Supporting Information

A Broadband Light-trapping Nanostructure for InGaP/GaAs Dual-junction Solar Cells Using Nanosphere Lithography-assisted Chemical Etching

Shang-Hsuan Wu[1], Gabriel Cossio[1,2], Daniel Derkacs[3], and Edward T. Yu[1,2]*
[1] Microelectronics Research Center, Chandra Family Department of Electrical and Computer Engineering, The University of Texas at Austin, Austin, Texas 78758, United States
[2]Center for Dynamics and Control of Materials, The University of Texas at Austin, Austin, Texas 78712, United States
[3]SolAero Technologies Inc., Albuquerque, NM 87123, United States

Email: ety@ece.utexas.edu

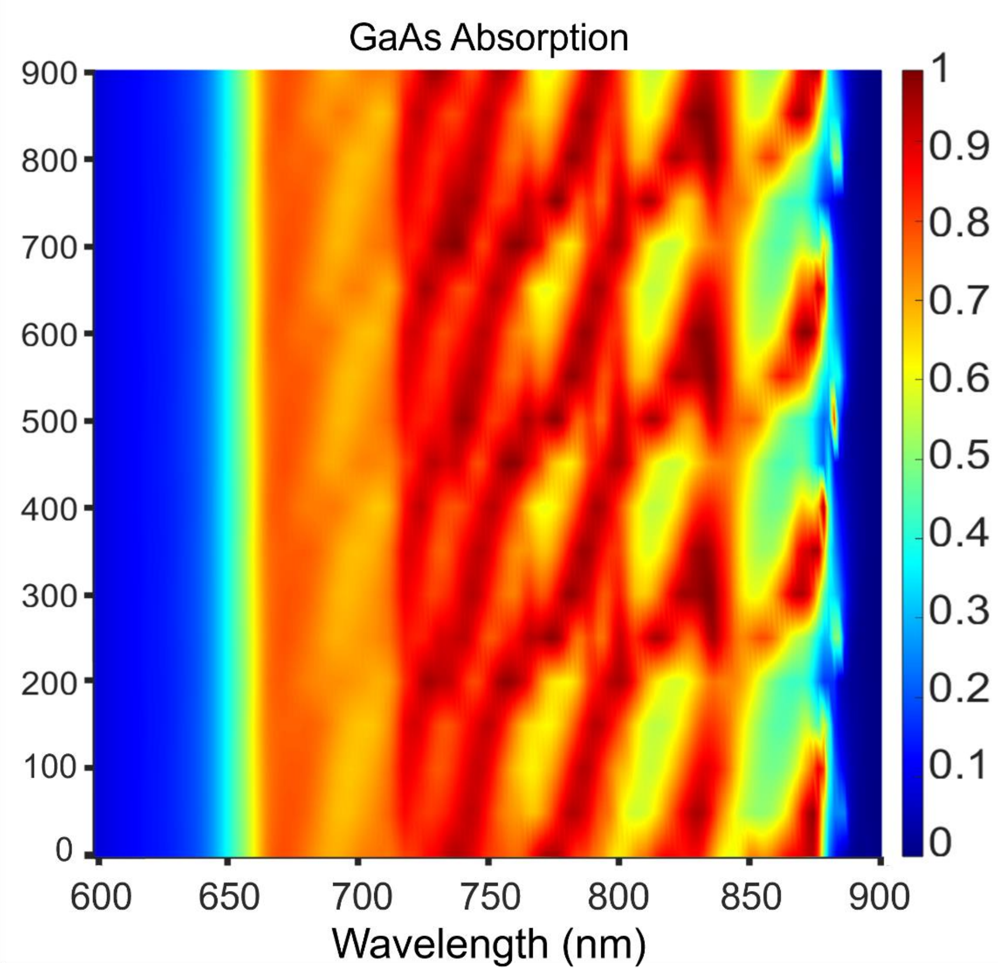

Figure S1. Effect of spacer thickness on optical absorption within GaAs layer when combined with grating structure (p = 500 nm, d = 250 nm, h = 100nm).

Supplementary Note 1. Choice of Dielectric Spacer Thickness

Figure S1 shows the change in absorption in the GaAs layer of the nanotextured device discussed in the main text as a function of the Al_2O_3 dielectric layer. The GaAs absorption spectrum shown in Figure S1 is for a device with p = 500nm, d = 250 nm, and h = 100nm, and the absorption spectrum is obtained from RCWA simulations. As may be expected, the simulated GaAs absorption spectrum appears periodic with respect to the Al_2O_3 dielectric thickness. This can be explained via vertical Fabry Perot resonances, where the constructive and destructive interference of electromagnetic field energy is partially reflected from the different semiconductor layers and the metallic back contact. Therefore, increasing the Al_2O_3 dielectric thickness causes the accumulation of phase differences between the electromagnetic fields, which appear to be periodic with integer multiples of ~ 250 nm changes in the dielectric thickness. An Al_2O_3 dielectric layer thickness of 350 nm was chosen near the first dielectric thickness, maximizing the GaAs absorption and satisfying various experimental and commercial manufacturing requirements.

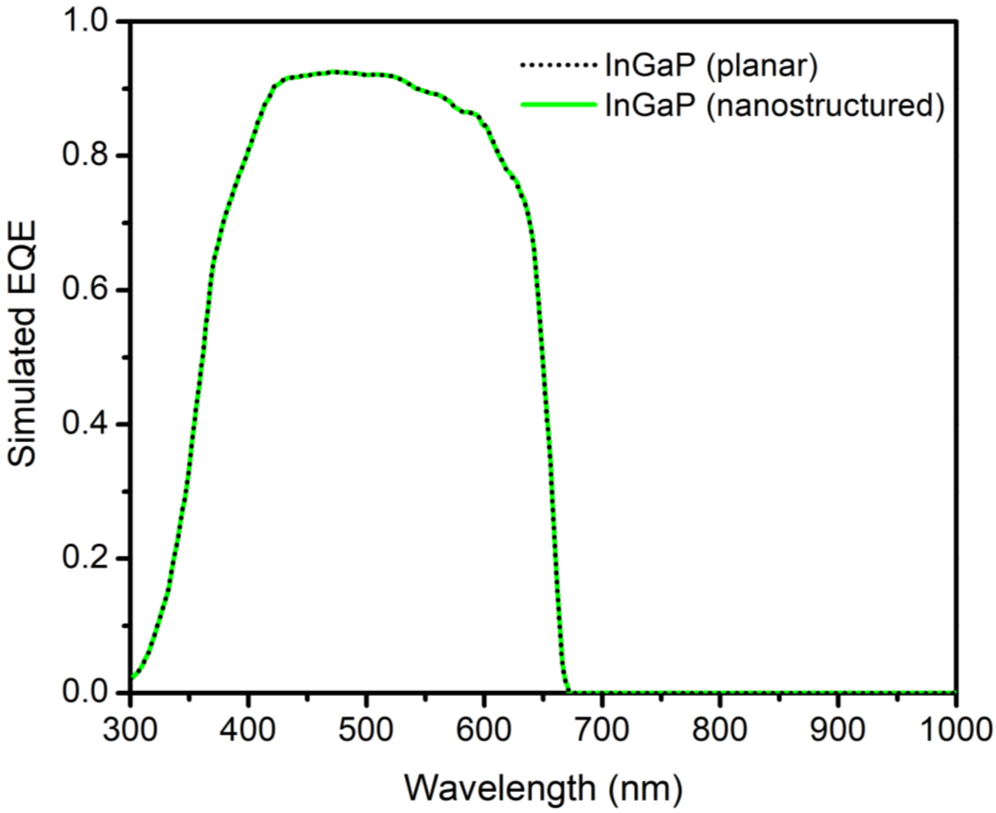

Figure S2. Simulated EQE spectra of InGaP layer for planar, and nanostructured device structures.

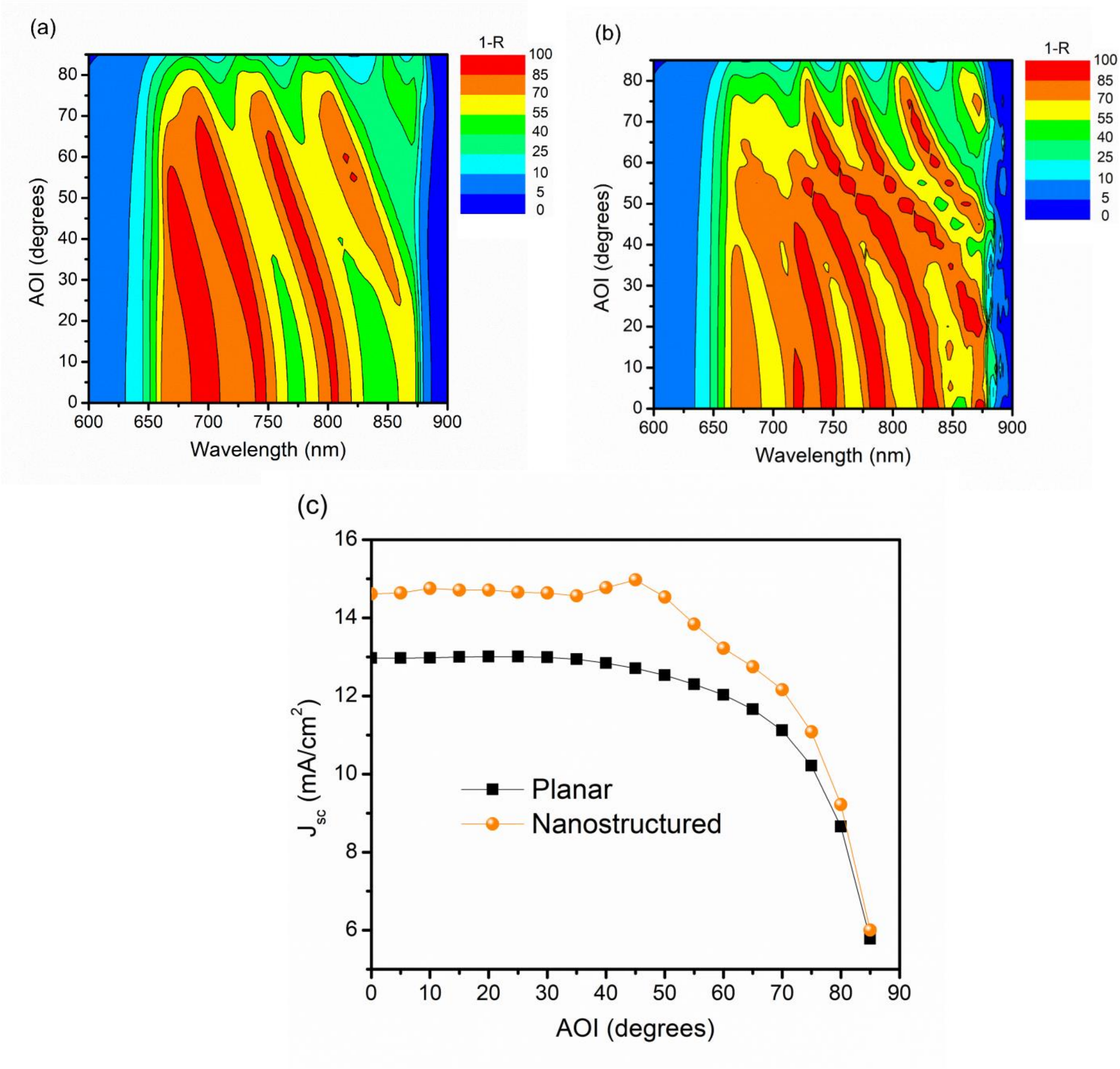

Figure S3. Simulated optical absorption (1 – R) in GaAs layer as a function of incident wavelength (600 – 900 nm) and angles of incidence (AOI, 0-85 degrees), with (a) planar device structure (no dielectric spacer, no grating structure). (b) Nanostructured device structure (p = 500nm, d = 250 nm, h = 100 nm, and t = 350 nm). (c) Simulated angle-dependent Jsc values of GaAs bottom cells with planar and nanostructured devices under AM 0 illumination.

Supplementary Note 2. Omnidirectional Current Enhancement

A main benefit of high-efficiency ultrathin film solar cells is their ability to conform to curved surfaces. Their flexible mechanical properties provide exciting opportunities for high-power and low-weight applications such as automobile-integrated solar, building-integrated solar, and UAV power generation. However, Fresnel reflection may ultimately limit the usefulness of solar cells on curved surfaces or in dynamic operating environments where the solar cells are constantly illuminated by oblique angles of incidence (AOI). A robust light trapping solution would thus additionally enable improved omnidirectional current generation. **Figure S3** shows that the light-trapping nanostructures presented in this work enable enhanced current generation at all angles of incidence. Interestingly, the photogenerated current is maximized at an AOI of 45^o, providing a 17.83% current enhancement relative to a traditional planar cell structure. The physical mechanism enabling the enhanced current at 45^o AOI is outside the scope of this research and may be further described in follow-up work.

Table S1. Device layer structure grown by metal-organic chemical vapor deposition (MOCVD).

Layer	Material	Bandgap (eV)	Thickness (nm)
Contact	p^{++}-GaAs	1.42	15
BSF	p^{+}-AlGaAs	1.76	500
Base	p-GaAs	1.42	500
Emitter	n-GaAs	1.42	
Window	n^{+}-InGaP	1.90	50
Tunnel diode	n^{++}-InGaP	1.90	9
Tunnel diode	p^{++}-AlGaAs	1.90	12
Filter	p-InGaP	1.90	600
Cap	p^{++}-GaAs	1.42	150
Etch stop	Undoped InGaP	1.90	500
GaAs substrate			

↑ Epitaxial direction

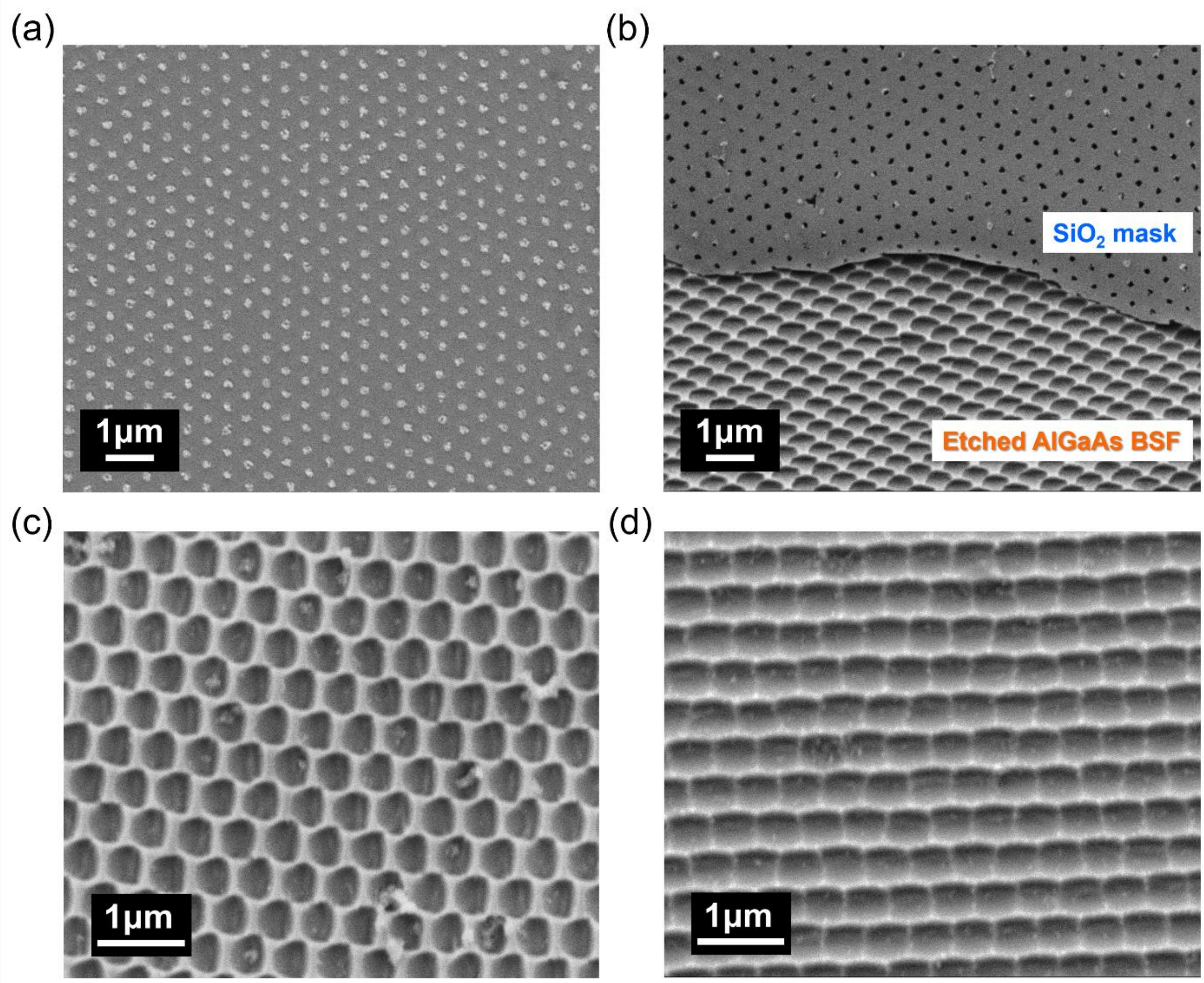

Figure S4. SEM images of (a) O_2 RIE etched polystyrene nanospheres, (b) interface between SiO_2 etch mask and wet etched AlGaAs BSF layer, (c) 2min, (d) 3min citric acid/H_2O_2 etched AlGaAs BSF layer.

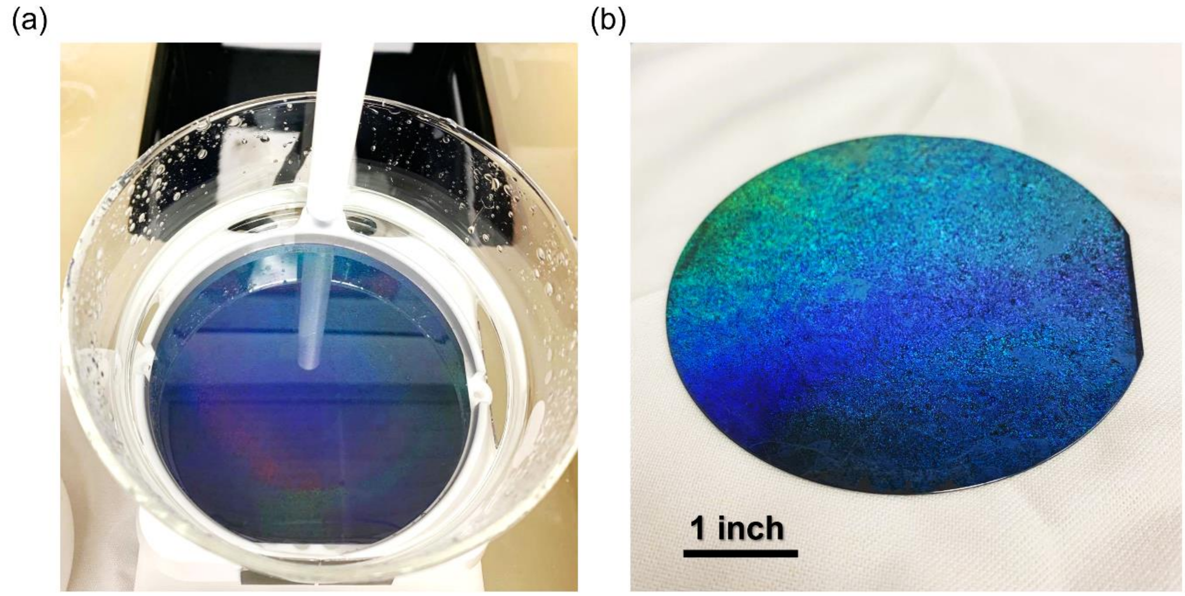

Figure S5. Photograph of (a) 4-inch InGaP/GaAs isotype wafer wet etched in citric acid/H_2O_2 solution. (b) Nanostructured AlGaAs BSF layer in InGaP/GaAs isotype wafer.

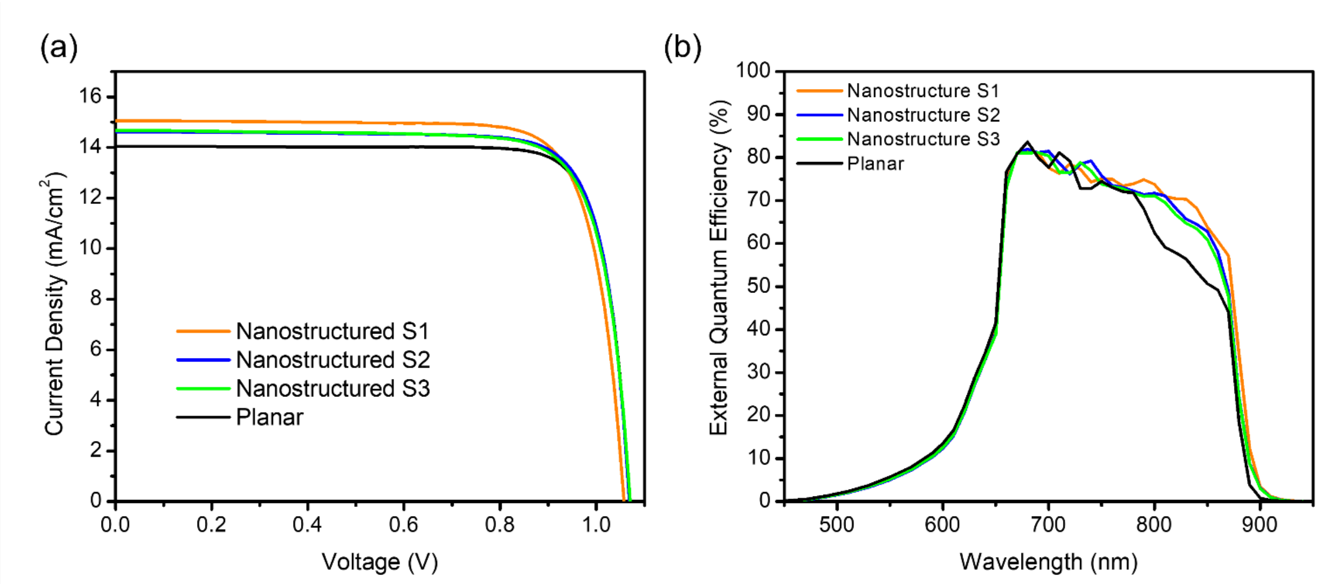

Figure S6. (a) J-V characteristics and (b) External quantum efficiency and specular reflectance spectra of planar and different nanostructured GaAs bottom cells under AM0 illumination.

Supplementary Note 3. Ideal Diode Electrical Model for Simulated J-V Curves

The ideal diode method[1] is used to compute the electrical properties of the device. The electrical characteristics of the device can be calculated from the absorption spectrum based on the basic quantities below:

The energy carried by one photon at a wavelength λ is:

$$E(\lambda) = hv = \frac{hc}{\lambda} \tag{1}$$

where h= 4.1357×10^{-15}[eV·s] is Planck's constant, c= 2.998$\times$ 10^{8} [m/s] is the speed of light, and λ [m] is the wavelength. Given an AM0 spectrum S(λ) [W/m^2·nm], the total number of photons incident at a wavelength λ is therefore:

$$n_s(\lambda) = \frac{S(\lambda)}{E(\lambda)} = \frac{\lambda}{hc}\, S(\lambda) \tag{2}$$

The absorption spectra $A(\lambda)$ of GaAs or InGaP absorber layers are computed by DiffractMOD simulation models. Given these spectra, the number of absorbed photons at a wavelength λ within each layer is:

$$n_i(\lambda) = \frac{S(\lambda)A(\lambda)}{E(\lambda)} = \frac{\lambda}{hc}\, S(\lambda)A(\lambda) \tag{3}$$

To account for losses due to recombination and other effects, it is necessary to define collection efficiency (η_i). For the GaAs and InGaP absorber layers, η_i is assumed to be 100%. Another efficiency (η_s) for the shadowing effect from the electrodes is defined as 100% (no shadow effect). The combined number of electron-hole pairs generated at a wavelength λ and collected by the electrodes is therefore:

$$n_{e-h}(\lambda) = \sum_i \eta_i \eta_s n_i(\lambda) = \frac{\lambda}{hc} \sum_i \eta_i \eta_s\, S(\lambda)A(\lambda) \tag{4}$$

The total number of electron-hole pairs collected by the electrodes is therefore:

$$N_{e-h} = \int n_{e-h}(\lambda)\, d\lambda \tag{5}$$

Given the parameters defined above, several electrical outputs can be computed:
The external quantum efficiency (EQE) is defined as:

$$EQE(\lambda) = \frac{n_{e-h}(\lambda)}{n_s(\lambda)} = \sum_i \eta_i\, A(\lambda) \tag{6}$$

The J-V curves can be computed based on the Schockley diode equation:

$$J_D = J_{S0}\left(e^{\frac{qV_D}{kT}} - 1\right) \tag{7}$$

where J_D is the diode current, J_{S0} is the reverse bias saturation current, q is the elementary charge, V_D is the voltage across the diode, k= 8.6173×10^{-5} [eV/K] is Boltzmann's constant, and T [K] is the absolute temperature.

The short-circuit current density can be computed as:

$$J_{SC} = qN_{e-h}\ [mA/cm^2] \tag{8}$$

The open-circuit voltage is:

$$V_{oc} = \frac{kT}{q} \ln\left(\frac{J_{SC}}{J_{S0}} + 1\right)\ [V] \tag{9}$$

The solar cell power conversion efficiency is defined as:

$$PCE = \frac{J_{SC} V_{oc} FF}{P_{in}} \times 100\% \tag{10}$$

where FF is the filling factor, which is defined ideally to 0.85, and P_{in} is the total incident light intensity ($136.61\ mW/cm^2$) under AM0 illumination and P_{in} is defined as:

$$P_{in} = \int S(\lambda) d\lambda \, [mW/cm^2] \tag{11}$$

Reference

[1] S. M. Sze, *SEMICONDUCTOR DEVICES: PHYSICS AND TECHNOLOGY, 2ND ED*, Wiley India Pvt. Limited, **2008**.