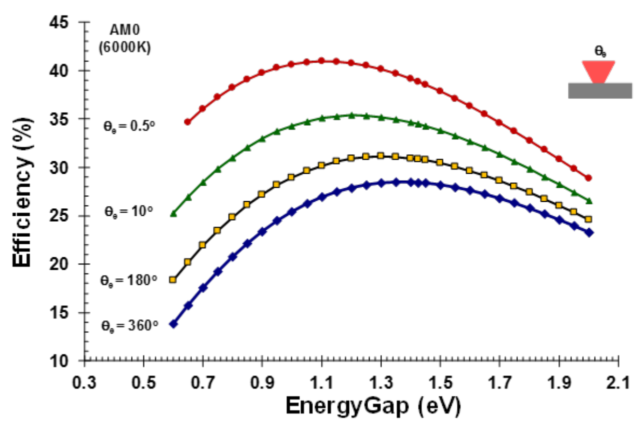

Figure 1: Plot of theoretical efficiency versus energy gap under a 6000K blackbody spectrum, assuming detailed balance and four different radiative emission angles.

In deriving Equation (1), we follow the work of Henry, making the simplifying assumption that the absorption profile in the cells is a step-function which shifts with the energy gap (E_g) of the cell material [6]. Furthermore, we introduce a dark current factor F_{dc} to account for both photon recycling and restricted emissions, as well as non-radiative losses or non-equilibrium effects such as hot carrier extraction which can enhance or inhibit recombination [7]. In equilibrium, the ideal dark current factor is limited only by radiative recombination and is related to the effective refractive index above and below the absorber layers (n_t and n_b) such that:

$$F_{dc} = \pi\left(n_t^{\,2} + n_b^{\,2}\right) \tag{2}$$

In addition, the fill factor is assumed to scale with the open circuit voltage (V_{oc}), such that:

$$FF = 0.0249V_{oc}^3 - 0.1383V_{oc}^2 + 0.2917V_{oc} + 0.7036 \tag{3}$$

The lowest curve in Figure 1 assumes isotropic emissions and no photon recycling ($n_t = n_b = 3.5$), which is a more severe limit than is typically assumed in detailed balance calculations, but one that may be an appropriate starting point for optically-thin absorbers such as quantum well and quantum dot solar cells [7]. The second curve assumes hemispherical emissions, as would characterize a photovoltaic device with a perfect back reflector ($n_t = 1$ and $n_b = 0$). The third curve assumes the emission profile from the front surface can be further restricted to better match the solar input ($n_t = \sin(\theta_e/2) = 0.087$), while the fourth curve assumes a perfect match of radiative emissions to the solar irradiation ($n_t = 0.0047$). As will be discussed in the next section, engineering the well profile in quantum well solar cell structures may provide a pathway to realize a restricted emission cell that might be incorporated into the bottom of a multi-junction device or as a stand-alone, more robust, and lower-cost single-junction device.

3 LOWER DARK CURRENT FACTOR

Some of the most efficient single-junction thin-film III-V cells reported to date have employed high performance back reflector structures [8-10]. Table I summarizes the performance of three specific GaAs-based single-junction solar cells with efficiencies greater than 26%. Open circuit voltages in excess of 1.10 V have been reported in high performance GaAs devices with antireflection (AR) coatings that both minimize non-radiative recombination and incorporate a high-quality back reflector structure. The back reflector effectively restricts the angular profile of the radiative emissions from the III-V cell, and enhances the voltage output of cells operating at or near the radiative limit. Dark current factors as low as ~ 25 have been achieved in the best devices reported to date.

Reference	J_{sc} (mA/cm^2)	V_{oc} (V)	FF (%)	Eff (%)	F_{dc} (est)
Radboud [8]	29.5	1.045	84.6	26.1	260
Alta [9]	29.6	1.107	84.1	27.6	24
NREL [10]	29.5	1.101	85.8	27.8	30

Table 1: Performance characteristics under AM1.5 illumination of three high-efficiency AR-coated GaAs solar cells incorporating back reflector structures.

Even higher open circuit voltages have been achieved in GaAs-based test structures with back reflectors which also employ a thin absorber layer [11-12]. Figure 2 compares the illuminated current-voltage performance characteristics

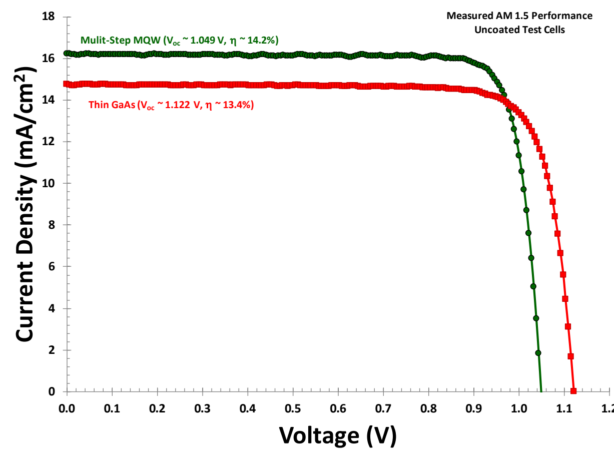

Figure 2: Comparison of the illuminated current-voltage characteristics from high-voltage, small area (0.25 cm^2), uncoated test cells fabricated via epitaxial liftoff from thin GaAs-based structures with and without multi-step multiple quantum well (MQW) structures.

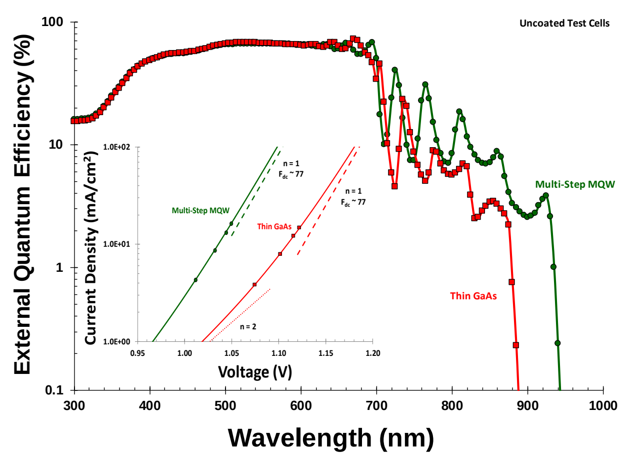

Figure 3: Comparison of the measured external quantum efficiency characteristics of thin GaAs-based structures with and without multi-step multiple quantum well (MQW) structures.

of prototype optically-thin GaAs-based cells with and without a multi-step quantum well absorber structure [11-12]. Under simulated AM1.5 illumination, small-area, uncoated test cells of the thin GaAs absorber structure exhibit an open circuit voltage (V_{oc}) of 1.122 V at a short circuit current density (J_{sc}) of 14.7 mA/cm^2 with a fill factor (FF) of 81.4%, resulting in a PV power conversion efficiency of 13.4%. The ultra-high operating voltage demonstrated here for a GaAs-based device has been achieved by reducing the underlying diode dark current, a result of employing advanced band gap engineering, reducing the GaAs absorber layer thickness, and including a back reflector structure which effectively restricts the radiative emission angle [11].

When InGaAs quantum wells are added to the depletion region, uncoated test cells exhibit a lower V_{oc} of 1.049 V but a higher J_{sc} of 16.2 mA/cm^2 and FF of 84.5%, resulting in an enhanced PV power conversion efficiency of 14.2% [12]. Comparison of the measured external quantum efficiency (EQE) spectrums from the high-voltage GaAs-based structures with and without multiple InGaAs quantum wells is shown in Figure 3 and is consistent with the observed increase in J_{sc}. The measured EQE shows extended infrared absorption beyond the GaAs band edge out to nearly 950 nm due to absorption in the InGaAs wells. The multiple quantum well structure also exhibits enhanced collection efficiency between 720 nm and 880 nm. Oscillations in the EQE are observed due to optical cavity effects, as the back reflector and top surface of the thin-film cell structure effectively define a Fabry–Pérot etalon.

The diode dark current of the optically-thin high-voltage structures, as inferred from measured J_{sc}-V_{oc} values at varying illumination intensity, is shown inset in Figure 3. Non-radiative recombination within the junction depletion region results in a dark current component with an n=2 voltage dependence that typically impacts the diode current of GaAs-based devices at lower bias. However, as the voltage approaches one-sun bias levels, the limiting n=1 component of the dark current emerges. Because these structures employ optically thin absorber layers, the simplified step-function absorption profile assumed in Equation (1) is not valid. However, the expected radiative dark current can still be calculated by employing the measured EQE and generalized detailed balanced concepts [12-13]. The dark current factor inferred from these calculations is on the order of 77 in both optically-thin devices.

4 PATHWAY TO HIGHER EFFICIENCY

To attain single-junction devices with efficiencies exceeding 30%, lower dark current factors will need to be achieved. Lower dark current factors can be realized by minimizing non-radiative recombination and further restricting the radiative emission angular profile. While back reflectors can restrict emissions out of the back of a photovoltaic device, a different approach will be required to restrict emissions out of the front surface of the device. Strained quantum well structures have been identified as one possible mechanism for restricting angular emissions [3,14]. In particular, a suppression in light-hole transitions results in an anisotropic emission pattern which can be beneficial for photovoltaic devices.

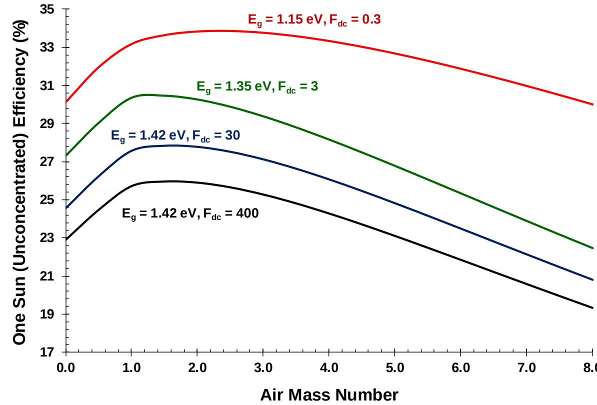

Figure 4: Plot of projected efficiency versus air mass spectrum, assuming four different combinations of energy-gap and dark current factors.

As previously reviewed [15], a growing body of evidence suggests that tailoring the compositional profile of InGaAs wells may effectively suppress radiative recombination even further. Several different mechanisms may potentially contribute to an effective reduction in the radiative recombination coefficient from step-graded wells, including enhanced restricted luminescent emissions. In any event, significant offsets between calculated and measured emission spectrums are observed in devices employing step-graded well profiles [16]. Step-graded InGaAs well structures thus provide a possible pathway to achieve lower dark current factors and higher efficiency performance.

Figure 4 illustrates how further device development and optimization can lead to single-junction cells with efficiencies exceeding 30% over a wide range of solar spectrums. These calculations assume a Bird–Riordan model of the air mass spectrums [17], 95% collection efficiency with a ~400 nm ultraviolet cutoff, and dark diode characteristics described using Equations (1) and (3). The lower two curves in Figure 4 project the efficiency of GaAs cells with two different dark current factors, similar to the devices summarized in Table I. The upper two curves in Figure 4 illustrate how the performance can be enhanced by lowering the energy gap (as with InGaAs wells) and further lowering the dark current factor (as with restricted angular emissions). Magnolia's ongoing research and development efforts are focused on enhancing photovoltaic efficiency along this pathway by combining advanced nanostructured absorber layers with structures that minimize non-radiative recombination and enhance incident light trapping.

5 CONCLUSION

Thin-film single-junction III-V devices can offer high efficiency and robust performance for a variety of energy harvesting applications at lower costs than multi-junction III-V devices typically used for space power. Moreover, single-junction III-V cells can potentially match or even exceed the peak efficiency performance levels of present day multi-junction devices by incorporating advanced structures that restrict the angular emission profile. As a starting point for the development of cost-effective, high-performance III-V energy-harvesting devices, we have demonstrated optically-thin GaAs-based cells with ultra-high voltage outputs. Such high-voltage thin-film devices can serve as a baseline cell for the incorporation of nano-enhanced absorber structures with a limiting conversion efficiency of greater than 40%.

ACKNOWLEDGEMENTS

The authors thank Dr. Jay Lewis of DARPA/MTO for technical discussions and guidance, as well as Ms. Susan Nicholas and Mr. Oscar Cerna of DARPA for their on-going support. This research was developed with funding from the Defense Advanced Research Projects Agency (DARPA). The views, opinions and/or findings expressed are those of the author and should not be interpreted as representing the official views or policies of the Department of Defense or the U.S. Government.

REFERENCES

[1] A. Luque. A. Marti, and C. Stanley, "Understanding Intermediate-Band Solar Cells," Nature Photonics, vol. 6, pp. 146-152 (February 2012).

[2] J. Rodiere, L. Lombez, A. Le Corree, O. Durand, and J,-F. Guillemoles, "Experimental Evidence of Hot Carriers Solar Cell Operation in Multi-Quantum Wells Heterostructures," Appl. Phys. Lett., vol. 106, no. 183901 (May 2015).

[3] J.G.J. Adams, W. Elder, P.N. Stavrinou, J.S. Roberts, M. Gonzalez, J.G. Tischler, R.J. Walters, J. Abell, I. Vurgaftman, J.R. Meyer, P. Jenkins, K.W.J. Barnham, and N.J. Ekins-Daukes, "Experimental Measurement of Restricted Radiative Emissions in Quantum Well Solar Cells," Proceedings of the 35th IEEE Photovoltaic Specialists Conference, pp. 1-5 (June 2010).

[4] 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).

[5] W. Shockley and H. J. Queisser, "Detailed Balance Limit of Efficiency of p-n Junction Solar Cells," Journal of Applied Physics, Volume 32, pp. 510-519 (March 1961).

[6] C.H. Henry, "Limiting Efficiencies of Single and Multiple Energy Gap Terrestrial Solar Cells," J. Appl. Phys., vol. 51, pp. 4494-4500 (August 1980).

[7] R. E. Welser, A. K. Sood, R. B. Laghumavarapu, D. L. Huffaker, D. M. Wilt, N. K. Dhar and K. A. Sablon, "The Physics of High-Efficiency Thin-Film III-V Solar Cells," Solar Cells - New Approaches and Reviews, L. A. Kosyachenko (Ed.), InTech, DOI: 10.5772/59283 (October 2015).

[8] G. J. Bauhuis, P. Mulder, E. J. Haverkamp, J. C. C. M. Huijben, and J. J. Schermer, "26.1% Thin-Film GaAs Solar Cell Using Epitaxial Liftoff," Solar Energy Materials & Solar Cells, vol. 93, pp. 1488-1491 (May 2009).

[9] B. M. Kayes, H. Nie, R. Twist, S. G. Spruytte, F. Reinhardt, I. C. Kizilyalli, and G. S. Higashi, "27.6% Conversion Efficiency, A New Record for Single-Junction Solar Cells Under 1 Sun Illumination," Proc. of the 37th IEEE Photovoltaic Specialists Conference, pp. 4-8 (June 2011).

[10] M. A. Steiner, J. F. Geisz, I. Garcia, D. J. Friedman, A. Duda and S. R. Kurtz, "Optical Enhancement of the Open-Circuit Voltage in High Quality GaAs Solar Cells," J. Appl. Phys., vol. 113, no. 123109 (March 2013).

[11] R. E. Welser, G. G. Pethuraja, J. W. Zeller, A. K. Sood, K. A. Sablon, S. R. Tatavarti, and N. K. Dhar, "High-Voltage Thin-Absorber Photovoltaic Device Structures for Efficient Energy Harvesting," Proc. of SPIE, vol. 9115, no. 91150F (May 2014).

[12] R. E. Welser, A. K. Sood, S. R. Tatavarti A. Wibowo, D. M. Wilt and A. Howard, "Radiative Dark Current in Optically-Thin III-V Photovoltaic Devices," Proc. of SPIE, vol. 9358, no. 93580Q (February 2015).

[13] U. Rau, "Reciprocity Relation Between Photovoltaic Quantum Efficiency and Electroluminescence Emission of Solar Cells," Phys. Rev. B, vol. 76, no. 085303 (August 2007).

[14] J. G. J. Adams, W. Elder, G. Hill, J. S. Roberts, K. W. J. Barnham and N. J. Ekins-Daukes, "Higher Limiting Efficiencies for Nanostructured Solar Cells," Proc. of SPIE, vol. 7597, no. 759705 (January 2010).

[15] R. E. Welser, A. K. Sood, J. S. Lewis, N. Dhar, P. Wijewarnasuriya, and R. L. Peters, "Development of III-V Quantum Well and Quantum Dot Solar Cells," International Journal of Engineering Research and Technology, vol. 9, pp. 29-44 (March 2016).

[16] R. E. Welser, A. K. Sood, N. K. Dhar, and P. S, Wijewarnasuriya, "Observation of Reciprocity between EQE and Radiative Luminescence in III-V Nanostructured Solar Cells," International Journal of Electronic and Electrical Engineering, vol. 9, pp. 11-19 (April 2017).

[17] http://rredc.nrel.gov/solar/models/spectral