Scientific Research Publishing

Journal of Materials Science and Chemical Engineering, 2017, 5, 54-60
http://www.scirp.org/journal/msce
ISSN Online: 2327-6053
ISSN Print: 2327-6045

Optimizing a Single-Absorption-Layer Thin-Film Solar Cell[1] Model to Achieve 31% Efficiency

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How to cite this paper: O'Connor, J.E. and Michael, S. (2017) Optimizing a Single-Absorption-Layer Thin-Film Solar Cell Model to Achieve 31% Efficiency. *Journal of Materials Science and Chemical Engineering*, **5**, 54-60.
http://dx.doi.org/10.4236/msce.2017.51008

Received: November 2, 2016
Accepted: January 1, 2017
Published: January 4, 2017

Abstract

This research builds upon the authors' previous work that introduced and modeled a novel Gallium-Arsenide, Emitter-less, Back-surface Alternating Contact (GaAs-EBAC) thin-film solar cell to achieve >30% power conversion efficiency. Key design parameters are optimized under an Air-Mass (AM) 1.5 spectrum to improve performance and approach the 33.5% theoretical efficiency limit. A second optimization is performed under an AM0 spectrum to examine the cell's potential for space applications. This research demonstrates the feasibility and potential of a new thin-film solar cell design for terrestrial and space applications. Results suggest that the straight-forward design may be an inexpensive alternative to multi-junction solar cells.

Keywords

Thin-Film, Solar Cell, Back-Contacts, Gallium-Arsenide, Modeling

1. Introduction

The renowned British mathematician George Box once quipped, "Essentially, all models are wrong, but some are useful" [1]. Generalizations, mathematical processes and other factors prevent models from perfectly representing solar cell behavior; however, simulation can be useful to investigate various design alternatives before a prototype is built. Our previous work [2] showed that *a high-level of confidence can be attained for a given model by carefully accounting for key design parameters, benchmarking model behavior to experimental results, and making single-variable adjustments to predict new behavior*.

At the time of this publication, power conversion efficiency η for a single-absorption-layer (*i.e.* single *p-n* junction) solar cell remains at 28.8%: well below

[1]Patents pending.

the ~33.5% theoretical limit [3] [4]. Since silicon cell η is restricted to approximately 26% due to intrinsic losses, research has focused mainly on direct bandgap, III-V compounds such as Gallium-Arsenide (GaAs) to approach theoretical efficiency. To this end, [5] [6] [7] demonstrate that strong internal and external luminescence promoted by good optical characteristics is important to high-efficiency (HE) operation for thin-film cells. Hence, improved optical performance has become a dominant theme for thin-film cell design as absorption layer thickness approaches sub-wavelength dimensions.

1.1. Previous Research

The authors' previous research [2] developed the novel structure shown in **Figure 1(a)** to simulate a HE GaAs cell from [4] [8] [9]. Though not a perfect representation, the model was useful for examining various design parameters. Extensive research was conducted to ensure that the simulation accurately reproduced experimental results before the GaAs Back-surface Alternating-Contact (GaAs-BAC) cell shown in **Figure 1(b)** was derived. All variables were held constant for

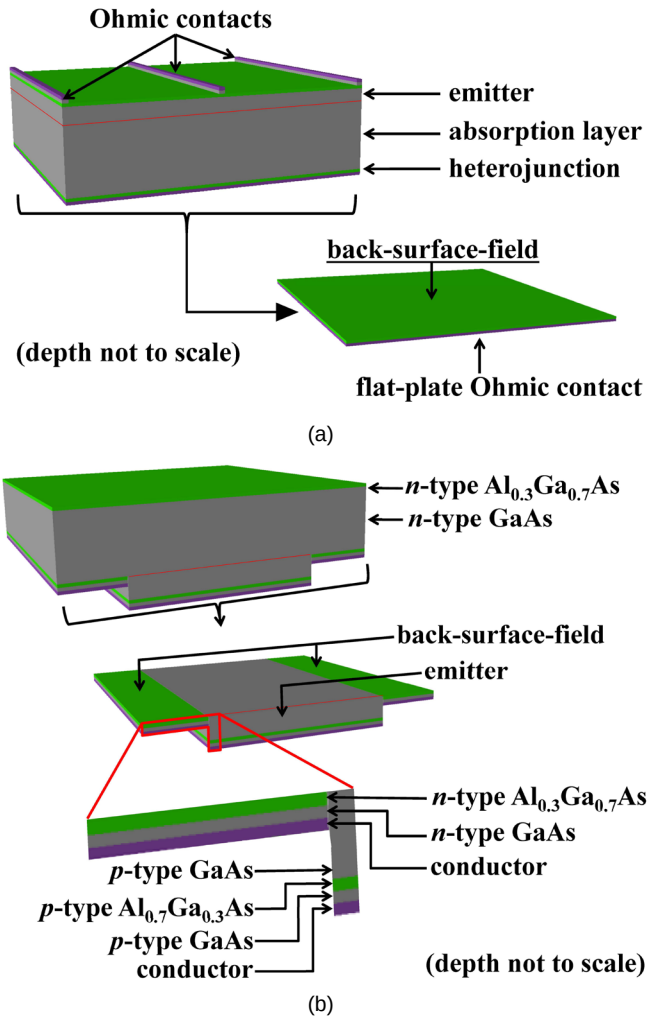

Figure 1. (a) 3D model of the HE GaAs cell from [4] [8] [9]. (b) 3D model of the GaAs-BAC cell from [2].

the new design while only the emitter and associates electrical contacts were moved to the back-surface. The small, but significant design change improved optical and electrical performance such that model η improved from 28.8% to 30.3%; open-circuit voltage V_{OC} improved from 1.12 V to 1.13 V; short-circuit current density J_{SC} improved from 29.7 mA/cm^2 to 30.1 mA/cm^2; and *FF* improved from 86.5% to 88.8%. To further improve cell η, the emitter was removed from the GaAs-BAC cell model to produce the novel design shown in **Figure 2(a)**. *FF* and η improved slightly to produce the output characteristics shown in **Figure 2(b)**.

1.2. Purpose and Approach

The purpose of this research is to optimize the thin-film GaAs-EBAC cell model from [2] in order to further approach theoretical η. We again utilize Silvaco® *ATLAS* software to alter design variables, predict electrical characteristics, and simulate the transport of charge carriers through the cell structure [10]. This research represents the final stage before prototype development.

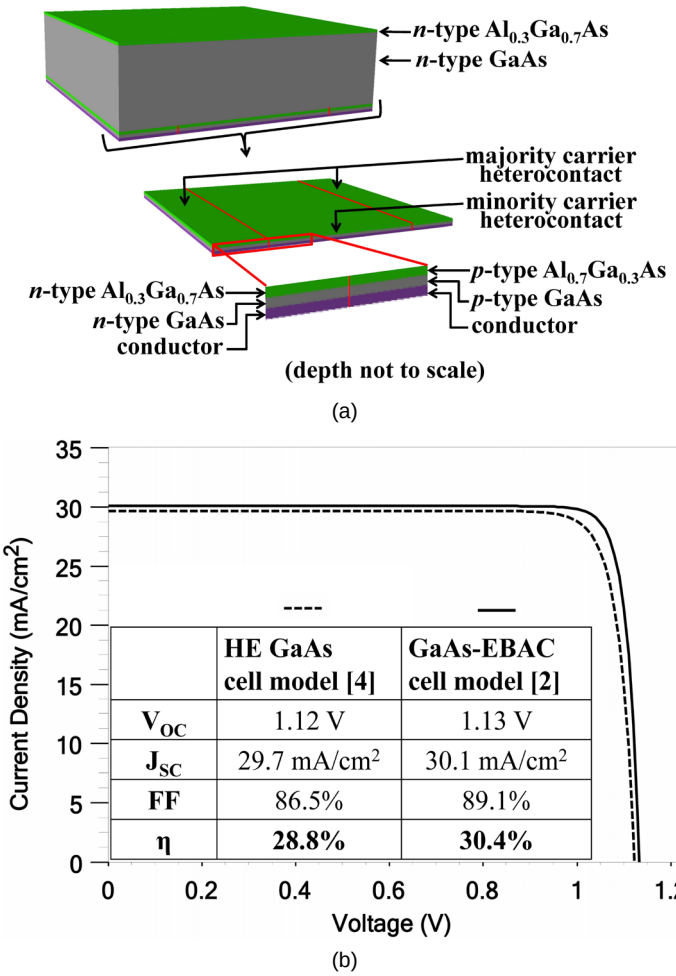

Figure 2. (a) 3D model of the GaAs-EBAC cell from [2]. (b) J-V curves and output parameters of the HE GaAs cell from [4] and the GaAs-EBAC cell from [2].

2. Optimizing the GaAs-EBAC Cell Model

In this section we examine the impact of back-surface reflectivity, absorption layer thickness and absorption layer doping concentration on cell η in order to optimize performance under Air-Mass 1.5 Global (AM1.5G) and AM0 solar spectrums.

2.1. Optimizing the GaAs-EBAC Cell for Terrestrial Application

GaAs-EBAC cell terrestrial performance is simulated at 300˚K under an AM1.5G solar spectrum. *Back-surface reflectivity*, *absorption layer thickness* and *absorption layer doping concentration* are varied to examine impacts on model performance and maximize η.

Reflectivity of the bottom contacts contributes directly to photon recycling, which contributes to a higher *effective* minority carrier lifetime [5] [6] [7] [8] [9]. Radiative recombination is modeled in *ATLAS* as

$$R_{rad} = B\left(np - n_i^2\right) = Bn_i^2\left[\exp\left(\frac{E_{F_n} - E_{F_p}}{kT}\right) - 1\right] \approx Bn_i^2 \exp\left(\frac{E_{F_n} - E_{F_p}}{kT}\right), \quad (1)$$

where B is the intrinsic radiative recombination coefficient, E_{Fn} - E_{Fp} is the energy difference between electron-hole-pair (EHP) quasi-Fermi levels, k is Boltzmann's constant, and T is the operating temperature. When reflectivity is varied from 90% to 99%, the model indicates a positive correlation with J_{SC} and V_{OC}, and no correlation with FF as shown in **Table 1**.

Absorption layer thickness contributes to EHP generation in the cell. Maximum thickness should not exceed minority carrier diffusion length in order to ensure carrier capture at the electrical contacts. Spectral generation rate g is defined as

Table 1. Design variable impact on GaAs-EBAC cell output parameters under AM1.5G at 300˚K.

Back-Surface Reflectivity (%)	**90***	**93**	**96**	**99**
V_{OC} (V)	1.13	1.13	1.14	1.15
J_{SC} (mA/cm^2)	30.1	30.2	30.2	30.38
FF (%)	89.1	89.1	89.1	89.1
η (%)	30.4	30.4	30.5	30.5
Absorption Layer Thickness (μm)	**1.0**	**1.2***	**1.4**	**1.6**
V_{OC} (V)	1.14	1.13	1.13	1.13
J_{SC} (mA/cm^2)	29.7	30.1	30.2	30.2
FF (%)	89.2	89.1	89.1	89.1
η (%)	30.2	30.4	30.4	30.3
Absorption Layer Doping (cm^{-3})	**2×10^{17}***	**5×10^{17}**	**8×10^{17}**	**2×10^{18}**
V_{OC} (V)	1.13	1.15	1.16	1.16
J_{SC} (mA/cm^2)	30.1	30.0	29.8	28.5
FF (%)	89.1	89.3	89.3	89.3
η (%)	30.4	30.7	30.8	30.1

*Baseline design parameter setting.

$$g(\lambda,d)=\left[1-R(\lambda)\right]\eta'\phi(\lambda)\alpha(\lambda)\exp\left[-\alpha(\lambda)d\right], \quad (2)$$

where R is the front-surface reflectivity, λ is the spectral wavelength, η' is the internal quantum efficiency, ϕ is the photon flux, d is the depth (thickness) of the cell and α is the absorption coefficient. When absorption layer thickness is varied from 1 μm to 1.6 μm, the model indicates a positive correlation with J_{SC} and a negative correlation with V_{OC} and FF as shown in **Table 1**.

Absorption layer doping is the intentional distribution of impurities within a semiconductor's crystal lattice to increase the density of majority carriers-either electrons or holes. Increased doping generally improves V_{OC} (*i.e.* the splitting of quasi-Fermi levels) in non-degenerately doped materials and negatively impacts-minority carrier mobility and lifetime; therefore, optimization is required. When doping is varied from 2×10^{17} cm^{-3} to 2×10^{18} cm^{-3}, the model indicates a positive correlation with V_{OC} and FF, and a negative correlation with J_{SC} as shown in **Table 1**.

Complex cell designs often require innovative methods (*i.e.* genetic algorithms, Monte-Carlo simulation, etc.) to optimize the design; however, the simplicity of the GaAs-EBAC cell model permits an iterative approach to achieve the best design variable combination and minimize the risk of converging on a local maximum. Optimization produces a maximum η of 31% when back-surface reflectivity ≈ 99%, absorption layer thickness ≈ 1.2 μm and doping concentration ≈ 8×10^{17} cm^{-3}. Decreasing back-surface reflectivity to a conservative value of 96% reduces η only slightly to 30.9%.

2.2. Optimizing the GaAs-EBAC Cell for Space Application

GaAs-EBAC cell space performance is simulated at 350˚K under an AM0 solar spectrum. The design is well-suited for space operation due to the intrinsic radiation hardness of GaAs [11]; the superior temperature coefficient of GaAs (as compared to silicon) [12] [13] [14]; the high packing density of the back-contact design (W/m^2) [15]; and the high power density (W/kg) of HE thin-film cells [16].

Design parameters from section 2.1 are varied again with results shown in **Table 2**. Optimization produces a maximum η of 25% when back-surface reflectivity ≈ 99%, absorption layer thickness ≈ 1.0 μm and doping concentration ≈ 8×10^{17} cm^{-3}. Decreasing back-surface reflectivity to 96% reduces η slightly to 24.9%. The lower η under the AM0 spectrum (compared to AM1.5G) is attributed to high temperature operation which has a negative impact on V_{OC}: approximately −1.4 mV/˚K [13]. A temperature coefficient adjustment was calculated for a HE triple-junction cell using the manufacturer's specification sheet [17], which yielded η of 26.8% at 350˚K under an AM0 spectrum. Thus, our model indicates that conceding just 1.8% η can dramatically reduce design complexity, which could improve system reliability and decrease manufacturing cost.

3. Conclusion and Future Work

In this work, parameters were optimized for a GaAs-EBAC cell model [2] in

Table 2. Design variable impact on GaAs-EBAC cell output parameters under AM0 at 350˚K.

Back-Surface Reflectivity (%)	**90***	**93**	**96**	**99**
V_{OC} (V)	1.07	1.07	1.07	1.07
J_{SC} (mA/cm^2)	35.6	35.6	35.7	35.7
FF (%)	87.3	87.3	87.3	87.3
η (%)	24.4	24.5	24.5	24.5
Absorption Layer Thickness (μm)	**1.0**	**1.2***	**1.4**	**1.6**
V_{OC} (V)	1.08	1.07	1.07	1.07
J_{SC} (mA/cm^2)	35.2	35.6	35.6	35.6
FF (%)	87.3	87.3	87.2	87.2
η (%)	24.3	24.4	24.4	24.3
Absorption Layer Doping (cm^{-3})	**2×10^{17}***	**5×10^{17}**	**8×10^{17}**	**2×10^{18}**
V_{OC} (V)	1.07	1.09	1.10	1.13
J_{SC} (mA/cm^2)	35.6	35.4	35.1	33.3
FF (%)	87.3	87.4	87.5	87.6
η (%)	24.4	24.7	24.8	24.1

*Baseline design parameter setting.

Silvaco® *ATLAS* which demonstrated the potential for a single-absorption-layer, thin-film cell to achieve 31% η at 300˚K under an AM1.5G terrestrial solar spectrum, and 25% η at 350˚K under an AM0 space solar spectrum.

Results suggest that the novel GaAs-EBAC cell design has record-setting potential for terrestrial applications and offers a good alternative to multi-junction cells for space applications. In fact, the model produced η within 1.8% of a leading HE triple-junction cell [17].

Future research will investigate the effects of random texturing on the front-and-back surfaces to exceed 98% photon internal reflection as absorption layer thickness is reduced to less than a spectral wavelength. Additionally, a prototype will be developed to experimentally verify the GaAs-EBAC cell design.

Patent applications have been filed for ideas presented in this paper [18] [19].

References

[1] Box, G. and Draper, N. (1986) Empirical Model-Building and Response Surface. John Wiley & Sons Ltd., New York.

[2] O'Connor, J. and Michael, S. (2016) A Novel, Single-Junction Solar Cell Design to Achieve Power Conversion Efficiency above 30 Percent. *Materials Sciences and Applications*, In Press.

[3] Shockley, W. and Queisser, H. (1961) Detailed Balance Limit of Efficiency of P-N Junction Solar Cells. *Journal of Applied Physics*, **32**, 510-520. https://doi.org/10.1063/1.1736034

[4] Green, M., Emery, K., Hishikawa, Y., Warta, W. and Dunlop, E. (2016) Solar Cell Efficiency Tables (Version 47). *Progress in Photovoltaics Research and Applications*, **24**, 3-11. https://doi.org/10.1002/pip.2728

[5] Yablonovich, E. (2011) The Optoelectronic Physics That Just Broke the Efficiency Record in Solar Cells.

[6] Miller, O., Yablonovich, E. and Kurtz, S. (2012) Strong Internal and External Luminescence as Solar Cells Approach the Shockley-Queisser Limit. *IEEE Journal of Photovoltaics*, **2**, 303-311. https://doi.org/10.1109/JPHOTOV.2012.2198434

[7] Miller, O. and Yablonovich, E. (2013) Photon Extraction, the Key Physics for Approaching Solar Cell Efficiency Limits. *Proceedings of SPIE Conference Optics + Photonics*, San Diego, 25-29 August 2013, 880807-1-880807-10.

[8] Kayes, B., *et al.* (2011) 27.6% Conversion Efficiency—A New Record for Single Junction Solar Cells under 1 Sun Illumination. *Proceedings of IEEE Photovoltaic Specialist Conference*, Seattle, 19-24 June 2011, 4-8. https://doi.org/10.1109/pvsc.2011.6185831

[9] Kayes, B., *et al.* (2012) Light Management in Single-Junction III-V Solar Cells. *SPIE Optics + Photonics Conference Plenary Presentation*, San Diego, 12-16 August.

[10] SILVACO® (2016) ATLAS™ User's Manual. https://dynamic.silvaco.com/dynamicweb/jsp/downloads/DownloadManualsAction.do?req=silentmanuals&nm=atlas

[11] Kems, S., *et al.* (1988) The Design of Radiation-Hardened ICs for Space: A Compendium of Approaches. *Proceedings of the IEEE*, **76**, 1470-1509. https://doi.org/10.1109/5.90115

[12] Singh, P. and Ravindra, N. (2012) Temperature Dependence of Solar Cell Performance—An Analysis. *Solar Energy Materials & Solar Cells*, **101**, 36-45. https://doi.org/10.1016/j.solmat.2012.02.019

[13] Silverman, T., *et al.* (2013) Outdoor Performance of a Thin-Film Gallium-Arsenide Photovoltaic Module. *Proceedings of the IEEE Photovoltaic Specialists Conference*, Tampa Bay, 16-21 June, 103-108. https://doi.org/10.1109/pvsc.2013.6744109

[14] O'Connor, J. and Michael, S. (2016) Impact of Operating Temperature and Absorption-Layer Thickness on All-Back-Contact Solar Cell Efficiency. *Proceedings of EU Photovoltaic Solar Energy Conference*, Munich, 20-24 June 2016, 983-986.

[15] Anthony, B., *et al.* (2016) Advanced Design and Manufacturing for Solar Arrays. *Space Photovoltaic Research and Technology Conference Plenary Presentation*, Cleveland, 20-22 September.

[16] O'Connor, J. and Michael, S. (2016) Design and Optimization of a Novel Back-Contact Solar Cell in Silvaco®. *Space Photovoltaic Research and Technology Conference Plenary Presentation*, Cleveland, 20-22 September.

[17] Spectrolab (2016) XTJ PRIME Specification Sheet. www.spectrolab.com/DataSheets/cells/XTJ_Prime_Data_Sheet_7-28-2016.pdf

[18] Michael, S. and O'Connor, J. (2016) GaAs Solar Cell with Back-Surface, Alternating-Contacts.US Patent Application 15/207, 128.

[19] O'Connor, J. and Michael, S. (2016) Emitter-Less, Back-Surface, Alternating-Contact Solar Cell. US Patent Application 15/282, 460.