The cell doctor: A detailed 'health check' for industrial silicon wafer solar cells

Cell Processing

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ABSTRACT

In principle solar cells are very simple: they convert sunlight to electricity and can be characterized by a single number – the solar cell efficiency. Manufacturers obviously want to achieve this efficiency at the lowest possible cost, so it is critical that the efficiency/cost ratio be optimized. To this end, knowledge of where the biggest gains can be achieved is key. This paper presents an in-depth loss analysis method developed at the Solar Energy Research Institute of Singapore (SERIS) and details how various losses in a silicon wafer solar cell can be quantified, which is not done in the case of a conventional solar cell measurement. Through a combination of high-precision measurements, it is shown that it is possible to fully quantify the various loss mechanisms which reduce short-circuit current, open-circuit voltage and fill factor. This extensive quantitative analysis, which is not limited to silicon wafer solar cells, provides solar cell researchers and production line engineers with a 'health check' for their solar cells – something that can be used to further improve the efficiency of their devices.

Introduction

In the PV industry there is continual pressure to increase solar cell efficiency. However, it is actually not that important to know the theoretical maximum efficiency limit of a certain solar cell design; instead, it is more important to understand – and quantify – the loss processes that currently limit cell efficiency. Consequently there is a need for a full bottom-up solar cell loss analysis that is based on high-precision measurements and quantifies the losses for the most relevant solar cell parameters, specifically short-circuit current (I_{sc}), open-circuit voltage (V_{oc}), fill factor (*FF*) and efficiency (η). In this paper, the work of Aberle et al. [1] is extended by further analyzing the losses limiting V_{oc} and *FF*. The results will be demonstrated using standard industrial aluminium-back-surface field (Al-BSF) silicon wafer solar cells from the R&D pilot line of the Solar Energy Research Institute of Singapore (SERIS).

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Standard high-precision measurements associated with the advanced loss analysis

The presented loss analysis is based on a set of high-precision measurements, i.e. secondary calibrated dark and light current–voltage characteristics (*J-V*) and full-area illuminated spectral response (internal quantum efficiency IQE and external quantum efficiency EQE), and effective carrier-lifetime measurements by the photoconductance decay method. A detailed quantification of the I_{sc}, V_{oc} and *FF* losses of the solar cell are provided, and thus the cell's most severe efficiency losses can be analyzed.

First, the electrical properties of the solar cell are determined. From the light *J-V* curve in Fig. 1(a), the standard solar cell parameters are derived, i.e. open-circuit voltage V_{oc}, short-circuit current density J_{sc}, fill factor *FF*, efficiency η, and maximum power point voltage V_{mpp} and corresponding current J_{mpp}. From the dark *J-V* curve in Fig. 1(b), the shunt resistance is determined by a linear fit in the –50mV to +50mV range. The series resistance under one-sun maximum power point conditions $R_{s,mpp}$ and the total recombination current (the effective saturation current density J_0) of the solar cell are then determined from the light and dark *J-V* measurements

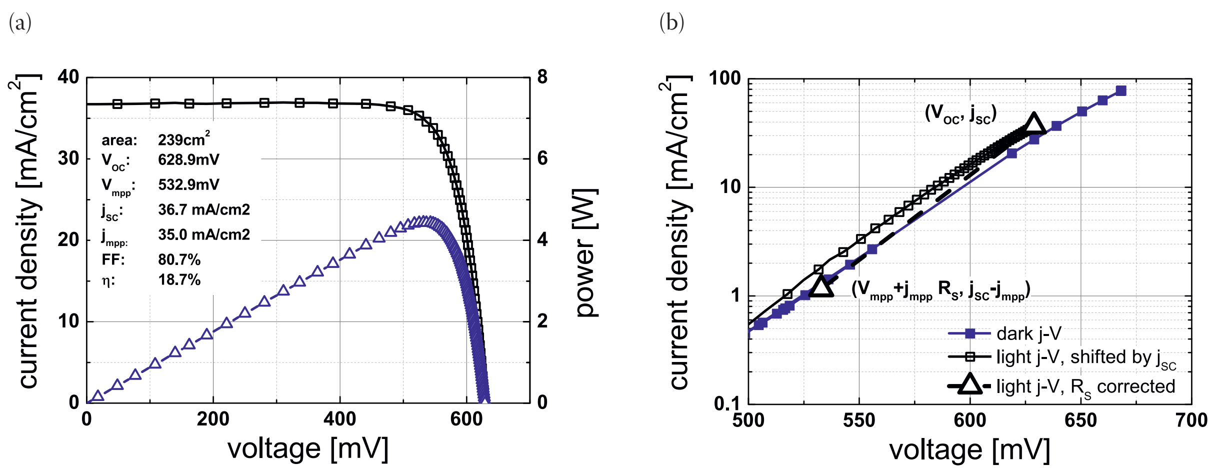

Figure 1. Current–voltage curve of a standard industrial p-type Al-BSF silicon wafer solar cell: (a) subjected to a one-sun illumination; (b) measurements taken in the dark.

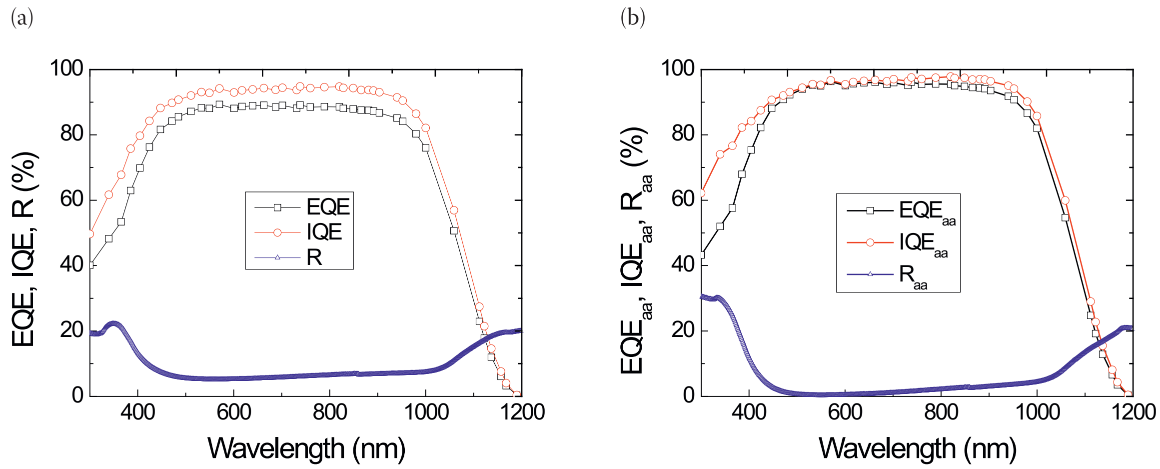

Figure 2. External and internal quantum efficiency and reflectance measurements of a standard industrial p-type Al-BSF silicon wafer solar cell: (a) full-area, and (b) active-area corrected.

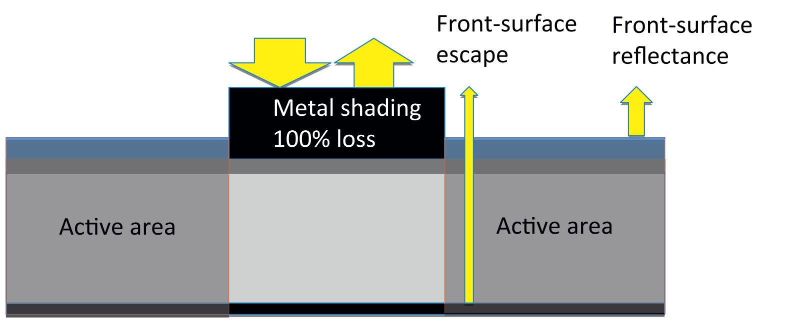

Figure 3. Schematic illustration of optical losses at the front of a silicon wafer solar cell.

using the method of Aberle et al. [2]. The experimentally determined full-area quantum efficiencies are then active-area corrected as shown in Fig. 2 (the correction is for reflection from the metallized areas as schematically depicted in Fig. 3).

In the following, the corresponding measurement results for a standard Al-BSF solar cell fabricated at SERIS (schematic shown in Fig. 6) are given.

Current losses

Quantification of the losses in the maximum power point current density (J_{mpp}) is carried out by applying a bottom-up loss analysis [1] that quantifies the seven most important current loss mechanisms, i.e. (1) front metal grid shading; (2) front-surface reflectance in the active area; (3) front-surface escape; (4) shunt resistance; (5) non-perfect active-area quantum efficiency; (6) forward bias current at the maximum power point ('diode recombination'); and (7) photon absorption within the front-side dielectric passivation/anti-reflective (AR) layer (i.e. silicon nitride SiN_x).

Current loss analysis

The various current losses are quantified at the maximum power point by applying relatively simple mathematical formulae [1]. The losses due to metallization, front-surface reflectance and front-surface escape (this is light that 'escapes' from the solar cell device without being absorbed – see Fig. 3) are calculated from the measurements and using the photon flux of the AM1.5G spectrum. The current losses due to shunt resistance and diode recombination are calculated from a one-diode model using the measured resistance at the maximum power point. The recombination losses in the solar cell are determined using the calculated IQE that is properly corrected for the non-ideal reflection by the front metal grid.

The resulting current losses for the investigated Al-BSF solar cell are shown in Fig. 4. It is clear from this that most of the current is lost by the non-perfect IQE of the solar cell, which explains the PV industry's interest in solar cell designs featuring a selective emitter and a passivated rear. The current loss due to metal shading is also significant, which is why all-back-contact solar cells and metal-wrap-through and emitter-wrap-through solar cells are attracting a lot of attention.

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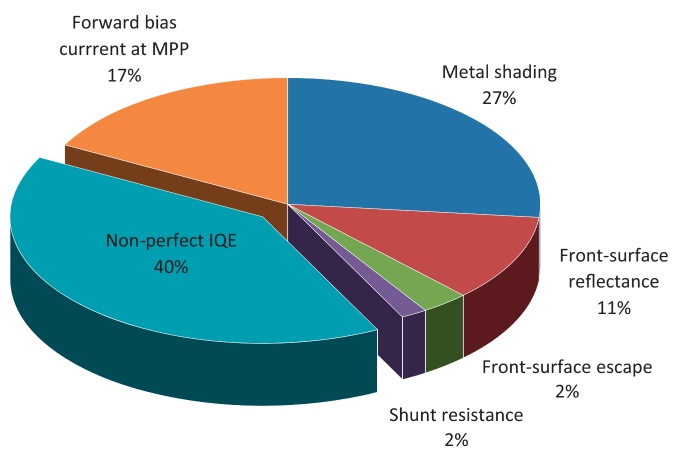


Figure 4. Pie chart of the relative current losses at the maximum power point for a standard industrial p-type Al-BSF solar cell. The total current losses amounted to 12.7mA/cm^2 in this specific case.

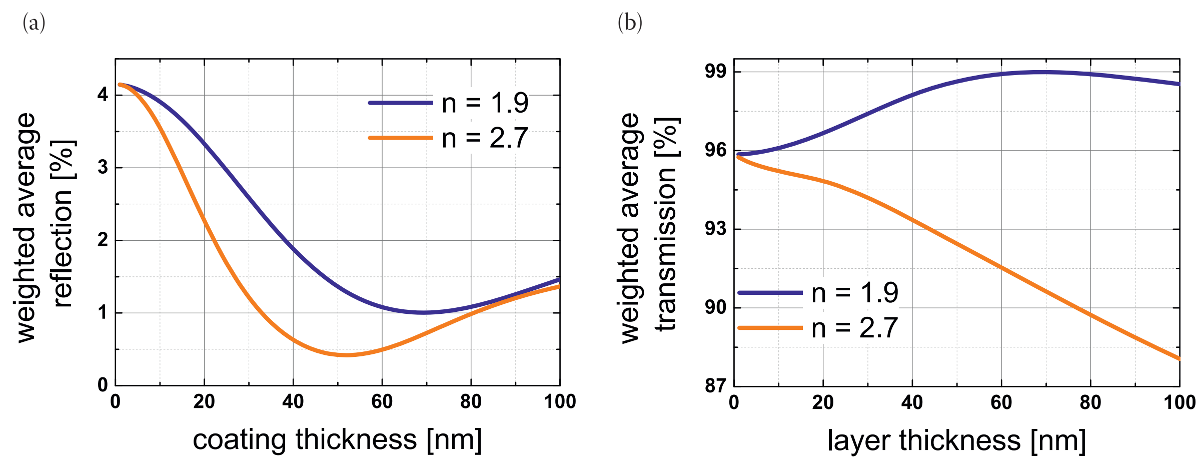


Figure 5. Investigation of two different coating materials with refractive indices n = 1.9 and n = 2.7 for a silicon solar cell with pyramidal texture and encapsulated with a material with refractive index n = 1.5: (a) calculated WAR, and (b) calculated WAT.

Absorption in the front-side silicon nitride passivation/anti-reflective coating

A current loss mechanism that is typically grouped under the 'non-perfect IQE' category is the parasitic photon absorption in the front SiN_x AR coating. Measuring the reflectance of the solar cell surface is not sufficient for an optimization of AR coatings to be performed if there is non-negligible absorption in the coating material. This is particularly important for AR coatings that are optimized for solar cells within PV modules. If account is taken of the optical properties of the encapsulation material and the glass cover sheet, the desirable refractive index for the cell's AR coating is actually higher than the refractive index for optimum reflectance in air. A higher refractive index is typically connected to a higher absorption coefficient and, consequently, causes higher parasitic absorption losses.

Unfortunately there is no direct way to measure the absorption in an AR coating once it is deposited onto a solar cell. Furthermore, the absorption losses occur in the short-wavelength range (< 500nm) and many of the materials used also absorb light in this region. Glass, ethylene-vinyl acetate (EVA) and silicon – either because of their large thicknesses or high absorption coefficients – absorb considerable fractions of the light. Moreover, these fractions are much larger than the fraction of light absorbed by the AR coating. This also makes an indirect extraction of the absorption by the AR coating from measurements very difficult.

The absorption by the AR coating can, however, be calculated very accurately if the optical material parameters – refractive index and absorption coefficient – are well known. For this purpose, a computer-based simulation method has been developed which allows the light absorption by the AR coating of a textured silicon wafer to be calculated. The method is based on work published elsewhere [4] and spectroscopic ellipsometry measurements of the optical parameters.

Rather than minimizing the reflectance from the solar cell surface, the method is used to maximize the fraction of light transmitted into the silicon. This can lead to significant differences in the assessment of the coatings. The example given in Fig. 5 shows the investigation of two AR coatings, with refractive indices of n = 1.9 and n = 2.7, on a silicon wafer with pyramidal texture and encapsulated with a material with refractive index n = 1.5 (corresponding to glass). The material with refractive index n = 1.9 has a very small absorption coefficient, while the material with n = 2.7 is considerably absorbent. Fig. 5 shows the weighted average reflectance (WAR) and the weighted average transmission (WAT). These two quantities represent the fraction of solar photons reflected or transmitted respectively, and are calculated via the expressions:

$$WAR = \frac{\int d\lambda\, \phi(\lambda) R(\lambda)}{\int d\lambda\, \phi(\lambda)}$$
$$WAT = \frac{\int d\lambda\, \phi(\lambda) T(\lambda)}{\int d\lambda\, \phi(\lambda)} \qquad (1)$$

where $\phi(\lambda)$ is the solar photon flux and $R(\lambda)$ and $T(\lambda)$ are the reflectance and transmission.

From the reflectance, which is the quantity that can be measured directly, the material with n = 2.7 appears to be more favourable. However, when looking at the transmission, it becomes clear that the material with n = 1.9 is the better choice. This is because the material with n = 2.7 shows a very strong absorption.

The example presented shows clearly that parasitic absorption needs to be considered in the optimization of AR coatings. As a general rule, if there is a choice between two AR materials, it is better to opt for the material with the lower absorption instead of the one with the more favourable refractive index. In the actual cell investigated in this paper, a coating material similar to the one with n = 1.9 was used. The contribution of AR coating losses to the non-perfect IQE is negligible for this material. However, the AR coating absorption will have a noticeable contribution in the case where higher index materials are required (for example if the cell is encapsulated or a stack is used).

> "If there is a choice between two AR materials, it is better to opt for the material with the lower absorption instead of the one with the more favourable refractive index."

Voltage losses

The open-circuit voltage of a solar cell is determined by internal cell recombination. The open-circuit voltage which would result if there were only bulk recombination (for a given wafer type) is considered to be the upper V_{oc} limit of the investigated solar cell. There are then four main loss mechanisms for the open-circuit voltage of the solar cell: (1) front-surface voltage loss due to surface recombination at the non-contacted (passivated) regions of the cell; (2) front-surface voltage loss due to surface recombination at the contacted regions (metal contacts) of the cell; and (3, 4) rear-surface voltage losses due to contacted/non-contacted solar cell regions. The total recombination can be specified by a total recombination current

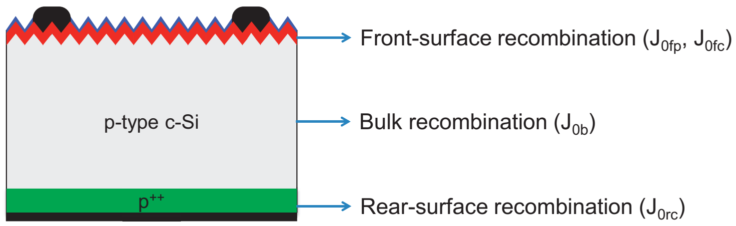


Figure 6. Sketch of a standard industrial Al-BSF solar cell, indicating the different solar cell regions which contribute to recombination losses.

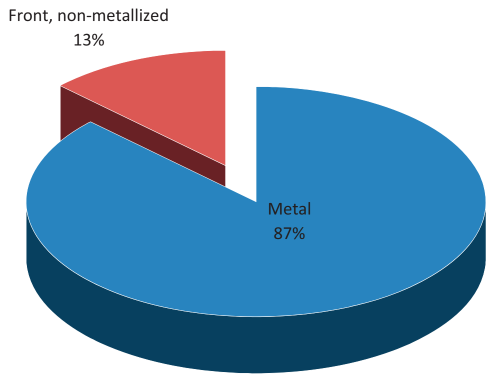


Figure 7. Voltage losses of a typical industrial p-type Al-BSF solar cell.

J_0 given by the equation

$$J_0 = J_{0b} + J_{0fp} + J_{0fc} + J_{0rp} + J_{0rc} \quad (2)$$

where J_0 is the sum of the individual components stemming from the bulk and the front and rear non-contacted/contacted regions respectively (see Fig. 6). The relationship between J_0 and V_{oc} is given by

$$V_{oc} = \frac{kT}{q}\ln\left(\frac{J_{sc}}{J_0}\right) \quad (3)$$

Because the doping level and the bulk lifetime of the starting wafers are usually known (or the maximum bulk lifetime can be evaluated using the model of Kerr-Cuevas [6,7]), the bulk recombination current J_{0b} can be easily calculated [5–7]. This in turn provides an upper V_{oc} limit that can be achieved with the particular wafers used. The surface recombination current J_{0fp} of the passivated (non-contacted) regions of the solar cell can be extracted from photoconductance decay measurements performed on symmetrically passivated lifetime samples according to the Kane-Swanson method [3]. The total surface recombination current associated with the front and rear metal contacts J_{0fc} and J_{0rc} can then be determined. This subsequently allows the open-circuit voltage to be calculated using Equation 3, and this value can then be compared with the measured open-circuit voltage. Alternatively, the individual components J_{0fc} and J_{0rc} can be measured by means of lifetime-calibrated photoluminescence spectroscopy.

As an example, Fig. 7 shows the relative V_{oc} loss of a typical industrial p-type Al-BSF solar cell. As can be seen, the main voltage losses, as expected, are due to the metallized regions of the solar cell (i.e. the full-area Al-BSF). This explains why the PV industry is moving towards passivated rear surfaces and reduced front-surface metallization.

> "The main voltage losses, as expected, are due to the metallized regions of the solar cell."

Fill factor losses

There are three main mechanisms for the fill factor *FF* losses of a solar cell: (1) loss due to series resistance (R_s); (2) loss due to shunt resistance (R_{sh}); and (3) loss due to non-ideal recombination. The two resistances R_s and R_{sh} (under maximum power conditions) are measured, and an advanced *FF* loss analysis [8] then allows the corresponding *FF* losses to be extracted.

Series resistance losses

The (measured) R_s of the solar cell under maximum power conditions can be broken down into more detail if the layout of the metal contact grid is known (see Fig. 8(a)). For simple contact-grid layouts (such as the H-patterned grid shown in Fig. 8(b)), there are several analytical programs available in order to calculate this breakdown [9].

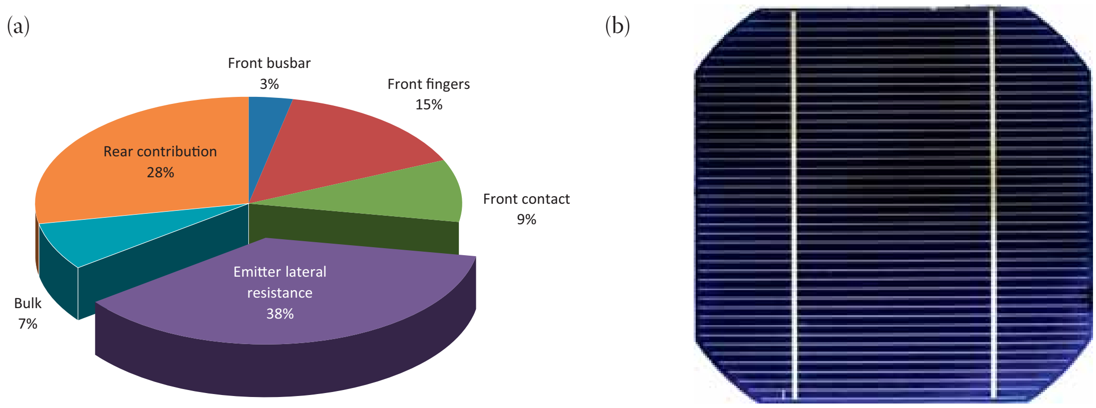


Figure 8. (a) Breakdown of measured series resistance of a standard industrial p-type Al-BSF solar cell processed at SERIS; (b) the simple H-patterned metal grid used. The total series resistance due to the front grid and the bulk were calculated to be 0.44Ωcm², and the remainder of the series resistance (0.16Ωcm² out of the total of 0.61Ωcm²) was attributed to the rear contact.

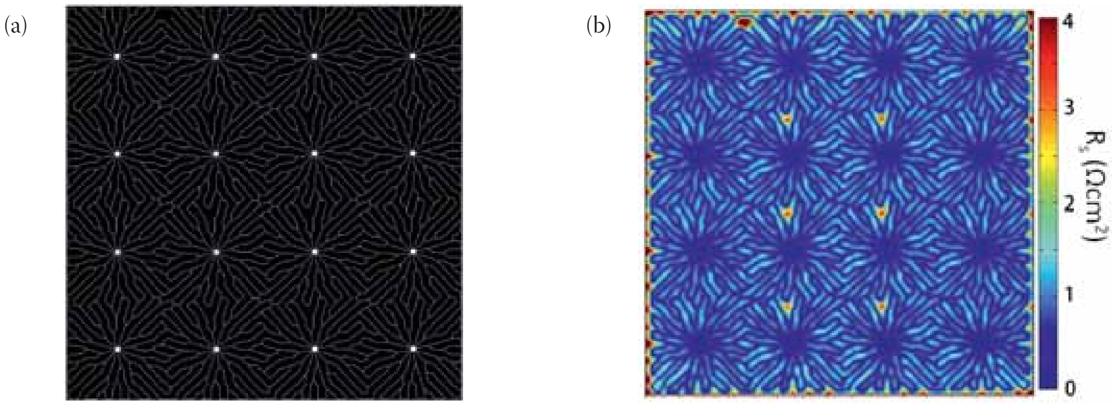


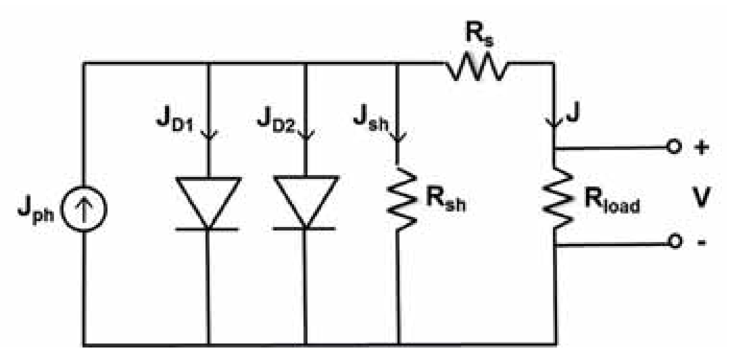
Figure 9. (a) Image of the front-side metal grid of a metal-wrap-through solar cell. (b) Corresponding local distribution of the series resistance of the solar cell under maximum power conditions, after being processed by the GRIDDLER software [10].

For more complicated (arbitrary) layouts, SERIS has developed its own software called GRIDDLER [10]. This software can import metal grid patterns from images and perform a meshing and a subsequent finite element analysis, for determining (for example) the percentage of R_s of the solar cell stemming from (1) the grid itself, (2) emitter lateral series resistance, (3) back-surface field lateral series resistance, and (4) bulk series resistance. Furthermore, a perturbation analysis allows the determination of how the grid patterns can be changed with the aim of attaining their optimum layouts.

Fill factor loss analysis

Taking the measured R_s and R_{sh} under maximum power conditions of the solar cell as input parameters, an advanced *FF* loss analysis [8] can be performed by describing the current–voltage characteristics of the solar cell via the two-diode model shown in Fig. 10. The *FF* of the solar cell is then determined by the diode saturation currents J_{01} and J_{02}, describing ideal and non-ideal recombination in the solar cell, as well as by the series and shunt resistances R_s and R_{sh}. To analyze *FF* losses, it is important to determine the relative contributions of these quantities.

An 'upper limit' fill factor FF_{J01} can be calculated by assuming only bulk recombination, in other words assuming no non-ideal second-diode recombination, no series resistance and an infinite shunt resistance. The loss in *FF* due to second-diode recombination currents (non-ideal recombination), and to R_s and R_{sh}, can then be calculated [8]. This is illustrated in Fig. 11 for the standard industrial p-type Al-BSF solar cell of Fig. 6. It is clear that R_s is the biggest contributor to the *FF* loss of this cell. However, for more advanced, higher-efficiency solar cells the contribution of the J_{02} component becomes larger. For such cells it is extremely important to know the root cause of the *FF* losses in order to devise the optimal strategy for improvement.



$$J = J_{ph} - J_{01}(e^{\frac{q(V+JR_s)}{kT}} - 1) - J_{02}(e^{\frac{q(V+JR_s)}{n_2 kT}} - 1) - \frac{(V+JR_S)}{R_{sh}}$$

Figure 10. Two-diode model of a solar cell, and the corresponding mathematical description of the *J-V* characteristics of the cell.

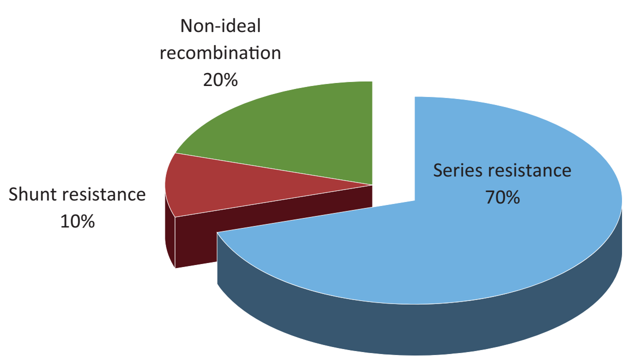


Figure 11. *FF* loss analysis of a standard industrial p-type Al-BSF solar cell.

> "The loss quantification method enables the largest root causes of poor cell performance to be focused on first, before 'turning knobs' to fine-tune secondary effects."

Conclusion

As remarked by Lord Kelvin 140 years ago, "To measure is to know." In this paper it has been shown that current, voltage and fill factor losses for silicon wafer solar cells can be fully quantified by a combination of high-precision measurements and relatively simple modelling. This analysis results in a 'health check' for the solar cell under test and clearly illustrates the most effective route for the manufacturer of the solar cell towards achieving higher efficiencies. The loss quantification method has been found to be extremely useful at SERIS for optimizing various types of solar cell design, as it enables the largest root causes of poor cell performance to be focused on first, before 'turning knobs' to fine-tune secondary effects.

Acknowledgements

The authors thank their colleagues from the Silicon Photovoltaics Cluster of SERIS for their assistance in sample processing and characterization. SERIS is sponsored by the National University of Singapore (NUS) and Singapore's National Research Foundation (NRF) through the Singapore Economic Development Board (EDB).

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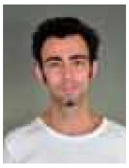
Prof. Armin Aberle is the CEO of SERIS at the National University of Singapore (NUS). His research focuses on reducing the cost of electricity generated with silicon solar cells (wafers and thin films). He is an editor of several journals and established the Silicon PV Department at ISFH in Germany in the 1990s. He then worked for 10 years in Australia, as a professor for photovoltaics at the University of New South Wales (UNSW). In 2008 Armin joined NUS to establish SERIS, with a particular responsibility for the creation of a Silicon PV Department.

Dr. Rolf Stangl is a senior research scientist at SERIS. He is a project leader for hybrid heterojunction solar cells and a competence team leader for electrical characterization/simulation. He was awarded his Ph.D. degree in organic solar cells for work conducted at Fraunhofer ISE in Freiburg, Germany, after which he worked for several years as a research fellow on silicon heterojunction solar cells at the Helmholtz Centre Berlin for Materials and Energy. After a sabbatical leave in Nanjing, China, Rolf joined SERIS in April 2011. He has (co-)authored many scientific papers and holds several patents in the area of wafer-based silicon solar cells.



Dr. Ian Marius Peters received his diploma in 2006 and his Ph.D. degree in 2009 in physics from the Albert Ludwig University of Freiburg, Germany. Between 2004 and 2011 he worked at Fraunhofer ISE, after which he joined the National University of Singapore (NUS) as a research fellow. Ian is head of the simulation group at SERIS, where he focuses on research in solar energy conversion, advanced optics and photonics, and material science. He has published more than 30 papers in peer-reviewed journals.

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