Quantitative evaluation of loss mechanisms in thin film solar cells using lock-in thermography

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We describe the measurement and modeling of lock-in thermograms for three differently processed crystalline silicon on glass thin film silicon solar modules. For the purpose of defect impact evaluation, a bias series of lock-in thermograms for a single cell in each module is measured. The resulting images around maximum power point bias show pronounced Peltier heat redistribution inside the cell, which needs to be taken into account for quantitative evaluation of the thermography results. This is done using a finite differences electronics simulation of the current flow inside the module and convolution of the heat distribution patterns with the thermal blurring. The procedure makes it possible to extract relevant cell performance parameters like the area diode dark saturation current and nonlinear edge shunting current densities as well as to evaluate the relative impact of these on the efficiency under simulated illumination. © 2011 American Institute of Physics. [doi:10.1063/1.3651397]

I. INTRODUCTION

Infrared lock-in thermography (LIT) is a useful characterization technique widely used in solar cell research.¹ An infrared camera captures a stream of temperature images of a periodically excited sample that is instantly lock-in correlated with the excitation frequency. The resulting images can be interpreted as a map of heat generation. Currently, LIT is mostly applied for wafer-based cells. The application to thin film cells is less developed.¹²,³ This is surprising since the low thermal conductivity of the glass substrate leads to appreciable thermoelectric cooling of the contact holes close to the edges––a lateral current flow that causes shunts. In the example, strong currents flow from the laser used in the interconnection procedure (pattern of point-like shunts). In the figure it can be seen that the homogeneous area of the contact holes to the edges is depleted, unlike microcrystalline Si, where Si crystallites are embedded in an amorphous matrix.

In this contribution we apply LIT to crystalline silicon on glass (CSG) modules.⁵ Instead of investigating large-scale inhomogeneities in the complete module,²³,⁶ we evaluate local phenomena in single cells. This approach takes advantage of what is known from investigations of wafer-based silicon solar cells.¹

The phenomena that are visible in a close-up of a single cell are summarized in Fig. 1. The contacting of both p⁺ and n⁻ layer of the p⁺-p-n⁻ structure is done via contact holes. In the figure it can be seen that the homogeneous area of the cell can be damaged due to the laser that separates the cells (lines at the upper and lower edge) and due to a structuring laser used in the interconnection procedure (pattern of point-like shunts). In the example, strong currents flow from the contact holes to the edges—a lateral current flow that causes appreciable thermoelectric cooling of the contact holes close to the recombination-active edges. Therefore the contact holes near the edges show a negative LIT signal.

In this contribution, we show how to gather quantitative information about the local diode properties from LIT in the presence of the disturbing thermoelectric heat redistribution. This is done using an electro-thermal simulation of the device. Additionally, the simulated structure allows reliable predictions about the effect of measures taken to improve the device. It is found that the edge recombination current is seriously affecting the efficiency of the investigated sample. The predicted efficiency increase of approximately 1% (abs.) is confirmed experimentally when etching the damaged cell areas.

II. SAMPLES AND PREPARATION

The samples analyzed in this contribution were produced in developmental tests at CSG Solar in Thalheim, Germany.⁷ The special feature of this thin film silicon on glass technology is that the Si is fully crystalline with no amorphous fraction left, unlike microcrystalline Si, where Si crystallites are embedded in an amorphous matrix.

In most thin film technologies, contacting is done monolithically using a transparent conducting oxide (TCO) for one of the contacts. CSG solar, in contrast, employs an unusual interdigitated contacting scheme,⁵ which consists of 0.5 mm wide Al pads spanning 2 cells each. Each contact pad has dozens of contact holes, half of which contact the n⁺ layer of one cell and the other half contact the p⁺ layer of the next cell. The whole back surface of the cell is covered by these Al pads. This interconnection scheme results in a low series resistance of the module but reduces shunting effects significantly due to its high resistance parallel to the cell axis. For details on the contacting and its shunt-reducing property, see Refs. ⁵ and ⁶.

Another effect of this contacting scheme is that sites of p⁺ and n⁻ contact holes are separated from each other in the image plane and thermoelectric cooling at the Si-Al contacts becomes clearly visible, see Fig. 1. The corresponding (macroscopic) thermoelectric heating close to the p-n junction is

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added to the dissipative heating through the junction current. Minority carrier effects like localized junction cooling are not visible in the thermograms since minority carrier diffusion lengths are in the order of magnitude of the cell thickness (1.5 μm), i.e., short compared to the imaging resolution. For details on the microscopic effects close to the p-n junction, see Refs. 8 and 9; for the absolute values of the Peltier coefficients, see Ref. 10.

The three samples investigated in this experiment differ mainly in the kind of light trapping structure on the glass (the other fabrication parameters are similar but also not constant). In the “abrade” texture, the glass is roughened by abrasive blasting followed by a dip in hydrofluoric acid. For the “beads” texture, silica beads (diameter approximately 0.5 μm) are deposited on the glass surface using a sol-gel process. The “planar” samples are made using untextured glass. For details on the texture and the CSG fabrication process, see Refs. 5, 7, and 11.

The edges of the individual cells are separated by 25 μm wide grooves, which is below the resolution of LIT for experimentally available lock-in frequencies (<100 Hz). At 100 Hz a signal amplitude drop of more than 3 dB is found for details smaller than 0.7 mm as compared to 2.3 mm for wafer-based silicon cells. For a detailed discussion of resolution in lock-in thermography in the case of thin-film structures, see Ref. 4. Therefore, signals from the edge of one cell cannot be safely distinguished from signals from the edge of the neighboring cell. To avoid this difficulty and other module effects, single cells were contacted. This was done by evaporating 50 nm gold layers which short the neighboring cells and applying conductive adhesive (see the contacting scheme shown in Fig. 2(a)). Contact resistance to the conductive adhesive used seems to be a problem, which is why a 4-terminal contacting scheme as shown in Fig. 2(b) was adopted.

All LIT measurements were performed on samples covered by a 25 μm thick black polyethylene foil for high and homogeneous emissivity.

III. SERIES RESISTANCE AND PELTIER COEFFICIENT

In order to correct for the thermoelectric heat transport visible in Fig. 1, the Peltier coefficient of the highly doped p+ and n+ regions in the cell must be known. It is highly desirable to measure them on samples as close to the production module as possible. Using the thermographic procedure outlined in Ref. 12 the Peltier coefficient can be measured on series resistance test structures made using a processing sequence that differs only slightly from that of a regular module. As described above, the interdigitated pattern of Al pads and p+ and n+ contact holes makes the series connection between the cells. If only one type of contact holes is used, i.e., replacing one half of the contact holes, the current follows similar paths, but never crosses the p-n junction. Such test structures were used to measure the Peltier coefficients.

In a purely resistive test structure, the Joule and Peltier heating signals can be separated by adding and subtracting the signals $S$ at forward (+) and reverse (−) bias

$$S^+ = (S^+ + S^-)/2,$$

$$S^- = (S^+ - S^-)/2.$$

Joule and Peltier signals of the p+ resistance test structure are shown in Fig. 3. The contact holes carry a current corresponding to the short circuit current of the module ($\approx 25$ mA/cm²), the excitation frequency was 25 Hz.
Applying a quantitative evaluation procedure, a Peltier coefficient of (+90 ± 5) mV can be derived. Similar images for the n⁺ region give a value of (−90 ± 5) mV. These values are a function of the doping and, to a lesser degree, purity and geometry due to the phonon drag effect. The measured values correspond to dopant concentrations in the order of 10¹⁹ cm⁻³ as used in the highly doped layers of these modules. For these high concentrations, the dependence of the Peltier coefficient on the concentration is rather weak, such that the measured values are applicable to other modules as well.

Apart from the Peltier coefficient information, the images allow an evaluation of the relative importance of contact resistance and sheet resistance effects. The Peltier image shows the damaged region close to the cell edges is almost free from that kind of error.

**IV. SIMULATION**

For a complete simulation of dark lock-in thermography images both the electrical and thermal behavior of the cell must be modeled. The images are given through the (dissipative and thermoelectric) heating power density distribution as well as heat conduction inside the sample. The electrical behavior is found from a custom 2D finite differences simulation. Heat conduction can be modeled by a convolution of the heat source distribution with the thermal point spread function (PSF). Then, using measured values for the sheet resistance and Peltier coefficients as well as reasonable starting values for the cell parameters, an iterative fit between a range of simulated and experimental images can be done.

**A. Electrical simulation: Finite differences method**

The electrical behavior of the cells under investigation is determined numerically using a finite differences approach and solved using a successive over-relaxation algorithm. The 1.5 μm thick structure is assumed to be 2D only, with horizontal current densities \( j_{p,n} (A/m) \) in the p⁺ and n⁺ layers of the diode and a vertical current density \( j_{diode} (A/m²) \) crossing the junction. From the equation of continuity and the definition of the electrical potential in the highly doped layers

\[
\begin{align*}
\nabla \cdot j_p &= -j_{diode}, \\
\nabla \cdot j_n &= +j_{diode}, \\
-\nabla V_p &= R_{sh}^p j_p, \\
-\nabla V_n &= R_{sh}^n j_n
\end{align*}
\]

The diode current in the cell area and at the cell edges is assumed to follow a diode equation

\[
j_{diode} = j_0 \left[ \exp \left( \frac{V_{p} - V_{a}}{n k T / e} \right) - 1 \right] - j_L.
\]

with a single ideality factor \( n \). Resistive effects cannot influence the value of \( n \) since the local bias \( (V_p - V_n) \) is used in the equation. A possible bias dependency of the ideality factor itself is not taken into account. The light-induced current density \( j_L \) is not used in the simulation of dark lock-in thermography but to assess the relative importance of the loss mechanisms in the simulation for the energy conversion efficiency.

<table>
<thead>
<tr>
<th>Structure</th>
<th>( R_{sh}^p (\Omega) )</th>
<th>( R_{sh}^n (\Omega) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abraade</td>
<td>474 ± 11</td>
<td>401 ± 8</td>
</tr>
<tr>
<td>Beads</td>
<td>557 ± 8</td>
<td>445 ± 7</td>
</tr>
<tr>
<td>Planar</td>
<td>493 ± 28</td>
<td>407 ± 21</td>
</tr>
</tbody>
</table>

*Table I. Sheet resistances, measured for 30 adjacent pad-to-pad distances of 1 mm. The value for a single measurement is well reproducible, and the given variation is mostly due to deviations in the contact hole placement.*
represented by an additional contribution to the diode current with a separate ideality factor and saturation current density.

Assuming constant sheet resistances \( R_{\text{p,n}}^{\text{sh}} \), Eq. (3) leads to

\[
\begin{align*}
\nabla^2 V_p &= + R_{\text{p}}^{\text{sh}} j_{\text{diode}}, \\
\nabla^2 V_n &= - R_{\text{n}}^{\text{sh}} j_{\text{diode}}.
\end{align*}
\]

Current densities and potentials as well as finite differencing close to a contact hole are visualized in Fig. 4.

Special boundary conditions apply for the contact holes. There, the value of the potential is fixed and an additional term is added to the equation of current continuity: current flow to/from the environment. Another detail easily implemented into the finite differences model is that for each deep contact hole \( n^- \) the p-n junction is locally removed.

The finite differences calculation gives arrays of values for the potentials, the diode current, the sheet resistance current, and the contact hole currents. With this data it is straightforward to draw a map of power dissipation, i.e., Joule heating in the sheet resistances and \((V_p - V_n) \cdot j_{\text{diode}}\) at the p-n junction. The thermoelectric heat transport from the contact holes to the p-n junction is calculated using measured values for the Peltier coefficients. The sum of both effects is the 2D heat source distribution \( Q(x,y) \).

**B. Thermal simulation**

The spreading of the heat caused by dissipative and Peltier effects in the module is fully described by the system’s temperature response to an oscillating point-like source, the (complex-valued) PSF, \( P(r) \). The temperature field as a response to a 2D heat source distribution \( Q(x,y) \) is then given as the convolution of the heat source distribution with the point spread function. This convolution corresponds to a multiplication with the thermal transfer function (TTF) in Fourier space.

\[
T_m(x,y) = F^{-1}\left(F[Q(x,y)] \times F(k_x, k_y)\right).
\]

The TTF \( F(k) \) is related to the PSF through \( F(k) = F[P(r)] \). The advantages of using the TTF instead of the PSF are that Eq. (6) is numerically more efficient than a direct convolution and that, in contrast to the PSF, the TTF has a simple analytical expression for our problem of a thick substrate with a thin, highly heat conductive layer on top.

\[
F(k) = \frac{1}{d_f l_f/(D_f + k^2) + \lambda s \sqrt{1/\omega D_s + k^2}},
\]

with \( k^2 = k_x^2 + k_y^2 \) spatial frequency, \( \omega = 2\pi f \) excitation angular frequency, \( D \) diffusivity, and \( \lambda \) thermal conductivity. The index \( f \) refers to the thin silicon film (the active cell) of thickness \( d_f \) and the index \( s \) to the glass substrate.

The result of the convolution (6) is a map of temperature modulation amplitude in mK and signal phase. This temperature modulation is the solution of the heat equation for the given heat source distribution. The highest signal-to-noise ratio for a single-phase signal is found for the \(-45^\circ\) signal. This signal can also be normalized to units of W/m^2 for straightforward comparison with the experimental data. A detailed description of the TTF and its properties as well as the derivation of Eq. (7) can be found in Ref. 4.

Strictly speaking, the simulation of the thermal behavior is not valid at the cell edges since the laser grooves separate the silicon layer and heat transport can only occur through the glass at these locations. The effect of the cut silicon layer is reflection of the heat that is being transported inside the silicon leading to an asymmetry in the temperature pattern for a source at the groove edge. The average intensity is not influenced by the laser groove. Therefore we use the simple convolution (6) for the whole cell including its edges, which is justified if the asymmetry of the profile close to the cell edge is taken into account in the evaluation.

**V. RESULTS**

All experimental thermograms were measured using a Thermosensorik TDL 640 setup equipped with an InSb detector camera sensitive in the mid-range IR (3–5 μm). A square-wave (rectangular) bias of 300, 350, ..., 500 mV was applied. The samples were thermostatted at (25 ± 1)°C. To obtain a good signal-to-noise ratio, the low-voltage images were integrated for up to 2 h. Higher cell voltages are not interesting since higher voltages lead to currents that are much higher than the typical short circuit current density of \( \approx 25 \text{ mA/cm}^2 \) in these modules.

The lock-in frequency was chosen to be 10 Hz at a frame rate of 100 Hz. This corresponds to a drop in signal amplitude of more than 3 dB for details smaller than 1.4 mm. All except the first harmonic of the response to the square-wave excitation is filtered out by the correlation procedure. At a rate of 10 frames per lock-in period, the suppression of high harmonics is already strong. Therefore, the thermal response to harmonic excitation as given by Eq. (7) is...
appropriate for the evaluation. Lower excitation frequencies than 10 Hz would lead to a lower spatial resolution of the thermograms.

Due to the linearity of the heat equation, the complex lock-in signal has a direct proportionality to the heat production. This is not true for the amplitude and phase images since these are found using nonlinear operations (square and arctan, respectively). Furthermore, positive (heating) and negative (cooling) signals occur which cannot be found from the amplitude image, since it is always positive. The best signal-to-noise ratio for homogeneous sources is found for a real-valued signal at a phase angle of $\frac{-45^\circ}{\sqrt{2}}$ of the complex-valued signal $S(x,y)$

$$S_{-45^\circ}(x,y) = \frac{\text{Re} \tilde{S}(x,y) - \text{Im} \tilde{S}(x,y)}{\sqrt{2}}.$$  \hfill (8)

This is true for excitation frequencies below 100 Hz as may be verified by evaluating Eq. (7) for homogeneous excitation, $k = 0$. This phase angle was used for all images, both experimental and simulated.

### A. Experimental and simulated thermograms

Applying the iterative fit procedure described above to the measured thermograms, a satisfactory fit is reached for the set of parameters detailed in Table II. The experimental and simulated $-45^\circ$ images for all three sample types are shown in Fig. 5. A change of dark saturation currents $j_0$ of $\pm 10\%$ results in appreciable deviations of experimental and simulated images; this is a measure of the experimental uncertainty of the fit procedure. The ideality factors $n$, too, are subject to uncertainty; $\pm 0.2$ for $n_{\text{area}}$ and $\pm 0.5$ for $n_{\text{groove}}$. This implies corresponding changes of the respective $j_0$ values. Groove currents flow in line-shaped regions along the cell edges (at least as resolved by LIT), the natural unit would therefore be A per cm cell length. For better comparison with area currents, the groove currents were normalized with the cell width of 0.6 cm.

Given these values, several trends can be seen in the experimental and simulated images in Fig. 5. The experimental images show three distinct loss mechanisms: area currents, groove currents, and damaged points (only in the abrade and planar sample). For negative bias only low signal amplitudes are observed for all three mechanisms, indicating their diode-like characteristic. The relative intensity, however, shifts for different bias voltages. For very low bias (<200 mV) the point-like defects are dominant over the groove signal and the area signal is small. With increasing bias, first the influence of the damaged points diminishes until (at bias $\geq$500 mV) the area current dominates the signal. The shift of contrast is due to the differing ideality factors $n$ of the three loss mechanisms, with the damaged points having the highest, the groove currents an intermediate, and the area current the lowest $n$. Such behavior is known from wafer based solar cells, where laser-damaged areas may well lead to very high ideality factors ($n > 4$). The physical mechanism that causes diode-like behavior with very high ideality factors in these localized areas can be explained theoretically assuming donor-acceptor-pair recombination via deep levels.

The recombination currents and ideality factors in the homogeneous area of the cell, in contrast, can be understood

<table>
<thead>
<tr>
<th></th>
<th>Abrade</th>
<th>Beads</th>
<th>Planar</th>
</tr>
</thead>
<tbody>
<tr>
<td>$j_0$,$\text{area}$ (mA/cm$^2$)</td>
<td>$3.0 \times 10^{-4}$</td>
<td>$2.3 \times 10^{-4}$</td>
<td>$1.6 \times 10^{-4}$</td>
</tr>
<tr>
<td>$n$,$\text{area}$</td>
<td>1.8</td>
<td>1.6</td>
<td>1.7</td>
</tr>
<tr>
<td>$j_0$,$\text{groove,left}$ (mA/cm$^2$)</td>
<td>$9.1 \times 10^{-2}$</td>
<td>$2.1 \times 10^{-3}$</td>
<td>$1.1 \times 10^{-3}$</td>
</tr>
<tr>
<td>$j_0$,$\text{groove,eight}$ (mA/cm$^2$)</td>
<td>$5.9 \times 10^{-2}$</td>
<td>$2.0 \times 10^{-3}$</td>
<td>$2.2 \times 10^{-3}$</td>
</tr>
<tr>
<td>$n$,$\text{groove}$</td>
<td>4.5</td>
<td>2.5</td>
<td>3.0</td>
</tr>
</tbody>
</table>

FIG. 5. (Color online) Experimental (left) and simulated (right) thermograms for the abrade and bead textured sample as well as the untextured sample (HE0431−3, 6, 9). Data at 350 and 450 mV not shown; all scalings in mW/cm$^2$. 

TABLE II. Best values for the manual fit shown in Fig. 5.
by established theory. Five recombination processes are known to occur: radiative recombination, Auger recombination, surface recombination, bulk Shockley-Read-Hall (SRH) recombination in the base, and depletion region SRH recombination. Radiative recombination is a negligibly small contribution in silicon devices. Moderate Auger recombination is present in the highly doped layers of the cell structure but is not dominant due to their low thickness (p+ and n+ both about 100 nm in the ≈1.5 μm thick silicon layer). Compared to the emitter region in bulk silicon solar cells, where Auger recombination is strong, the doping in the n+ and p+ region is more than a factor of 10 lower, which reduces the impact of Auger recombination by a factor of 10^2. Therefore it is also neglected in the following.

Bulk SRH recombination at defect states and surface recombinations both show an ideality factor of n = 1 (if the lifetime is independent of carrier concentration) and can be treated jointly using an effective minority carrier (electron) lifetime \( \tau_{e,\text{eff}} \) (Matthiessen’s rule)

\[
\tau_{e,\text{eff}}^{-1} = \tau_{e,\text{defect}}^{-1} + \tau_{e,\text{surf}}^{-1}. \tag{9}
\]

The recombination current due to these two mechanisms is then

\[
j_1 = \frac{e\sqrt{D_e n_i^2}}{s_{\text{eff}} N_A} \exp\left(\frac{eV}{kT}\right), \tag{10}
\]

with the electron diffusivity \( D_e \), the carrier concentration in intrinsic silicon \( n_i \), and the doping density \( N_A \) in the p-type base.

Even a simple textbook model\(^{17}\) of depletion region SRH recombination shows two important properties

\[
j_2 \propto \frac{1}{\tau_{e,\text{eff}}} \exp\left(\frac{eV}{n kT}\right). \tag{11}
\]

It is proportional to 1/\( \tau \) and has an ideality factor \( n \approx 2 \). The ratio of \( j_1 \) and \( j_2 \) at a given bias is thus a function of the lifetime since the former is proportional to 1/\( \sqrt{\tau} \) and the latter to 1/\( \tau \). Therefore homogeneous depletion region recombination will be dominant for very short minority carrier lifetimes.

In wafer-based solar cells the contribution of a one-dimensional, homogeneous depletion region current according to (11) is negligible (the \( n = 2 \) diode contribution in the 2-diode model is of a different and inhomogeneous origin).\(^{15,18}\) For lower lifetimes as given in the thin film silicon devices investigated, the \( j_2 \) contribution may be dominant.

The measurements indicate that this is in fact the case. More detailed calculations of the \( j_2 \) contribution (both analytical\(^ {19,20}\) and numerical\(^ {18}\)) give ideality factors \( n \) in the range of 1.6–1.85 instead of 2 as in the approximate model.\(^ {17}\) The exact value of \( n \) depends on the doping profile and the energy of the recombination active defect states. Therefore, the measured ideality factors (Table I) are a strong indication of the dominance of SRH depletion region recombination. An order of magnitude calculation shows that also the absolute value of \( j_2 \) indicates SRH depletion region recombination as the dominant mechanism. Using the detailed calculations of Ref. 18 to determine \( \tau_{e,\text{defect}} \) values of 3, 4, and 7 ns are found for the lifetimes in the three samples (abrade, beads, and planar) corresponding to diffusion lengths of between 3 and 5 μm. These values are sufficient for a good collection efficiency in the thin film device and therefore plausible. Assuming that the surface recombination lifetime is not orders of magnitude lower than \( \tau_{e,\text{defect}} \) (i.e., adequate surface passivation), then, Eq. (10) gives \( n = 1 \) currents much lower than those calculated according to Ref. 18 which confirms the dominance of SRH depletion region recombination in these devices.

The simulation does not include the damaged points, which leads to a visible deviation between experiment and simulation for very low bias. The pattern of the points can be correlated to the laser used to structure the Al layer on the back of the sample (Fig. 2(a)). At certain locations the laser passes two times due to the programming of the structuring sequence. Especially during the second pass this may lead to damage in the semiconductor since at the second pass the reflecting Al layer is already completely removed. Although these damage sites are clearly visible in the thermograms, even in the sample where they are strongest (planar), they start to dominate the overall characteristic only for bias voltages below 200 mV, i.e., well below the maximum power point of the cell. Therefore it is admissible to treat the effects of the damaged points as a small contribution to the area current in the fit procedure.

An interesting property of the thermograms is a bar pattern that becomes visible at high bias. Below every second row of contact holes (visible in the images as sites of Peltier cooling), the area current is markedly increased resulting in a pattern of high and low signal. The reason is that the sheet resistance through the p+ layer is higher than in the n+ layer (see Table I). Thus the current path from the p+ contact hole directly through the p-n junction and through the n+ sheet resistance to the n+ contact holes is preferred resulting in a higher signal under the p+ contact holes. For a solar cell under illumination, this series resistance effect leads to slightly different operating points for regions under n+ and p+ contact holes and thus a reduced efficiency. The strength of this effect as well as the relative influence of the groove recombination will be investigated in Sec. V B.

B. Relative influence of the loss mechanisms

Given the good agreement between simulated and experimental images, the influence of measures taken to reduce individual loss mechanisms may be evaluated in the simulated cells. To that end it is necessary to know the light-induced current density in the device, which is influenced by the quality of light trapping structures including the glass texture. Since these are not available from LIT data, they are taken from the values measured directly after the production of the whole 122 × 105 cm^2 modules, normalized to the sample size.

One possibility to improve the performance of these modules is to remove the laser-damaged areas at the cell edges (grooves) through an additional chemical etching step. The potential effect of this measure can be simulated by...
setting the dark saturation currents of the edge diodes $J_{0, groove} = 0$. The calculation shows a potential for a significant increase in cell performance, especially for the abrade textured sample: 1.3% absolute increase in efficiency (0.4% for the bead textured sample, 0.2% for the planar sample).

As described in the previous section, the differing sheet resistances in the $p^+$ and $n^+$ layers lead to an inhomogeneous cell voltage under illumination which is known to affect the cell efficiency negatively. In order to estimate the impact of this effect, the $p^+$ and $n^+$ sheet resistances were simulated to be equal (the average of the two). The influence of this measure is, however, negligible.

VI. CONCLUSIONS

In this contribution, dark lock-in thermography images of CSG solar modules were evaluated quantitatively. In order to correctly account for prominent thermolectric heat redistribution visible in LIT, a reverse simulation was used to infer the cell parameters (dark saturation currents and ideality factors) of the individual loss mechanisms. The electronic behavior was modeled using a finite differences approach for simple implementation of the boundary conditions associated with the unusual contacting scheme. The thermal behavior under excitation was modeled using the thermal transfer function for a highly heat conductive layer on a thick glass substrate.

Three loss mechanisms were identified and quantified: The influence of point-like nonlinear shunting due to the laser structuring the Al interconnection pads was found to be negligible under operating conditions. Also the prominent feature of a bar pattern in the thermograms was found to be of no consequence to the cell performance. The edge recombination, however, was found to be a major factor limiting the efficiency of the modules investigated.

In direct consequence of the results presented in this contribution, several process optimizations were carried out by CSG Solar with the effect that an efficiency increase was realized consistent with the values predicted by the simulation.

ACKNOWLEDGMENTS

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