

INFLUENCE OF A VERY EFFICIENT BACK REFLECTOR ON THE QUANTUM EFFICIENCY OF SOLAR CELLS

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Very reflective back side reflectors directly below the active region of a solar cell alter the photon absorption and carrier collection dynamics in a manner that can be exploited for enhanced efficiency. The enlarged optical path increases the short circuit current, and the confinement and (re)absorption of the photoluminescence leads to a higher open circuit voltage through the photon recycling effect, which is critical in radiative limited solar cells. Furthermore, interesting features arise in the experimental external and internal quantum efficiencies (EQE and IQE) for solar cells with such reflective back side reflectors. This includes an increase in EQE magnitude compared to cells on absorptive substrates, and an extension of the IQE edge towards longer wavelengths. The former characteristic is due to an increased photon path length in the active region, which is a consequence of the high reflection occurring in the back side. The latter, however, is not a real feature of the interaction between the light and the solar cell materials, but a consequence of the way the IQE is defined and calculated. The resulting separation of the IQE and EQE near the bandedge of the solar cell thus questions the concurrent definitions for the IQE commonly referred to in the literature, which is clarified in this work. The influence of the definition of quantum efficiency in the material diffusion length extraction is also discussed.

Keywords: Photovoltaics, gallium arsenide, photon recycling, thin film III-V semiconductors, quantum efficiency.

1 INTRODUCTION

Radiative limited GaAs solar cells have shown great potential to exploit the photon recycling (PR) effect via the use of a back side reflector (BSR), which has been shown to enhance the overall power conversion efficiency compared to cells on their native substrates [1-5]. The open circuit voltage (V_{OC}) is the most influenced figure of merit due to the suppression of the radiative component of the dark current, and is expected to increase exponentially for increasing reflectivity through the effective use of PR [6].

Exploiting the PR effect requires the careful management of the light paths within the high quality crystalline device by confining the photoluminescence (PL) within the absorbing p - n junction for re-absorption. As the front interface to air has a small critical solid angle, the omnidirectional PL can be mostly confined through the formation of an optical cavity using a highly reflective BSR directly after the active region [6]. Furthermore, the incident sunlight path length through the cell nearly doubles as a result of the BSR, which allows for a reduction in material without significantly deteriorating the photocurrent, thus further enhancing the V_{OC} [7].

The growth of two identical solar cells, one on the native substrate and the other with a BSR directly below the active region after substrate removal, leads to measurable changes which can be observed primarily as 1) an increase in V_{OC} , due to exploitation of PR, and 2) an increase in short circuit current (J_{SC}), due to the enhanced sunlight optical path. These cells can then be compared to determine the influence of the BSR on the voltage and on the photocurrent, which can be deeply understood via the external quantum efficiency (EQE). The study on voltage has been performed previously [7-8], but a more thorough study is necessary to better understand the influence of the BSR on the external and internal quantum efficiencies. The EQE is defined as the

probability of extracting a photoexcited electron-hole pair per incident photon. The internal quantum efficiency (IQE), on the other hand, has two concurrent definitions in the literature. The first is the probability of extracting photoexcited electron-hole pairs per absorbed photon, and gauges the internal carrier dynamics, and hence, the material's quality [9-11]. The second definition involves all the photons entering the cell rather than the light absorbed in the cell [12-14]. The primary difference between these two definitions is where the light is absorbed, since the second definition assumes all light entering the cell is absorbed. Since the quantum efficiency curves play a key role in the extraction of important active material parameters of the solar cells via modeling, such as the minority carrier diffusion lengths and recombination velocities at the interfaces to the active region, it is important to determine which definition is correct for this kind of analysis.

The paper is outlined as follows. Section 2 summarizes the experimental methods used in preparing traditional GaAs solar cells, i.e., on their native substrate, and those removed from said substrates in order to define the BSR directly below the active region of the solar cell; the experimental measurement setups are also concisely described. Section 3 presents a detailed analysis of the influence of a BSR on the measured EQE and IQE of solar cells grown at Fraunhofer ISE. The differences in IQE results for these two types of solar cells can help clarify the definition of this quantity in literature. Finally, the role of the quantum efficiency curves in extracting material parameters such as diffusion lengths is discussed. Conclusions are given in Section 4.

2 EXPERIMENTAL METHODS

GaAs solar cell structures were grown by low (a) pressure Metal-Organic Vapor Phase Epitaxy (MOVPE) in a standard upright fashion on 4 inch (100) p -doped

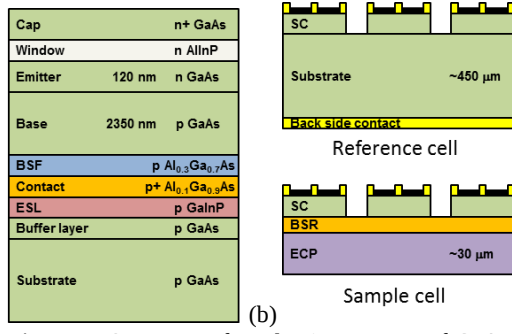


Figure 1: Summary of production process of GaAs solar cell samples. (a) MOVPE grown layers with materials and labels, and (b) design of devices on the original substrate (top) – reference cell – and as thin film with back reflector (bottom) after applied back surface technology – sample cell.

GaAs wafers with a 2° cutoff off [100] orientation. The structures consist nominally of an n+ doped GaAs cap layer, an n-doped AlInP window layer, a 120 nm n-doped GaAs emitter, a 2500 nm p-doped GaAs base, a p-doped Al_{0.3}Ga_{0.7}As back surface field (BSF), a p-doped Al_{0.1}Ga_{0.9}As contact layer, and a p-doped GaInP etch stop layer (ESL), as depicted in Figure 1a.

The solar cells under test were grown with the same structure and in the same epitaxial run. The reference cell, i.e., the cell kept on the original substrate, was produced under standard top-down photolithography technology, with Ohmic contacts and an MgF/TaO double layer anti-reflective coating (ARC), as shown in the top of Figure 1b. In order to produce the required light confinement for the exploitation of photon recycling, a metallic BSR with a normal incidence reflectivity of ~95% over a wide range of wavelengths was defined just below the active region in the sample cell. The metal deposition was done after the removal of the original substrate by a chemical etch step with NH₄OH:H₂O₂ = 5:1. The stabilization of the thin film was done using a thick (~30 μm) electroplated metal (ECP). The final shape and design of the cell is presented in the bottom of Figure 1b.

The EQE of the solar cells is measured under short circuit conditions using the differential spectral responsivity method [15]. The EQE is normalized to absolute values with the short circuit current from the light I-V characteristics obtained under AM1.5g at 25°C including a spectral mismatch correction. The front side total reflection was measured in a CARY 500i by collecting the monochromatic beam reflected by the sample using an integration sphere.

3 RESULTS AND DISCUSSIONS

3.1 Influence of BSR on the Figures of Merit of Solar Cells

Figure 2 presents the measured reflectivity – $R(\lambda)$ – and external quantum efficiency – $EQE(\lambda)$ – results for the solar cells processed on the original substrate and under the form of thin films (TFSC) with a BSR, referred hereafter as reference and sample cells, respectively. The measured short circuit current densities and open circuit voltages for these cells are summarized in Table I under standard measurement conditions of the AM1.5g spectrum (IEC 60904-3 with 1 kW/m²).

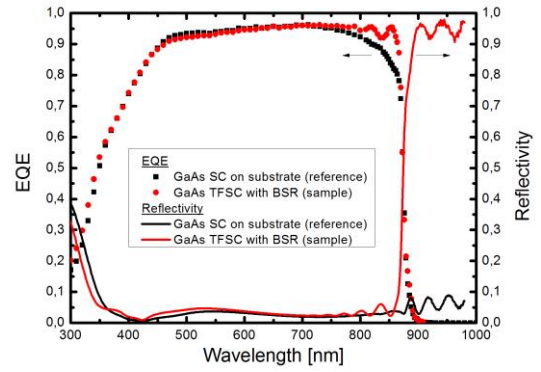


Figure 2: Spectral optical and optoelectronic characterization data for the solar cells treated in this work: EQE (left) and Reflectivity (right).

First, one can notice the effectiveness of the BSR applied to the sample cell in the reflection for wavelengths longer than the GaAs bandgap (870 nm), as demonstrated by the high reflectivity shown as red line in Fig. 2. On the other hand, the reference cell only reflects back 5 to 10% of the incoming light, therefore illustrating that the near-infrared wavelengths are absorbed by the substrate. Note that these wavelengths do not contribute to current (i.e. EQE does not increase) but instead lead to parasitical heating of the device.

TABLE I: FIGURES OF MERIT OF THE SOLAR CELLS

Sample	J_{sc} [mA/cm ²]	V_{oc} [V]
Cell on substrate (reference)	29.05	1.055
Thin film cell with BSR (sample)	29.38	1.074

The EQE of the sample cell (red circles) shows a corresponding increase for long wavelengths (760 – 870 nm) compared to the reference cell in Fig. 2. Overall, this results in an increased J_{sc} (see Table 1) of 1.1%. As the only difference between these cells is the BSR, we can conclude that this is due to the extended optical path of the incident light in the cells, resulting in more absorption and therefore carrier collection. The small differences observed in EQE for shorter wavelengths are due to differences in the reflectivity introduced by fluctuations in the ARC layer properties. These artifacts disappear when the IQE is calculated (see Fig. 3). Another fact worth commenting on is the increase of 1.8% in V_{oc} . This can be attributed to the photon recycling effect due to the formation of an optical cavity by the BSR, as detailed discussed elsewhere [7, 8].

In Fig. 3, the IQE of the solar cells is illustrated as black squares for the reference cell and red circles for the sample cell, where the IQE is computed using Equation 1

$$IQE(\lambda) = \frac{EQE(\lambda)}{1 - R(\lambda)} \quad (1)$$

One can notice two main differences: 1) an extension of the IQE towards longer wavelengths for the sample cell with BSR, and 2) an increase in magnitude close to the bandgap. At first glance, one may interpret this as the material quality of the solar cells being quite different, with the material of the reference cell on substrate being the worst due to the lower IQE. However, this is not a reasonable argument, since these cells were grown in the

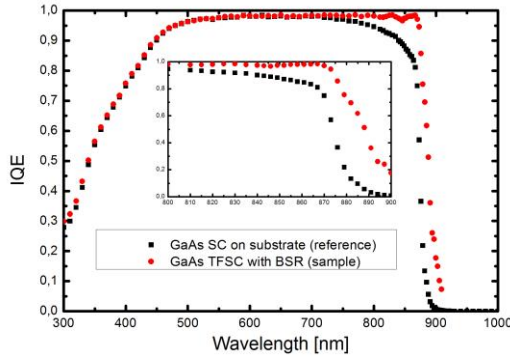


Figure 3: IQE experimental curves for the reference (black squares) and sample (red circles) cells as from Equation 1.

same epitaxial run. The materials should have the same properties. It is therefore worth investigating the definition of the IQE as given by equation (1).

3.2 Internal Quantum Efficiency for Solar Cells

The two concurrent definitions of the IQE involve the reflectivity $R(\lambda)$ and the absorptivity $A(\lambda)$. When IQE is calculated using equation 2a [9-11], one is probing the number of electron-hole pairs generated and collected in the form of electrical current for each photon absorbed inside the active region of a solar cell, and thus making use of the absorptivity. On the other hand, Equation 2b [12-14], same as Equation 1, which is the most common method, adopts the total light entering the cell, rather than the absorptivity.

$$IQE_{abs}(\lambda) = \frac{EQE(\lambda)}{A(\lambda)} = \frac{EQE(\lambda)}{1 - T(\lambda) - R(\lambda)} \quad (2a)$$

$$IQE_{trans}(\lambda) = \frac{EQE(\lambda)}{T_{in}(\lambda)} = \frac{EQE(\lambda)}{1 - R(\lambda)} \quad (2b)$$

For a solar cell on a thick absorptive substrate, the transmitted light $T(\lambda)$ through the whole structure of the device is practically negligible ($T \approx 0$). This results in $A(\lambda)$ being equivalent as $T_{in}(\lambda)$, and thus both definitions (equations 2a and 2b) lead to identical results. However, the concepts are not generally identical because the latter definition assumes that all light entering the cell is absorbed, but it does not matter where this light is absorbed (active region vs. substrate). For a cell on substrate, complete absorption occurs exclusively in the active region of the device if and only if the substrate is part of the active region, which is the case in silicon devices for example. However, in highly absorptive materials such as direct bandgap semiconductors, absorption in the substrate is typically a source of loss, and therefore does not contribute to the photocurrent. In such a case, there could be a significant difference in the IQE computed using both definitions for the most transparent photons (i.e. with energy close to the bandgap) if the active region transmits a non-negligible quantity to the substrate. In such a case, the fraction of photons parasitically absorbed in the substrate would result in an artificially reduced IQE according to equation 2b, since the transmission into the cell, $T_{in}(\lambda)$, would be larger than the absorption solely in the active region $A(\lambda)$. The definition according to equation 2b would thus not reflect the material quality of solely the active region

but instead the combined quality of the active region and the substrate. If one could extract the absorptivity solely in the active region, which is extremely difficult in practice for a GaAs solar cell on substrate, then equation 2a would more accurately reveal the behavior of the active region without losses to the substrate. The absorptivity in the active region can be extracted via optical modeling such as with the transfer matrix method (TMM) [16, 17]. Thus, one could extract more realistic material parameters for the active region by fitting the IQE to a theoretical model (discussed in section 3.3).

Another way of accessing the two different definitions expressed in equations 2 is via the experimental reflectivities. For a solar cell with an ideal BSR, the measured reflectivity (R_R) gives insight into the absorptivity of the active region. Equation 3a expresses this mathematically. For cells on an ideal absorptive substrate, the quantity $(1 - R_A)$, where R_A is the reflection of such cells, yields the portion T_{in} of the light entering the front side (Equation 3b).

$$A(\lambda) \approx 1 - R_R(\lambda) \quad (3a)$$

$$T_{in}(\lambda) = 1 - R_A(\lambda) \quad (3b)$$

In other words, it is possible to obtain the IQE described by equation 2a for devices with the same active region design, whether on absorptive or reflective substrates, using the experimental reflectivities or using modeling.

Thus, one way of consolidating these definitions of IQE is by modeling the optical properties of the solar cell and accounting for them in equations 2. Figure 4a shows the IQE using equation 1 with the experimental reflectivity for the reference cell on substrate and the sample cell with the BSR. By extracting solely the active region absorption using the TMM, the IQE can be computed for the reference cell using equation 2a. The black solid line demonstrates that the IQE for both reference and sample cells has increased in the wavelength range close to the bandedge. This improved agreement outlines that transmission through the active region is not negligible, which is quite clear from the thickness of the active region (2.47 μm). Taking into account this transmission by accounting for the relative absorption results in the same IQE, which is expected based on similar material quality. Note that the base thickness had to be enlarged to 2.8 μm to the curve fit better the experimental points. To avoid regions of negligible absorption where Equation 2a surpasses unity, the EQE is forced to go to zero for values less than 1×10^{-3} . The agreement between such theoretical manipulation to obtain IQE_{abs} for the reference cell (black solid line in Figure 4a) and the experimental points for the sample cell (red circles) corroborates our point of view. Once more, we emphasize that the increase in intensity and the extension of the IQE curve towards long wavelengths is not a real physical fact but a matter of definition.

To further demonstrate the consolidation of IQE definitions, the IQE_{abs} and IQE_{trans} is computed for both cells using equations 3(a) and 3(b), i.e. the absorptivity of the active region and the transmission into the cell respectively. The results are shown in Figure 4b, where the experimental reflectivities are used to go from one IQE definition to the other for each cell. By using the reflectivity of the sample cell to calculate IQE for the reference cell (black dashed line), the curve shows the expected extension in the long wavelength. The opposite

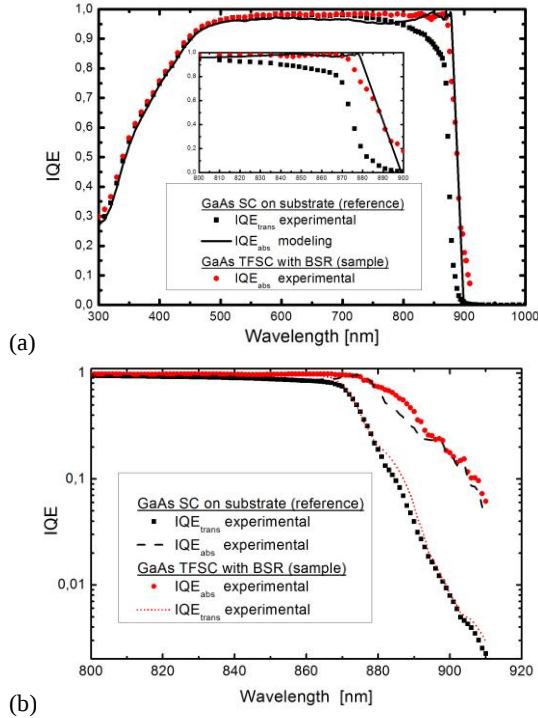


Figure 4: Illustration of ways to access the two definitions of IQE. The points are a representation of IQE obtained experimentally by the standard equation 1 (black squares represents IQE_{trans} for the reference cell and red circles represents IQE_{abs} for the sample cell). In (a), we used simulated optical properties to obtain IQE_{abs} for the reference cell (black solid line). In (b), we used the reflectivity of the solar cells to obtain IQE_{abs} for the reference cell (black dashed line) and IQE_{trans} for the sample cell (red dotted line).

method involves using the reflectivity of the reference cell to calculate the IQE for the sample cell (red dotted line), which shows the long wavelength region of the curve at the same level of the original IQE of the reference cell.

3.3 Modeling of the Quantum Efficiency to Extract of Material Diffusion Lengths

Theoretically, the QE of a solar cell depends on the active region's response to the incident light of wavelength λ , and can be separated into the contributions from the emitter, depletion region and base according to Equation 5:

$$QE(\lambda) = QE_{emitter}(\lambda) + QE_{depl}(\lambda) + QE_{base}(\lambda) \quad (5)$$

The individual contributions of each component of Equation 5 can be described by the Hovel model [12]. Each contribution is a function of important material and structural parameters, such as the minority carrier diffusion lengths (L), the active layers thicknesses (x), the minority carrier mobility (μ), and surface recombination velocities at interfaces to the active region (S). In a recent paper, Lumb *et al.* extended the model for solar cells subject to different boundary conditions at the back side such as coherent and incoherent reflections arising from a BSR [18].

Figure 5 illustrates the models defined in Ref. 18 fitted to the experimental EQE of the reference and sample solar cells from this work, assuming the same

hole and electron diffusion lengths. In the long wavelength range, a very good agreement is obtained between experimental data and the model for both cells. Due to the high agreement, the material properties of the two cells are nearly the same, as could be expected from cells originating in the same epitaxial run. This shows that the EQE can be used to properly extract the base diffusion length, since the electron diffusion length is extracted to be the same for the two different solar cells. Furthermore, this demonstrates that the IQE of the two cells should also be similar, if one interprets the IQE as gauging the material quality of the active region. If the IQE were used to extract material properties by the use of equation 1 in comparison to the modeling, then equation 2b should also be used rather than equation 2a. Otherwise, significant differences in diffusion lengths could be extracted from the modeling.

The short wavelength range of the simulations has a larger discrepancy between experiment and model due to the unknown contribution from the window layer. The models take into account the proper boundary conditions for each cell. For the reference cell, we applied the equations of the model with no reflection at the back side. For the sample cell, a weighted average between the results from the models with coherent (20%) and incoherent (80%) reflection at the back side led to the best fit. The remaining set of material parameters is shown in Table II, with mobilities from IOFFE database. Once more, a larger base thickness of 2800 nm had to be used. The reason for the overestimation of the base thickness can be the underestimation of the absorption coefficient in the modeling.

TABLE II: SET OF MATERIAL PARAMETERS USED IN FITTING EQE

Parameter	Value
Hole diffusion length (μm)	0.9
Electron diffusion length (μm)	5
Front side surface rec. velocity (cm/s)	1000
Back side surface rec. velocity (cm/s)	1
Hole mobility ($cm^2 V^{-1} s^{-1}$)	270
Electron mobility ($cm^2 V^{-1} s^{-1}$)	2500

4 CONCLUSIONS

With very reflective BSR applied directly below the active region of high quality crystalline thin film GaAs solar cells, a higher J_{SC} and V_{OC} was demonstrated when compared to a reference cell on its native substrate. The increased photocurrent is achieved by the enhanced path length within the solar cell, observed experimentally by an increase of up to 14.6% in EQE near the bandgap of GaAs. The reported increased V_{OC} is due to the exploitation of the photon recycling effect.

The IQE of the sample cell with BSR demonstrates an increase in magnitude and an extension to long wavelengths compared to the reference cell on substrate. This is not expected for solar cells with identical material quality and structures originating from the same epitaxial run. By modeling the devices optically, these differences are shown to be matter of the definition used to calculate IQE rather than physical artifacts. In order for the IQE to gauge the material quality of the active region without losses from the substrate, the definition of the IQE requires the absorptivity from the active region, which can be accessed via optical modeling. The extraction of

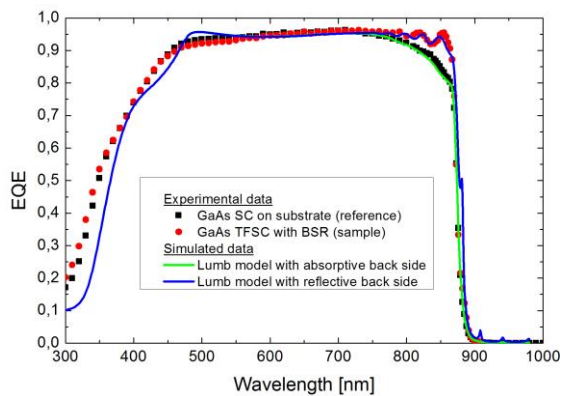


Figure 5: Modeled EQE using the model from Lumb showing a good agreement with the experimental data of the solar cells studied in this work. The same diffusion length was adopted in modeling both cells.

minority carrier diffusion lengths could be influenced by the definition of the IQE. To avoid this problem, the EQE is recommended to be used according to the proper boundary condition of the solar cell, as in the models developed by Lumb *et al.*

5 ACKNOWLEDGEMENTS

This research was supported by ESA through the project "Optimisation of Photon Density in Ultra-Thin GaAs Solar Cells" (ESTEC/Contract no 4000104852). The authors would like to thank the entire Fraunhofer ISE III-V group. Daniel Micha was partially supported by INCT-DISSE/CNPq/Brazil under the program "Ciência sem Fronteiras".

6 REFERENCES

- [1] G. J. Bauhuis, "26.1 % thin film GaAs solar cell using epitaxial lift-off," *Solar Energy Materials and Solar Cells*, vol. 93, pp. 1488-1491, 2009.
- [2] X. Wang, "Design of GaAs Solar Cells Operating Close to the Shockley-Queisser Limit," *IEEE Journal of Photovoltaics*, vol. 3, no. 2, 2013.
- [3] 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," *Proceedings of 37th IEEE Photovoltaic Specialist Conference*, 2011.
- [4] M. A. Steiner, "Optical Enhancement of the Open Circuit Voltage in High Quality GaAs Solar Cells," *Journal of Applied Physics*, vol. 113, p. 123109, 2013.
- [5] M.-. C. Tseng, "Fabrication and Characterization of GaAs Solar Cells on Copper Substrates," *IEEE Electron Device Letters*, vol. 30, pp. 940-942, 2009.
- [6] O. D. Miller, E. Yablonovitch and S. Kurtz, "Strong Internal and External Luminescence as Solar Cells Approach the Shockley-Queisser Limit," *IEEE Journal of Photovoltaics*, vol. 2, no. 3, pp. 303-311, 2012.
- [7] A. W. Walker, O. Höhn, D. N. Micha, L. Wagner, H. Helmers, A. W. Bett, F. Dimroth, "Impact of photon recycling and luminescence coupling on III-V single and dual junction photovoltaic devices," *Journal of Photonics for Energy* 5(1), p. 053087-1 – 053087-11, 2015.
- [8] A. W. Walker, O. Höhn, D. N. Micha, B. Blaesi, A. W. Bett and F. Dimroth, "Impact of Photon Recycling on GaAs Solar Cell Designs," *IEEE Journal of Photovoltaics*, vol. 5, no. 6, pp. 1636-1645, 2015.

- [9] U. Rau, D. Abou-Ras and T. Kirchartz, *Advances characterization techniques for thin film solar cells*, John Wiley & Sons, 2011.
- [10] B. Liu, R. Q. Png, L. H. Zhao, L. L. Chua and R. H. Friend, "High internal quantum efficiency in fullerene solar cells based on crosslinked polymer donor networks," *Nature Communications*, vol. 3, p. 1321, 2012.
- [11] W. J. Yang, "Internal quantum efficiency for solar cells," *Solar Energy*, vol. 82, pp. 106-110, 2008.
- [12] H. J. Hovel, *Semiconductors and Semimetals*, Vol. 11: Solar Cells, New York: Academic Press, 1975.
- [13] M. Law, M. C. Beard and S. Choi, "Determining the Internal Quantum Efficiency of PbSe Nanocrystal Solar Cells with the Aid of an Optical Model," *Nano Letters*, vol. 8, no. 11, pp. 3904-3910, 2008.
- [14] R. Brendel, M. Hirsch, R. Plüeninger and J. H. Werner, "Quantum Efficiency Analysis of Thin-Layer Silicon Solar Cells with Back Surface Fields and Optical Confinement," *IEEE Transactions on Electron Devices*, vol. 43, no. 7, pp. 1104-1113, 1996.
- [15] J. Metzendorf, "Calibration of solar cells. 1: The Differential Spectral Responsivity Method," *Applied Optics*, vol. 26, no. 9, pp. 1701-1708, 1987.
- [16] Emanuele Centurioni, Generalized matrix method for calculation of internal light energy flux in mixed coherent and incoherent multilayers. *Applied Optics*, 44(35), 7532-7539, 2005.
- [17] Charalambos C. Katsidis and Dimitrios I. Siapkas, General transfer-matrix method for optical multilayer systems with coherent, partially coherent, and incoherent interference. *Applied Optics*, 41(19), 3978-3987, 2002.
- [18] M. P. Lumb, C. G. Bailey, J. G. J. Adams, G. Hillier, F. Tuminello, V. C. Elarde and R. J. Walters, "Extending the 1-D Hovel Model for Coherent and Incoherent Back Reflections in Homojunction Solar Cells," *IEEE Journal of Quantum Electronics*, vol. 49, no. 5, pp. 462-470, 2013.