SEPARATION OF BULK DIFFUSION LENGTH & BACK SURFACE RECOMBINATION VELOCITY BY IMPROVED IQE-ANALYSIS

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ABSTRACT

Key parameters for the quantification of minority carrier recombination in solar cells are the effective bulk diffusion length, the bulk diffusion length and the back surface recombination velocity. Wafer thickness decreases and bulk quality increases the simultaneous determinatio of these parameters gains importance for cell process optimization in PV industry. Methods for obtaining these parameters have been described in literature, such as the linear approximation on the inverse IQE vs. light penetration depth. We will formulate the limitations of this approach using numerically and experimentally determined IQE-data. The ambiguity of the older approach is solved by an improved equation, making it possible to obtain these parameters from a fit on the IQE within 820 - 940 nm. In addition an equation incl. the loss in the emitter is presented. Both methods are ideally suited for fast LBIC scan evaluations.

INTRODUCTION

With decreasing wafer thickness and increasing bulk quality in current cell production lines the determination of the bulk diffusion length \( L_b \) and the back surface recombination velocity \( S_b \) gains importance for cell process optimization and monitoring in PV industry. One method for obtaining these parameters is based on the internal quantum efficiency (IQE), determined from spectral response and reflectance measurement data.

First calculations of the internal quantum efficiency of solar cells date back to the beginning of solar cell processing [1] with first detailed investigations of the influence of the emitter and the cell thickness to the IQE given in [2,3]. Several approximations for the contribution of the base to the IQE have been suggested [4-8] which given in [2,3]. Several approximations for the contribution of the base to the IQE have been suggested [4-8] which in the older approach is solved by an improved equation, making it possible to obtain these parameters from a fit on the IQE within 820 - 940 nm. In addition an equation incl. the loss in the emitter is presented. Both methods are ideally suited for fast LBIC scan evaluations.

The effective diffusion length \( L_{eff} \) in eq. 1 is the same that determines the base component of the dark saturation current density as long as potential fluctuations at the collecting junction, e.g. due to inhomogeneous doping profiles at grain boundaries, can be neglected [10].

The intention of our paper is fourfold:

1. discussion of the limitations of equation 2,
2. introduction of an improved equation for a more accurate determination of \( L_{eff} \) (with additional benefit for the simultaneous determination of \( L_b \) and \( S_b \)),
3. extension of the fit region towards the emitter (which is especially important for future thin cells),
4. suggestion for using these methods for fast evaluation of light beam induced current (LBIC) scans.

THE LIMITATIONS OF EQUATION 2

The general difficulties with eq. 2 are shown in Fig. 1. The inverse IQEs (calculated with IQE1D) in dependence of the light penetration depth normalized with the cell thickness are plotted for different \( L_b/S_b \)-pairs. The \( L_b/S_b \)-pairs are chosen to yield with eq. 1 the same effective diffusion length equal to the cell thickness \( (L_{eff}=W) \). Despite equal \( L_{eff} \)-values different inverse IQE curves are obtained in contradiction to eq. 2, which is also plotted in the figure. Deviations to eq. 2 occur for penetration depths much below half the cell thickness, for the two extreme cases (infinite and zero \( s_b \)) even down to 0.1 \( W \), which is for a 300 \( \mu \)m thick cell equivalent to \( \lambda = 900 \) nm. Comparing the curves with different internal back side reflection \( R_b \) ( \( L_b/W = 1 \) and \( s_b = 1 \) ) it is shown that the influence of \( R_b \) can not be neglected for
1/α > W/4. This figure also shows why eq. 2 had been ‘successfully’ applied by many research groups: it simply gives a good fit for standard 300 μm thick cells with moderate \( s_b = 1 \) and \( R_b = 0.6-0.8 \). With future thin cells including advanced back-side passivation and light-trapping schemes the application of eq. 2 becomes more and more critical.

**IMPROVED APPROXIMATION FOR THE IQE**

To overcome the problem stated before we suggest to use the following equation to obtain \( L_b \) and \( L_{eff} \) simultaneously (or \( L_{b} \) and \( S_b \) by using also eq. 1):

\[
IQE(\alpha) = \frac{1 - (\alpha \cdot L_{eff})^{-1}}{1 - (\alpha \cdot L_b)^{-2}} .
\]

(3)

This equation is derived from the contribution of the base [4] assuming a light penetration depth ‘large’ compared to the emitter thickness and ‘small’ compared to the cell thickness. Term ‘large’ depends on various emitter parameters, but can be taken in our case to fulfill \( 1/\alpha \gtrsim 14 \) μm (equivalent to \( \alpha \gtrsim 820 \)). In the following we will see that the term ‘small’ means \( 1/\alpha \lessgtr W/4 \), which is equivalent to \( \lambda \leq 940 \) nm for a 200 μm thin cell and \( \lambda \leq 960 \) nm for a 300 μm thick cell. Larger light penetration depths result in considerable deviations between eq. 3 and the IQE1D-data as shown for a 200 μm thin cell in Fig. 2. With \( 1/\alpha \lessgtr W/4 \) the additional assumption \( 1/\alpha \lessgtr L_b \) to be beyond the pole region of eq. 3 is usually fulfilled (or can be fulfilled by adjusting the fit region) and is further discussed in [11, 13].

**Determination of \( L_{eff} \) – an example**

Fig. 2 shows a comparison between numerical data generated by IQE1D, based on the cell parameters as given in Tab. 1, and the results when using eq. 3 for performing a fit on the IQE1D data. For simplification the space charge region width has been set to zero, which will change our results only marginally. Performing a fit with eq. 3 within the wavelength region \( \lambda = 820 – 940 \) nm (equal to \( 1/\alpha \approx 14-55 \)μm) results in \( L_{eff} = 152.1 \) μm which is in excellent agreement with the calculated value of \( 152.3 \) μm obtained by inserting the input parameters into equation 1. The fit also resulted in a bulk diffusion length of 183.2 μm, which is only 8.4% lower than the \( L_b \) input parameter.

Using eq. 2 for a fit between \( 1/\alpha \approx 14-55 \) μm on the IQE1D data results with \( L_{eff} = 135.6 \) μm in an 11% lower value than the calculated \( L_{eff,cal} \). This was an example where the effective diffusion length differed from the bulk diffusion length (152.3 μm vs. 200 μm). In the following section it is shown that this condition limits the application of eq. 2, whereas eq. 3 results in a considerable improved accuracy in the determination of \( L_{eff} \) for a large parameter field.

**Influence of \( L_b \) and \( S_b \) on the determination of \( L_{eff} \)**

The advantage of eq. 3 will be shown in the following by calculating the IQEs with IQE1D for several parameter sets \( L_b, S_b \) and the other parameters given in Tab. 1. The effective diffusion length is either calculated from the input parameters using eq. 1 (\( L_{eff,cal} \)) or obtained by a fit with eq. 2 or eq. 3 (\( L_{eff,fit} \)). The influence of \( L_b/W \) on the relative error of the effective diffusion length is given in Fig. 3a, showing that eq. 3 is considerably more accurate in the determination of \( L_{eff} \) than eq. 2. Equation 2 is limited to small diffusion lengths (\( L_b \ll W \)). Fig. 3a is also an example where equation 2 is not good for the determination of \( L_{eff} \) even for \( L_b \) being a factor 2.5 larger than the cell thickness. For the calculations \( S_b = 10 \) was chosen. Varying \( S_b \) and keeping \( L_b = 300 \) μm fixed results
in Fig. 3b, showing that only for $0.75 < S_b < 2$ (abbreviated in the following as $S_b = 1$) equation 2 results in a good approximation. Similar graphs have been obtained for bulk diffusion lengths and cell thicknesses between 100 and 500 $\mu$m, proving that a considerably increased accuracy in the determination of $L_{\text{eff}}$ is obtained by using eq. 3 instead of eq. 2.

From equation 3 back to equation 2

For the case $L_{\text{eff}} = L_b$, equation 3 reduces to equation 2. From eq. 1 follows that the approximations of either $L_b << W$ or $S_b = 1$ as stated before can be combined in the approximation $L_{\text{eff}} = L_b$. From this and the previous section follows that the application of eq. 2 is restricted to the approximation $L_{\text{eff}} = L_b$. 

SEPARATION OF $L_b$ AND $S_b$

The possibilities for a separation of $L_b$ and $S_b$ are shown in Tab. 2. Various $L_b$/$S_b$-pairs were taken as input parameters for IQE1D calculations and $L_{\text{eff}}$-values obtained by using eq. 1-3 as outlined previously. From a fit with eq. 3 also $L_b$ was obtained and $S_b$ calculated using again eq. 1. The comparison of the gray columns with the column for eq. 2 proves again that with eq. 3 the value $L_{\text{eff}}$ is obtained with a considerably higher accuracy than using eq. 2.

From the data given in this table the following statements on the separation of $L_b$ and $S_b$ can be made:

- A high accuracy on $L_b$ is given in case of 1. $L_b > W$ only if $S_b$ is small ($L_b = 300 \mu$m $\Rightarrow$ $S_b < 2000$ cm/s, $L_b = 500 \mu$m $\Rightarrow$ $S_b < 1000$ cm/s) and 2. $L_b < W$ for all $S_b$-values.

- Accuracy on $S_b$: The larger $L_b/W$ the better the accuracy for low $S_b$-values and the worse for high $S_b$-values (for $L_b = 300 \mu$m and $W = 200 \mu$m a good agreement is found for $S_b$-values between 100 and 2000 cm/s), $L_b << W$ results only in a low sensitivity on $S_b$ (for $L_b = 100 \mu$m, $W = 200 \mu$m and $S_b = 1e3$ cm/s, $S_b$ obtained by a fit is increased by nearly a factor of 2).

Tab. 2: A comparison of the $L_{\text{eff}}$-values, obtained by eq. 1 using the input parameters, by a fit with eq. 2 to the simulated IQE and, respectively, by a fit with eq. 3. The bold figures belong to cases where the error between fit result and $L_{\text{eff.cal}}$ was larger than 10%. The cell thickness $W$ was $200 \mu$m for all rows except the last one with $W = 500 \mu$m. For high back side recombination velocities the uncertainty was to large to determine $S_b$.

<table>
<thead>
<tr>
<th>$L_b$ [\mu$m$]</th>
<th>$S_b$ [cm/s]</th>
<th>$L_{\text{eff.cal}}$ [\mu$m$] eq. 1</th>
<th>$L_{\text{eff}}$ [\mu$m$] eq. 2</th>
<th>$L_{\text{eff}}$ [\mu$m$] eq. 3</th>
<th>$L_b$ [\mu$m$]</th>
<th>$S_b$ [cm/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>100</td>
<td>1230</td>
<td>979</td>
<td>516</td>
<td>125</td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>1000</td>
<td>415</td>
<td>405</td>
<td>410</td>
<td>841</td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>100</td>
<td>606</td>
<td>475</td>
<td>315</td>
<td>169</td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>1000</td>
<td>307</td>
<td>320</td>
<td>290</td>
<td>891</td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>2000</td>
<td>257</td>
<td>244</td>
<td>257</td>
<td>1636</td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>5000</td>
<td>213</td>
<td>183</td>
<td>212</td>
<td>3543</td>
<td></td>
</tr>
<tr>
<td>300**</td>
<td>1e6</td>
<td>175</td>
<td>132</td>
<td>173</td>
<td>241**</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>100</td>
<td>255</td>
<td>321</td>
<td>261</td>
<td>211</td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>100</td>
<td>214</td>
<td>231</td>
<td>217</td>
<td>203</td>
<td></td>
</tr>
<tr>
<td>200**</td>
<td>1e6</td>
<td>152</td>
<td>136</td>
<td>152</td>
<td>183**</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>100</td>
<td>102</td>
<td>108</td>
<td>105</td>
<td>104</td>
<td></td>
</tr>
<tr>
<td>100**</td>
<td>1e6</td>
<td>96</td>
<td>89</td>
<td>98</td>
<td>101**</td>
<td></td>
</tr>
</tbody>
</table>

EXPERIMENTAL RESULTS

IQE-data has been obtained from SR- and R-measurements of three mc-Si cells, which have been processed similarly, but were made out of material with different quality, resulting in comparable $S_b$-values but different $L_{\text{eff}}$-values, as seen in Tab. 3. For increasing $L_{\text{eff}}$-values the differences between the two evaluation methods (eq. 2 and 3) grow, showing that the more accurate equation 3 has to be taken to determine $L_{\text{eff}}$. 

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Tab. 3: A comparison of $L_{\text{eff}}$-values obtained from IQE-data by eq. 2 and 3. The bold figures belong to cases where the error between fit result and $L_{\text{eff.cal}}$ was larger than 10%. The cell thickness $W$ was $200 \mu$m for all rows except the last one with $W = 500 \mu$m. For high back side recombination velocities the uncertainty was too large to determine $S_b$.

<table>
<thead>
<tr>
<th>$L_{\text{eff}}$ [\mu$m$]</th>
<th>$S_b$ [cm/s]</th>
<th>$L_{\text{eff.cal}}$ [\mu$m$] eq. 2</th>
<th>$L_{\text{eff}}$ [\mu$m$] eq. 3</th>
</tr>
</thead>
</table>
The errors in $L_e$ and $S_b$ show that a high measurement accuracy is needed for the parameter separation.

Tab. 3: Experimentally determined $L_{eff}$ by eq. 2 and $L_{eff}, L_o$ and $S_b$ by our proposed method for three Si cells.

<table>
<thead>
<tr>
<th>Cell no.</th>
<th>$L_{eff}$ [µm] eq. 2</th>
<th>$L_{eff}$ [µm] eq. 3</th>
<th>$L_o$ [µm] eq. 3</th>
<th>$S_b$ [cm/s] eq. 1 + 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>214</td>
<td>226 (±6)</td>
<td>251 (±25)</td>
<td>2206 (±463)</td>
</tr>
<tr>
<td>2</td>
<td>189</td>
<td>198 (±4)</td>
<td>207 (±14)</td>
<td>2154 (±458)</td>
</tr>
<tr>
<td>3</td>
<td>138</td>
<td>145 (±14)</td>
<td>150 (±24)</td>
<td>3514 (±2412)</td>
</tr>
</tbody>
</table>

**INCLUDING THE LOSS IN THE EMITTER**

With decreasing cell thickness the fit region of eq. 3 should be shifted towards the emitter region. In case of low quality emitters also recombination in the emitter has to be taken into account, therefore we will shortly outline our recent work on the emitter contribution to the IQE. Including the emitter into eq. 3 can be made by describing the emitter with a dead layer region of thickness $d$ as presented in the following equation:

$$IQE(\alpha) = e^{-\alpha d} \frac{1-(\alpha \cdot L_{eff})^{-1}}{1-(\alpha \cdot L_b)^{-1}}.$$

(4)

Fig. 4 shows a calculated IQE with $S_b = 1\text{e}6$ cm/s and the other parameters given in Tab. 1. Even for this extreme case eq. 4 holds valid down to $1/\alpha = 1\ \mu\text{m}$, or more generally formulated down to 1.5-3 times the emitter thickness, which was also stated in earlier work of one of the authors [13].

**CONCLUSION**

By calculating IQEs with the software program IQE1D and experimentally determined IQE-data it has been shown that the linear approximation for the inverse IQE results only in a good fit of the effective diffusion length $L_{eff}$ for the case $L_{eff} = L_o$. The discrepancy with the linear approximated inverse IQE equation is solved by the presentation of an improved equation, making it possible to obtain both recombination parameters, $L_o$ and $L_{eff}$ simultaneously (or alternatively $L_o$ and $S_b$), from a fit on the IQE for wavelengths between 820 nm and a wavelength corresponding to a light penetration depth equal to $1/4$ of the cell thickness. Using this equation instead of the linear approximation results in at least a factor of 2 improved accuracy on the determination of $L_{eff}$, therefore also increasing the accuracy of $L_o$ and $S_b$. In addition an equation incl. the loss in the emitter has been presented. The simplicity of both methods make them suitable for fast LBIC scan evaluations, from which detailed information on the spatial distribution of $L_o$ and $S_b$ for advanced thin mc-Si solar cells can be obtained. Experiments will be carried out to determine the requirements on the measurement accuracy.

**ACKNOWLEDGEMENTS**

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**REFERENCES**

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