ACCURATE DETERMINATION OF THE IQE OF SCREEN PRINTED SILICON SOLAR CELLS BY ACCOUNTING FOR THE FINITE REFLECTANCE OF METAL CONTACS

B. Thaidigsmann, A. Wolf, D. Biro
Fraunhofer ISE, Heidenhofstr. 2, D-79110 Freiburg, Germany
e-mail: benjamin.thaidigsmann@ise.fraunhofer.de

ABSTRACT: The internal quantum efficiency (IQE) of a solar cell follows from the external quantum efficiency (EQE) and reflectance data of the front side. Most of the silicon solar cells currently produced feature metallised areas on the front. To account for the finite reflection of the metal grid, the reflection of the non-metallised area has to be extracted from the reflection data. Our results show that neglecting the finite reflection of the front metallisation results in a misinterpretation of the IQE by up to 9 % (relative). We show that the impact of the metallisation on the front reflectance scales linearly with the surface ratio of the metallisation and present a method to extract the reflectance of non-metallised areas from large-area reflectance measurements of screen printed solar cells. Our approach uses an algorithm to automatically determine the metallised surface area by means of microscope images and reference measurements of fully metallised samples to calculate the required reflectance data. This way the accuracy of the IQE is significantly improved.

Keywords: Characterisation, Metallisation, Optical Properties, Quantum Efficiency

1 INTRODUCTION

The internal quantum efficiency is defined as the fraction of charge carriers collected per incident photon that is neither reflected in the first place nor leaves the cell through the front surface after having entered the cell. A widely used method to calculate the IQE is to divide the external quantum efficiency (EQE) by (1−R_{cell}) for each wavelength. Here, R_{cell} denotes the reflectance measured for the partly metallised front surface of the cell. This procedure yields correct results, as long as the reflectance of the metallised area is close to 100 %. However, apparent from Fig. 1, screen printed metal contacts used in industrial production exhibit a reflectance way below unity decreasing to values between 50 % and 5 % for wavelengths below 350 nm.

Fischer proposed a more accurate approach that accounts for finite reflection of the front contacts by using [1,2]

$$IQE(\lambda) = \frac{EQE(\lambda)}{(1-R_{Si}(\lambda))(1-M)}.$$  \hspace{1cm} (1)

\hspace{1cm}

where $\lambda$ is the vacuum wavelength and $M$ is the metallised (shaded) area fraction. This approach requires the knowledge of the reflectance $R_{Si}$ of the non-metallised (silicon) surface. Figure 2 presents a comparison of both calculation methods applied to local EQE and reflectance data of a monocrystalline industrial silicon solar cell. The results from Eq. (1) differ by up to 9 % (5 % absolute) compared to those calculated with the simple method described above. The effect occurs most notably at short wavelengths below 400 nm.

Using the simple approach instead of Eq. (1) for the IQE calculation leads to a misinterpretation of the emitter current loss [1] $\Delta J_{SC,em}$ by more than 20 %, when approximating this value by

$$\Delta J_{SC,em} = q \int_{300nm}^{600nm} (1 - IQE(\lambda)) \Phi_{AM1.5G} d\lambda,$$  \hspace{1cm} (2)

using the photon flux $\Phi_{AM1.5G}$ of the global air mass 1.5 spectrum (IEC 904-3:2008) and the elementary charge $q$.

\hspace{1cm}

![Figure 1: Reflectance of fully metallised screen printed areas measured after firing. Three different Ag pastes are applied.](image1.png)

![Figure 2: Comparison of the local IQE of an industrial Si solar cell calculated by the simple approach IQE = EQE/(1-R_{cell}) and by Eq. (1). The measured reflectance R_{cell} and that of the non-metallised surface R_{Si} calculated from Eq. (3) are displayed as well.](image2.png)
This result confirms the necessity of an accurate calculation that accounts for the finite reflection of the front contacts. Other evaluation techniques for IQE data such as device modelling for example with PC1D [3] and quantitative evaluations as e.g. Basores’ inverse IQE-fit to determine the effective diffusion length [4] require data of high accuracy as well.

In most cases it takes a high effort to determine the reflectance of the non-metallised silicon surface of a finished cell, since the accuracy of small-spot measurements between the contact fingers is low and non-metallised reference samples are not always available. Fischer suggested to extrapolate the reflectance \( R_{\text{Si}} \) of the non-metallised area from the measured reflectance \( R_{\text{met}} \) and the known reflectance \( R_{\text{cell}} \) and fraction \( M \) of the metallised area using [1]

\[
R_{\text{Si}}(\lambda) = \frac{R_{\text{met}}(\lambda) - M \cdot R_{\text{cell}}(\lambda)}{(1 - M)}.
\]  

However, this relation has not been experimentally verified so far.

2 APPROACH

For verifying Eq. (3), we design a test grid that features finger pitches of \( p = 0.5 \) mm to \( p = 3 \) mm and finger widths of \( w = 70 \) µm, 100 µm, and 150 µm as well as non- and fully metallised areas. This grid is then used to fabricate reflectance samples from monocrystalline wafers with random pyramids as well as from multicrystalline wafers with acidic texture. Except for the modified front contact geometry, these samples are similar to industrial solar cells including a phosphorous-doped emitter with a sheet resistance of 50 Ω/□, a SiN\(_x\) anti-reflection coating (ARC) and a full area Al back contact. A spectrophotometer equipped with an integrating Ulbricht sphere permits the determination of the global reflectance. The spot size of the spectrophotometer is approximately 5 mm x 10 mm, much larger than the finger spacing of our samples. Thus, in case of partly metallised samples, the measurement yields an effective reflectance \( R_{\text{met}} \) with contributions from both, metallised and non-metallised parts, as it would be measured for a finished cell. The curves for \( R_{\text{met}} \) and \( R_{\text{Si}} \) follow from measurements on the fully and non-metallised areas, respectively. Thus, the only unknown parameter from Eq. (3) is the metallised area fraction \( M \).

3 RESULTS

In a first step we implement an algorithm that calculates a linear superposition

\[
R_{\text{fit}}(\lambda) = M_{\text{opt}} \cdot R_{\text{met}}(\lambda) + (1 - M_{\text{opt}}) \cdot R_{\text{Si}}(\lambda)
\]  

of the known \( R_{\text{met}} \) and \( R_{\text{Si}} \) curves according to Eq. (3) by means of the effective optical metallisation fraction \( M_{\text{opt}} \). The algorithm applies least-squares-fitting to reproduce the measured reflectance curve \( R_{\text{cell}} \) between 250 nm and 1000 nm using \( M_{\text{opt}} \) as a free parameter. Figure 3 shows the results. The average deviation of the interpolated and measured reflectance of the partly metallised area is 1.5 % (0.23 % absolute). The wavelength range for fitting is limited to values below 1000 nm, since we observed deviations from the linear interpolation in the infrared (IR) range. Here, the measured reflectance is lower than predicted (see Fig. 3). We attribute this deviation to internal shading due to lateral light propagation. Multiple reflections enable photons incident on the non-metallised area to travel laterally under the front contacts, where the metal hinders them from escaping. Our measurements reveal that this effect scales with both, the finger width and the finger density. The interpolation from Eq. (4) does not account for such interactions between metallised and non-metallised regions and therefore overestimates the escape reflection.

In a second step we use microscope images of the grid to determine the geometrical metallisation fraction \( M_{\text{geom}} = w/p \). For this purpose a second algorithm extracts the finger width \( w \) from an image of a single contact finger (see Fig. 4). The program eliminates possible tilt of the image and averages the brightness profile along the finger. To eliminate errors due to varying brightness of the images, the algorithm adjusts the threshold brightness to

\[
b_{\text{thres}} = b_{\text{BG}} + t \cdot (b_{\text{max}} - b_{\text{BG}})
\]  

according to the background brightness of the wafer surface \( b_{\text{BG}} \), the maximum brightness of a finger \( b_{\text{max}} \), and an experimentally calibrated threshold \( t = 0.32 \) which is adapted to measurements with image analysis software. In contrast to the finger width, the spacing \( p \) is not subject to process variations, it follows directly from the design of the grid.
Figure 5 compares the results for $M_{\text{geom}} = w/p$ to the $M_{\text{opt}}$ values extracted from the interpolation of the reflectance measurements by means of Eq. (4). The data reveal a linear dependence between the effective optical metallisation fraction and the geometrically measured metallisation fraction determined from microscope images. This relation holds for metallisation fractions between 2 % and 25 % and is equal for multi- and monocrystalline cells. Moreover, the correlation is independent of line width $w$ and pitch $p$ within the analyzed range of 70 µm to 150 µm and 0.5 mm to 3 mm, respectively. A linear fit that is forced through the origin yields a slope of $m = 0.956 \pm 0.005$. Two effects might explain why this value is not equal to unity. Firstly, the fingers exhibit a non ideal geometry (see Fig. 4), which could deflect photons to the non-metallised region \[5,6\], resulting in a reduced effective optical metallisation. This effect should scale with the number of illuminated fingers. Unfortunately, the fixed grid geometry of our samples and the limited accuracy of the measurements do not allow a closer analysis at present. Secondly the calibration of the threshold \(t\) used by the algorithm to determine the grid dimensions affects the geometrical fraction $M_{\text{geom}}$. Using a lower threshold value would result in a slope closer to unity.

Figure 4: Microscope image of a grid finger (top) and the corresponding averaged brightness profile (bottom). Our algorithm determines the finger width $w$ from the averaged brightness signal and the threshold brightness $b_{\text{thres}}$ from Eq. (5) using $t = 0.32$.

The above described results now enable us to calculate the reflectance

$$R_{\text{cell}}(\lambda) = \frac{m \cdot w \cdot R_{\text{met}}(\lambda)}{1 - \frac{m \cdot w}{p}}$$

of the non-metallised surface from the measured reflectance data $R_{\text{cell}}$ of the partly metallised front surface, the reference reflectance data of the metallised surface $R_{\text{met}}$, the factor $m = 0.956$, and the grid dimensions $w$ and $p$.

Figure 6 illustrates the results of this prediction compared to the reflectance measured for the non-metallised reference. The curves match very well; the average deviation between calculated and measured reflectance is less than 0.4 % (absolute). The deviation in the IR range arises presumably from the above described internal shading due to lateral light propagation. First experiments with thick (>= 100 µm) screen printed contact fingers on monocrystalline wafers showed the same linear relation even for contacts thickened by light induced plating of Ag \[7\]. A plot of $M_{\text{geom}}$ versus $M_{\text{opt}}$ for such wafers shows a similar slope factor $m$, thus the approach seems to suit for electroplated contacts as well.

4 SUMMARY

In conclusion, our experiments confirm the linear relation between reflectance and metallisation fraction for screen printed front contacts. Our approach enables an accurate prediction of the reflection of non-metallised area from the measured reflectance of the cell (including metallised parts) and a microscope image of the front contact. The described procedure allows a more accurate calculation of the IQE by accounting for the non ideal reflection and the shading of the front contacts after Eq. (1). Only little additional effort has to be put on the measurement of the grid dimensions of each cell and the one-time preparation of fully metallised samples for reference measurements.
Figure 6: Calculated reflectance curves for the non-metallised area extrapolated by Eq. (6) (solid red lines) compared to the reflectance measured for a non-metallised reference sample (dashed green lines) for varying metallisation $M_{geom}$. 

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