Collection Efficiency at Near-Bandgap Wavelengths in Actual Si Solar Cells

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Abstract. An expression for collection efficiency in actual Si solar cells is derived from the expression of Basore for inverse quantum efficiency vs. absorption depth at near-bandgap wavelengths. In the new expression, only internal rear-surface reflectance is an adjustable parameter. The new expression is used in reported actual Si solar cells, where it is compared to different approaches to evaluate collection efficiency including the linear fitting to inverse internal quantum efficiency versus absorption depth. This allows showing experimentally that these approaches are more liable to errors than the proposed expression for collection efficiency.

INTRODUCTION

Basore proposed the use of two different wavelength, λ, ranges for the analysis of data of quantum efficiency, *IQE*, of solar cells [1,2]. The first "conventional" λ-range is in the near infrared (800 nm<λ<1000 nm for Si cells), where the absorption length, α^{-1}, with α being the absorption coefficient, is short compared to $W/\cos\theta_1$ with W being the thickness of the base of the solar cell and θ_1 the optical path angle with respect to the cell's normal vector at the first pass of light across the cell ($\alpha^{-1}<<W/\cos\theta_1$). The second "extended" λ-range is at near-bandgap regime, where $\alpha^{-1}>>W/\cos\theta$ with θ being an average optical path angle [1–3]. In the aforementioned near infrared range, a linear fit to data of IQE^{-1} vs. α^{-1} can be performed by adjusting an effective diffusion length, L_{eff}, which contains the bulk diffusion length, L, and the back surface recombination velocity, S [1,2]. In the extended λ-range, a linear fit to data of IQE^{-1} vs. α^{-1} can be performed again by adjusting collection efficiency, η_c, rear-surface internal reflectance, R_B, and θ [1–3].

According to Basore, the near-bandgap λ-range is approximately 1080 nm to 1120 nm [2]. At longer λ-values the absorption coefficient is too uncertain, being affected by free-carrier absorption and temperature-induced variation in the bandgap. At shorter λ-values the absorption is not spatially uniform [2]. According to Basore, spatially uniform absorption only takes place after that light completes the first round-trip of the cell thickness [1], that is to say when $\theta=\theta_n$, which is the average path angle at third optical pass [2]. Consequently, in the near-bandgap λ-range, one can assign $\theta=\theta_n$. In addition, Basore assumes that trapped photons, which survive the first round-trip of the cell thickness, are reflected back into the cell with a random orientation [1]. It follows that $\theta=\theta_n=60°$.

The two aforementioned λ-ranges were proposed to exploit η_c and L_{eff} in order to assess L and S [1,2]. This approach has been argued in [4,5]. The fitting of IQE^{-1} vs. α^{-1} in the near-bandgap λ-range is still used to evaluate the parameters in the Basore expression for optical path length factor for near-bandgap wavelengths, Z_0, and, hence, assess light-trapping effectiveness [2,3]. The fit of IQE^{-1} vs. α^{-1} is performed with the expression for IQE^{-1} vs. α^{-1} at near-bandgap wavelengths of Basore [2,3]. In the present work, we use this expression to obtain directly an expression for η_c. Due to the aforementioned fact that $\theta=\theta_n=60°$, in this expression, only R_B is an adjustable parameter. We show that R_B can be adjusted so that the resulting η_c-curve can be fitted by a constant η_c-value in the near-bandgap λ-range (1080 nm to 1120 nm), as expected if absorption is uniform [2,3]. We calculate η_c-curves in

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two reported cells [6,7], where η_c was determined with different approaches, one of which is the fitting of data of IQE^{-1} vs. α^{-1} [7]. Results are discussed.

DERIVATION

The Basore expression for IQE^{-1} vs. α^{-1} at near-bandgap wavelengths is [2,3]

$$\frac{1}{IQE} = \frac{1}{W_{IQE}} \frac{1}{\alpha} + \frac{1}{\eta'_c} \tag{1}$$

where

$$W_{IQE} = \frac{w\eta_c(1+R_B)}{\cos\theta_n(1-R_B)} \tag{2}$$

and

$$\eta'_c = \eta_c \frac{(1+R_B)^2}{R_B(3+R_B)} \tag{3}$$

From (1) we obtain

$$\eta_c = IQE\left[\frac{\cos\theta_n(1-R_B)}{\alpha w(1+R_B)} + \frac{R_B(3+R_B)}{(1+R_B)^2}\right] \tag{4}$$

where, as inferred in the previous section, θ_n=60°.

APPLICATION AND DISCUSSION

We have calculated η_c-curves with (4) in two reported Si solar cells, cell A [6] and cell B [7]. Cell A is a 170 μm-thick $n^+/p/p^+$ PERC solar cell fabricated on mc-Si [6]. Cell B is a 180 μm-thick $p^+/n/n^+$ PERT solar cell fabricated on CZ-Si [7]. In both [6] and [7], η_c was evaluated by considering θ_n as an adjustable parameter. In [6], an η_c-curve was derived from (2), which only allows evaluating η_c at 1200 nm. At assignments to R_B and θ_n extracted from a fit to reflectance data, this η_c-curve gives η_c=0.65 at λ=1200 nm. In [7], a constant η_c-value was obtained according to [3] from fitting with (1) data of IQE^{-1} vs. α^{-1}.

Concerning cell A, we have calculated after [6] the η_c-curve shown in Fig. 1 with dotted line. An η_c-curve was then calculated with (4) at same values for R_B and θ_n as assigned in [6] (black dashed line in Fig. 1). As can be seen, both curves cannot be fitted at near-bandgap wavelengths by a constant η_c-value, as expected at uniform absorption. This shows that the approach in [6] is liable to be physically inconsistent. An η_c-curve (red short-dashed line) was calculated with (4) at same assignment for θ_n and a lower R_B-value. As can be seen, this η_c-curve is correct because can be fitted at near-bandgap wavelengths by a constant η_c-value. This value is η_c=0.67. It can be then deduced that the approach in [6] is also liable to provide wrong values of η_c at 1200 nm. In Fig. 1, it is shown moreover that a correct η_c-curve (black full line) can be obtained at θ_n=60, which is the correct θ_n-value according to this work. In the same figure, overlapping fit-curves to IQE^{-1}-data are shown, which were obtained with (1) at the constant η_c-value and assignments to R_B and θ_n relevant to the correct η_c-curves. It is worth mentioning, however, that the wrong assignments to R_B and θ_n relevant to the incorrect η_c-curves in Fig. 1 (short-dotted and black-dashed lines) allow fitting the IQE^{-1}-data nearly as accurately as the fit-curves reported in Fig. 1, if used together with the aforementioned wrong assignment η_c=0.65 [6]. This means that (1) is liable to fit IQE^{-1}-data at wrong assignments to both η_c and R_B.

Concerning cell B, in Fig. 2 a fit-curve to IQE^{-1}-data is reported as calculated with (1) at same values of η_c, R_B, and θ_n as assigned in [7] (red short-dashed line). In the same figure, it is shown that this curve overlaps with both a curve calculated with (1) at the correct value θ_n=60° (black full line) and a curve calculated with (1) at θ_n=0°, which is without doubt a wrong value for a textured cell (red-dashed line). In Fig. 2, the corresponding η_c-curves calculated with (4) appear to be correct and consistent with the η_c-value used to fit IQE^{-1}-data with (1). Consequently, from the comparisons in Fig. 2 it follows that both (1) and (4) can calculate correct curves at wrong assignments to θ_n.

Moreover, it should be remarked that the Basore model does not consider parasitic optical absorption other than at the back surface. If a cell with parasitic absorption at the front surface (p^+ or n^+ emitter) is evaluated using this model, the effect will be an apparent reduction in the value of R_B [2][8]. Cell B has a p^+-emitter and an Al rear-reflector [7]. Compared to the actual Al-reflectance at 1200 nm for incidence angles of 0°, 22.36° and 60° (see https://refractiveindex.info/), the R_B-values at θ_n=0° and θ_n=22.36° reported in Fig. 2 are equal or higher, while the R_B-values at θ_n=60° is lower. Hence, only the R_B-value at θ_n=60° can be considered as correct.

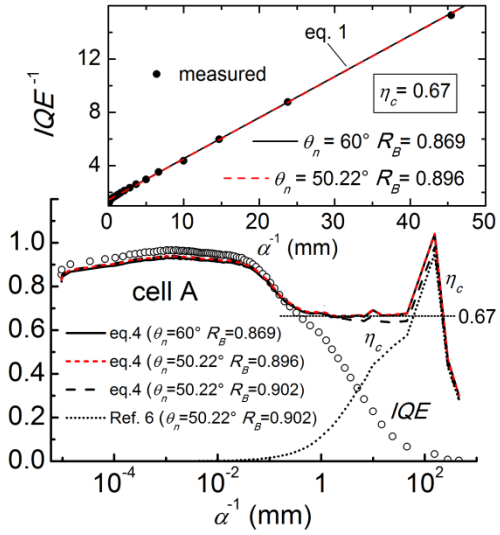

FIGURE 1. *IQE*- and IQE^{-1}-data relevant to cell A (circles) are shown together with the η_c-curve reported in [6], η_c-curves calculated with (4), the η_c-value fitting correct η_c-curves at near-bandgap wavelengths, and fit-curves to IQE^{-1}-data calculated with (1).

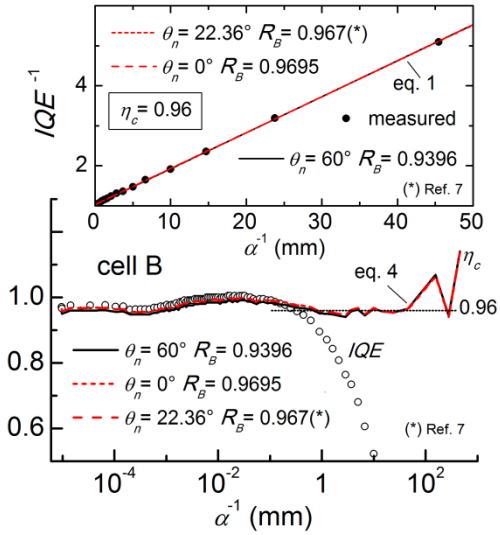

FIGURE 2. *IQE*- and IQE^{-1}-data relevant to cell B (circles) are shown together with η_c-curves calculated with (4), the η_c-value fitting η_c-curves at near-bandgap wavelengths, and fit-curves to IQE^{-1}-data calculated with (1).

CONCLUSION

From the previous comparisons it follows that taking θ_n as an adjustable parameter, as it is done in [6,7], in addition to leading to wrong η_c-values, as in cell A, and wrong θ_n-values, as in cell B, can also lead to wrong R_B-values, as in cell B, more easily than taking θ_n as a not-adjustable parameter equal to 60°. In conclusion, using (4) at θ_n=60° yields η_c-curves more correct than the η_c-curve in [6] and is not likely to result in wrong R_B-values

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