

INFLUENCE OF SPECTRAL MISMATCH, CELL REFLECTION PROPERTIES AND IQE ON THE EFFICIENCY MEASUREMENT

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ABSTRACT: The determination of the electrical parameters and in particular the efficiency of solar cells should be done according to STC. However, hardly any solar simulator or flasher features a spectrum perfectly matched to STC's ASTM G173 (AM 1.5g) spectrum. If the external quantum efficiency (EQE) of the calibration cell and the cell to be tested differ, any spectral mismatch of the applied spectrum compared to STC may not only lead to an erroneous measurement of current and cell efficiency but also to de-optimization of cell properties or misinterpretation of experimental results. As an example it is shown that the combination of spectral and EQE mismatch yield a different optimum of the (effective) layer thickness of the anti-reflection coating (ARC) resulting in a de-optimization according to STC. As a second example, the misinterpretation of benefits due to the implementation of selective emitter technology is discussed.

Keywords: Qualification and Testing, Antireflection Coatings, Selective Emitter

1 INTRODUCTION

It should be taken as granted that the electrical parameters and in particular the efficiency especially of commercially available solar cells is determined correctly according to the standard test conditions (STC)[1].

However, as not every solar simulator or flasher perfectly fulfills the STC requirements and especially the applied spectrum of the (flash) lamp differs from STC's standardized AM 1.5g spectrum (ASTM 173)[2], spectral mismatch errors may occur, mainly influencing the short circuit current of the solar cell.

Besides a principally incorrect determination of I_{sc} , two sometimes forgotten consequences arise from the combination of an inappropriate calibration method and a non-standardized spectrum which will be addressed in this paper.

The first point concerns the optimization of the optical properties of the solar cell using a non-standardized spectrum. In this contribution, the reflection of the solar cell is taken as an example.

The second point concerns the evaluation of new technologies like the selective emitter technology. Current selective emitter technologies often feature a removal or thinning of the heavily doped emitter regions which leads to an improved blue response.

2 THEORETICAL BACKGROUND

The short-circuit current density j_{sc} of a solar cell may be expressed by the equation

$$j_{sc} = q \int \phi(\lambda) \cdot IQE(\lambda) d\lambda - q \int \phi(\lambda) \cdot R(\lambda) \cdot IQE(\lambda) d\lambda$$

where q is the elementary charge, $\phi(\lambda)$ is the photon flux density of the applied spectrum, $R(\lambda)$ is the spectral reflection of the solar cell and $IQE(\lambda)$ is the internal quantum efficiency. The integral limits may be set to the spectral range where $IQE(\lambda)$ and $\phi(\lambda)$ do not vanish, which is for crystalline silicon solar cells the range ~300-1200 nm. The first term describes the maximum current density achievable with a given $IQE(\lambda)$ (including ARC absorption) with respect to the applied spectrum $\phi(\lambda)$, the second term is subtracted and represents the optical

losses by reflection. Minimizing the reflection is therefore a way to improve j_{sc} and is a standard procedure in every laboratory or company. But, as can be seen from the equation, this task is always done with respect to the applied spectrum which is in most cases not a perfect ASTM G173 (STC, AM 1.5g) spectrum [2] and, as the spectra of different IV-testers may vary, the optimal reflection $R(\lambda)$ might be not identical.

The reflection $R(\lambda)$ and internal quantum efficiency $IQE(\lambda)$ are often combined to the external quantum efficiency $EQE(\lambda) = (1-R(\lambda)) \cdot IQE(\lambda)$ giving the equation

$$j_{sc} = q \int \phi(\lambda) \cdot EQE(\lambda) d\lambda$$

In general, calibration of the IV-setup requires a calibration (cal) cell (with external quantum efficiency EQE^{cal}) being characterized at a calibration laboratory. The determined short circuit current density $j_{sc}^{cal}(\phi^{ref})$ refers to standard test conditions, and in particular the reference spectrum $\phi^{ref}(\lambda)$ (ASTM G173, AM1.5g)[2].

When the calibration cell is measured with a different spectrum $\phi(\lambda)$, the short circuit density $j_{sc}^{cal}(\phi)$ differs at first from the STC value $j_{sc}^{cal}(\phi^{ref})$ by Δj_{sc}^{cal} given by

$$\Delta j_{sc}^{cal} = q \int (\phi(\lambda) - \phi^{ref}(\lambda)) \cdot EQE^{cal}(\lambda) d\lambda$$

Calibrating the IV-setup is then done by adjusting the spectral intensity of $\phi(\lambda)$ to guarantee $\Delta j_{sc}^{cal} = 0$.

For the subsequent measurement of another cell, a similar equation may be set up by defining the relation $EQE^{cell} = EQE^{cal} + \Delta EQE$, where $\Delta EQE(\lambda)$ denotes the variation in external quantum efficiency between calibration cell and the cell under test. The difference in short circuit current density Δj_{sc}^{cell} between spectrum $\phi(\lambda)$ and reference spectrum $\phi^{ref}(\lambda)$ then reads as

$$\Delta j_{sc}^{cell} = q \int (\phi(\lambda) - \phi^{ref}(\lambda)) \cdot \Delta EQE(\lambda) d\lambda$$

Only for $\phi(\lambda)$ equaling the reference spectrum $\phi^{ref}(\lambda)$, the spectral mismatch is independent of the variation of the external quantum efficiency $\Delta EQE(\lambda)$.

Based on these basic equations, two examples shall demonstrate the consequences of spectral and EQE mismatch.

3 EXAMPLE 1: VARIATION OF REFLECTION $R(\lambda)$

Assuming a well defined pyramid structure, which approximates a random pyramid texture on Cz-Si, and geometric optics, the thickness as well as the refractive index of the dielectric layer (e.g. $\text{SiN}_x\text{:H}$) determine the reflection of the sample.

PC1D [3] was used to model the electrical and optical properties of samples with variable $\text{SiN}_x\text{:H}$ layer thickness. It should be noted that PC1D uses only an effective thickness for the ARC on a textured surface which corresponds to the real thickness on a flat surface. The parameter set used in the calculations is shown in Table I and the resulting $IQE(\lambda)$ and reflection $R(\lambda)$ are shown in Fig. 1.

Table I: PC1D parameter set used for the calculations

Parameter	Details
Wafer thickness	200 μm
Base doping	p-type, 2.5 Ωcm
Texture	random pyramid height 3 μm
Broadband reflection	6%
$\text{SiN}_x\text{:H}$ refractive index	2.05
SRV front	35000 cm/s
Emitter sheet resistance	90 $\Omega/\text{sq.}$
Minority carrier lifetime	100 μs ($L_{\text{bulk}} \sim 550 \mu\text{m}$)
Back surface field	uniform, depth 8 μm , $N_A = 5 \cdot 10^{18} \text{cm}^{-3}$
Internal rear reflection	75 %, diffuse

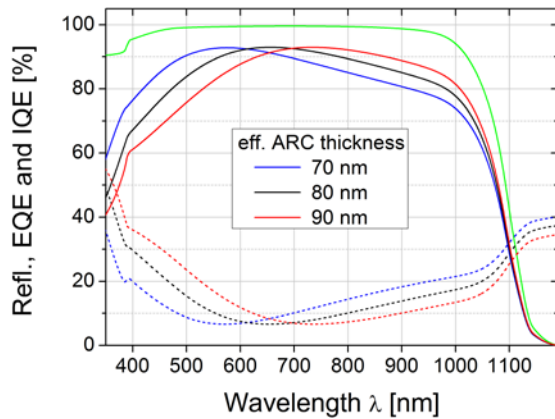


Figure 1: IQE, EQE and reflection curves as calculated by PC1D. A similar IQE is assumed for all curves.

For further exemplary calculations, the two spectra shown in Fig. 2 were used, one being the ASTM G173 global spectrum. The other spectrum is a modified ASTM G173 spectrum. The blue part of the ASTM G173 spectrum was reduced to approximate the often to low emission in the blue wavelength region of flash lamps. The absorption bands in the long wavelength range were filled up as flash lamps often do not feature these bands but actually feature strong emission lines in this region.

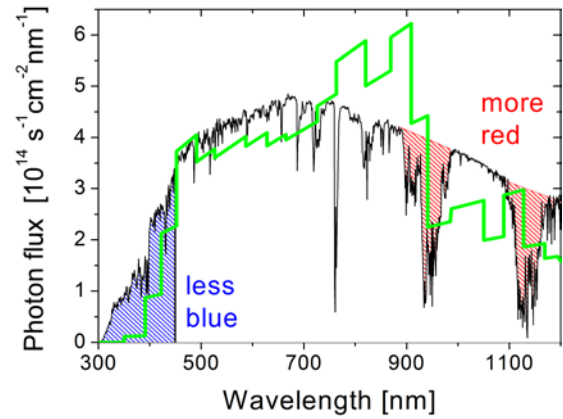


Figure 2: ASTM G173 spectrum (black spiky curve) and modifications to it used in the simulations. The shaded parts are subtracted (blue) or added (red). The green angled line represents roughly a flasher spectrum [4].

Using these spectra, the current was calculated for various thicknesses t of the $\text{SiN}_x\text{:H}$ layer. The results are shown in Fig. 3. Fill factor (FF) and open circuit voltage (V_{oc}) are only very slightly affected. Thus, cell efficiency becomes directly proportional to j_{sc} .

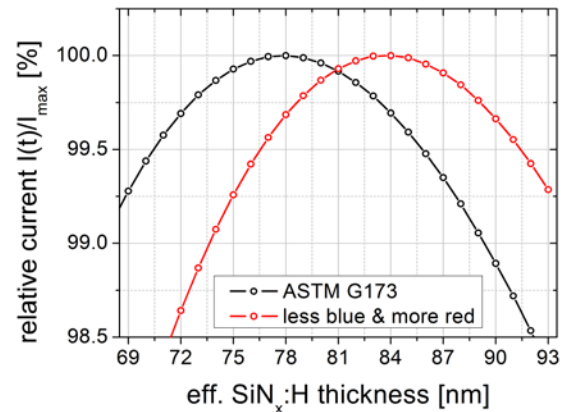


Figure 3: Normalized current versus eff. $\text{SiN}_x\text{:H}$ thickness for the spectra from Fig. 2 calculated by PC1D.

As expected, the optimal thickness differs for both spectra and an optimization with respect to the modified spectrum would in fact de-optimize the results on cell level, regarding standard test conditions. The relative current in Fig. 3 resembles roughly a parabolic shape and thus a certain small deviation in thickness is tolerable or not even verifiable. If the difference in thickness between the maxima of both curves increases, the deviation Δj_{sc}^{cell} increases significantly.

Vice versa it can be stated that the color impression of an 'optimized' solar cell compared to a cell optimized according to STC reveals the quality of the applied spectrum and that, if the color differs clearly, a noticeable de-optimization has occurred.

Of course, optimizing the optical properties of solar cells embedded in a module results in deviating values but the general statement remains valid.

4 EXAMPLE 2: VARIATION OF IQE(λ)

A typical example for a strongly varying $IQE(\lambda)$ is the comparison of a selective emitter (SE) and a non-selective (non-SE) emitter cell. The IQE, EQE and reflection of two exemplary cells are shown in Fig. 4.

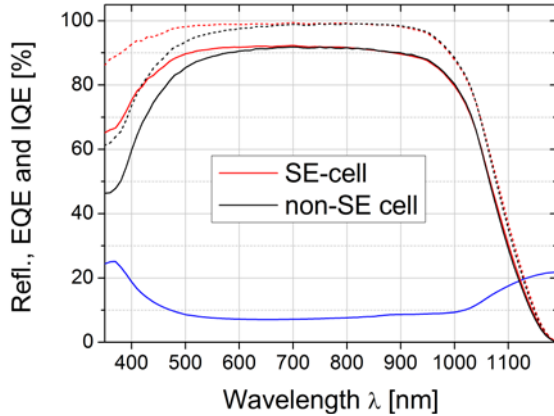


Figure 4: Measured IQE and EQE of a SE as well as a non-SE cell. Both cells feature the same reflection. As expected, both IQE and EQE split up in the blue/green region due to the improved emitter but are hardly distinguishable in the (infra-)red region dominated by bulk properties (high lifetime Cz-Si, full area Al-BSF).

In this case, the diffused phosphorous emitter of the SE was etched back between the contact fingers[5]. This etch-back has removed the heavily phosphorous doped surface layer (parts of the kink region of the typical kink and tail profile) which normally leads to an increased recombination of surface-near generated charge carriers. As this affects mainly blue/green light due to the short absorption length, the IQE and EQE of the SE cell is higher than for the non-SE cell.

In real life, the SE technology is typically developed or implemented after the non-SE technology and, at least in the beginning and evaluation phase, no proper calibration cell exists for SE cells and a non-SE cell is used instead. In order to demonstrate the effect of this procedure, the short circuit current density of both cells was calculated using the different spectra shown in Fig. 2 and the results are presented in Table II. As the non-SE cell is used for calibration, the intensity is adjusted to reach the same current density for this cell.

Table II: Calculated j_{sc} values (in mA/cm²) for the SE and non-SE cell (Fig. 4) using the spectra shown in Fig. 2. The spectral intensity was chosen so that the non-SE cell acts as calibration and always yields the same current density.

	ASTM G173	less blue & more red	flasher
non-SE	36.45	36.45*	36.45*
SE	37.36	36.88 (-0.48)	37.02 (-0.34)
gain	0.91	0.43 (-53%)	0.57 (-38%)

As expected, the SE cell features a higher j_{sc} than the non-SE cell and the gain of 2.5%_{rel} is remarkable. However, more important at that point is that the other two spectra yield a current which is principally lower (-0.48 and -0.34) or in other words that the observable

gain is noticeably reduced (-53% and -38%). Therefore the true benefit of the selective emitter technology regarding j_{sc} is (in this case) seriously underestimated.

It should be kept in mind at that point that also the open circuit voltage V_{oc} benefits from SE technology. Typical values for V_{oc} (~2 Ωcm, Cz-Si) are 625 mV for non-SE cells and 635 mV for SE cells or a gain of around 10 mV, respectively. The actual value depends on the base doping and other factors. Assuming a constant fill factor of 78%, the true efficiency gain $\Delta\eta$ between SE and non-SE cell would be $\Delta\eta \sim 0.73\%_{abs}$. The use of the other spectra would yield a gain of $\Delta\eta \sim 0.50\%_{abs}$ and $\Delta\eta \sim 0.57\%_{abs}$, respectively.

5 CONCLUSIONS

As the first example has shown, the result of the optimization of reflection (or more general EQE related) properties is inseparably connected to the spectrum of the used solar simulator or flasher. In fact, the typical procedure unavoidably leads to an unintentional de-optimization regarding STC. The only question remaining is how imperfectly matched the spectrum is compared to the STC's ASTM G173 and thus how large the effect is.

The second example has shown that a mismatched spectrum might complicate the correct evaluation of a new technology, in this case the selective emitter technology. Especially the combination of spectra with weak blue portion (as they are found from time to time) and calibration with a differing EQE is known to underestimate the benefit of SE technology.

From a commercial point of view, it is worth considering in any case that a mismatched spectrum combined with an inappropriate calibration might lead to an incorrect determination of the electrical parameters.

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