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### 1.1 1 Bగగాoduction

If you're a first time user of Griddler, congratulations! Griddler is an easy to use solar cell simulation program, and the manual merely serves as an occasional reference. If you have used Griddler already for some time, we work hard to make sure it continues to serve your practical needs. New features are continually added (e.g. rear local contact calculator, cell parameter database, from PRO version June 2016; cell cross sectional diagram with interface to cmd-PC1D emitter calculator, from PRO version October 2017) while other features are made easier to use and standardized (e.g. efficiency improvement diagrams workflow automated in PRO version April 2018; emitter sheet resistance, cmd-PC1D interface Joe and IQE calculations benchmarked against EDNA2 in PRO version May 2018). We make Griddler simple and powerful enough to use in our daily work to design, simulate and understand the limiting factors of solar cells, and we hope that it is just as easy to use in your specific work.

Griddler was created at the Solar Energy Research Institute of Singapore (SERIS) in 2013. In the years since, it continually evolved to help companies improve their solar cells, in a development cycle that can be described by the chain below.


Over time, we made Griddler the platform to design solar cells, calculate solar cell efficiency, quantify limiting factors, store published cell parameters gathered from all over the world, and predict the rooms for improvement by employing different design changes. It also works seamlessly with SolarEYE, which is a luminescence imaging platform that images and analyzes lab based cells and wafer samples, allowing the researcher to understand what are the main areas to improve in actual cells that are made in the manufacturing environment.

A lot of thought have been put in to make Griddler easy to use, practical, rigorous, and powerful. We hope that it suits your needs.

## 



The core of Griddler is a finite element model (FEM) representation of the solar cell planes as shown above. Generally there can be 1 to 8 planes: simplest case being 1 plane to describe a simple grid on the front
side, while the rear side is assumed to be perfectly laterally conductive and at ground potential, which would be the case if the user chooses "Full Area Rear Chuck Contacting" under the Rear Current Extraction option in the simulation page, see 2.7.4; most complex case is that for each of the front and rear sides there are separately the semiconductor plane, metal finger plane (if there is contact resistance between the fingers and semiconductor), metal busbar plane (if the user chooses dual print to make the busbars "floating"), and ribbons plane (if the user chooses "Solder ribbons at probe points" under the Current Extraction option. In the FEM representation, these planes (except the ribbons planes) are finely broken down into triangular meshes to implement the network model of the solar cell. The above picture shows a triangle element on each of the meshed front and rear semiconductor planes in green. The corners of the triangles are called nodes and each node has a voltage. The edges of the triangles connect the nodes together via resistors whose values depend on the sheet resistance of the region (e.g. relatively high values for semiconductor, low values for metal fingers and busbars), as well as the triangle shape according to the Galerkin method.

In each of the front and rear planes, if there are ribbons defined, then the ribbons are connected to the planes below wherever there is a solder/probe point (see 2.7.4). There is either a direct connection with no voltage drops, or a connection via a resistor if the user chooses nonzero contact point resistance (see 2.7.1). If the busbars are floating, then the busbar plane form intersecting nodes with the metal fingers plane as points of connection. If there is nonzero metal-semiconductor contact resistance, then each node on the metal fingers plane is connected to a node at the same position on the semiconductor plane via a contact resistance. If there is zero metal-semiconductor contact resistance, then the fingers and semiconductor planes are merged together as one.

Between the front and rear semiconductor planes is a sandwich layer where the photovoltaic properties of the solar cell are implemented. This sandwich layer provides a small equivalent circuit that connects to each node of the semiconductor layers, as shown inside the dotted blue boxes above. The equivalent circuit is also called the two diode model, because it is defined by two diodes of different I-V characteristics in describing the recombination currents happening inside the node. An additional current source is in parallel to these diodes to describe the light-induced current, and a parallel shunt conductance is used to describe shunt currents if any. The I-V characteristics of the equivalent circuit is

$$
\begin{gathered}
I\left(V_{\text {diode }, i}\right)=I_{L, i}-I_{01, i} \exp \left(\frac{q V_{\text {diode }, i}}{k T}\right)-I_{02, i} \exp \left(\frac{q V_{\text {diode }, i}}{2 k T}\right)-G_{\text {shunt }, i} V_{\text {diode }, i} \\
V_{\text {diode }, i}=V_{\text {node }, i}-V_{r e f, i}
\end{gathered}
$$

Where $V_{\text {diode, }, i}$ is the voltage across the equivalent circuit, $q$ is the elementary charge, $k$ is the Boltzmann constant, $T$ is the cell temperature in Kelvin. $I_{L, i}$ is the light induced current, $I_{01, i}$ and $I_{02, i}$ are the saturation currents of the $\mathrm{n}=1$ and $\mathrm{n}=2$ diodes, and $G_{\text {shunt, }, i}$ is the shunt conductance. $V_{\text {diode }, i}$ is given by $V_{\text {node }, i}-V_{\text {ref }, i}$, where $V_{\text {node, }, i}$ is the voltage of the node $i$ of concern, and $V_{\text {ref, } i}$ is an interpolated value of the voltage on the opposite semiconductor plane at the position of the node $i$. With this, we can formulate the current continuity condition at node i using Kirchhoff's node law:

$$
\sum_{\begin{array}{c}
\text { neighbour } \\
\text { nodes } j
\end{array}} \frac{V_{\text {node }, j}-V_{\text {node }, i}}{R_{\text {series }, i, j}}+I\left(V_{\text {diode }, i}\right)=0
$$

This allows a system of equations to be constructed for the voltages of the nodes to be solved iteratively. Once the semiconductor node voltages are solved on each plane, $V_{\text {diode, } i}$ and $l\left(V_{\text {diode, },}\right)$ are also simultaneously determined. The overall current of the solar cell is then simply the sum of $l\left(V_{\text {diode, },}\right)$ across all nodes on either the front or rear semiconductor planes, and the overall voltage of the solar cell is then the difference between the front node voltage where current is extracted, and the rear node voltage where current is extracted.

The operating point of the solar cell is defined by the level of illumination, as given by $I_{L, i}$, and the terminal voltage which sets the boundary condition of the front nodes where current is extracted. The rear node voltage where current is extracted is usually set to zero (ground). By a step and repeat process where the terminal voltage is varied and then the cell voltage is solved, one forms the overall I-V characteristics of the solar cell.

### 2.1 In

Both Griddler 2.5 free and PRO versions installers can be downloaded for 32 bit or 64 bit windows computers. The installation process is automatic and easy to follow and is described by the diagram below. Griddler is written in MATLAB and requires the Matlab compiler runtime (MCR R2013b) to run. The installer will autodetect the presence of the correct MCR version and download it if it is missing.


By default, you should be able to launch Griddler either from the start menu (below), or from C:IGriddler2_5 \Griddler2_5.exe (free version) C:IGriddler2_5_PRO\Griddler2_5_PRO.exe (PRO version).


If you use the PRO version, Griddler 2.5 PRO needs either a physical USB dongle provided by us or online activation to run. Either method requires periodic internet connection (for USB dongle about once a month; for online activation about once a day). The USB dongle looks like the one shown below and needs to be plugged into the computer while the program is running.


When you run the program for the first time, if it doesn't detect the USB dongle, then a pop up screen will show up with the following options. Select the appropriate (software bundle $=$ Griddler 2.5 PRO + Griddler IBC + Module simulation program purchase; standalone $=$ Griddler 2.5 PRO only).


Then you will be give the option below to enter a product key. Use the one provided to you and you can then continue to use the program.


## 2.2 목만도 Quick Guide

Upon launching Griddler, a splash screen should appear. Wait patiently for the program to launch as for the first time it may require half a minute or so to load the MCR. The front pages of Griddler 2.5 free and PRO versions are very similar and have four main options.


Griddler 2.5 Free Version Front Page


Griddler 2.5 PRO Front Page

Griddler work flow is very easy to navigate:


## 2.3

For Griddler 2.5 PRO, we roll out periodic updates, and you'll be notified of one when you reach the simulation page (below). Please be diligent, and click "Take Me to the Download Page" and download the latest installer. You can simply run the installer and it will overwrite the previous Griddler version from your computer.


The cell parameter database (see 3.2) is also periodically updated, about once each month. Griddler 2.5 PRO automatically searches and downloads the updates the first time you access the database after launching the program (below).


You can always check your version numbers by clicking "About" on the top menu bar. Hit "Download Release Notes" to see the changes made in each version of Griddler 2.5 PRO.


### 2.4 Desigun గ Pattern Page



The design phase of the solar cell often begins with the Design H-Pattern Page in Griddler. As most cells have an H -pattern metal grid, this page suffices for most cell designs. For non H pattern cells such as
metal wrap through (MWT) structures, you can design an aribitrary shaped metal pattern in AutoCAD and then import that pattern into Griddler (see 2.6). Above we show the Design H-Pattern Page and below we illustrate what the various options do.


Wafer type is the general shape: square is typical of multicrystalline wafers; pseudo-square is typical of monocrystalline wafers. Circular is typical of lab sized wafers.


For pseudo-square shape typical of monocrystalline wafers, ingot diameter defines the diagonal of the wafer.


If you choose Shingled Pattern, the cell will have only one busbar on each face of the wafer, placed along the wafer edge. Typically, shingled cells are cut from square or pseudo-square wafers, so that the wafer length is shorter than the wafer width, as shown in the above left. The above right shows a cell design with no shingling pattern.

(5) Number of Busbars, solder/probe points, and busbar width



The H pattern is made of busbars and fingers. Change "No of BB " and " BB width" to alter the number of busbars and their width. "Solder/Probe Points" refer to the number of contact points on each busbar. In IV testing (simulated by choosing "Extract Current at Each Probe Point" in the simulation page, see 2.7.4), these contact points are called probe points, denoting the spots where the I-V tester probe pins make contact to the busbars. In a module (simulated by choosing "Solder ribbons at probe points, extract current at ribbon ends" in the simulation page, see 2.7.4), these contact points are called solder points, denoting the spots where the ribbon in a module makes electrical contact to the busbar.

## (6) Busbar Style



Each busbar comes in unit segments, each segment containing one solder/probe point. Busbar style controls the shape the unit segment. There are 6 styles to choose from in Griddler 2.5 PRO, with each described by the corresponding drawing and dimensions indicated in the program. In Griddler 2.5 free version, there are 3 styles to choose from, and the dimensions related to the shape of the segment cannot be adjusted.

## (7) Busbar Ending



Each busbar may have ending segments that are different from the unit segments. Choosing "Straight" busbar ending means that there is no extra ending segment. Apart from this, there are 4 ending styles to choose from in Griddler 2.5 PRO, with each described by the corresponding drawing and dimensions indicated in the program. You cannot choose extra ending segment in Griddler 2.5 free version.


Single print means that the busbars and fingers are in the same metal layer. The entire metal layer is in electrical contact with the solar cell semiconductor (emitter), and there is metal induced recombination under both the busbars and fingers, as defined by metal contact $\mathrm{J}_{01}$ (see 2.7.5). Dual print means that only the fingers are contacting the solar cell semiconductor and has metal induced recombination; the busbars are "floating" in the sense that they electrically contact only the fingers, but not the semiconductor.


The H pattern is made of busbars and fingers. Change "No of fingers" and "Finger width" to alter the number of fingers and their width. You can also make the segments of fingers near to the busbars wider, by enabling "taper fingers". "taper fingers from" defines the widest width of the fingers, and "over distance of" defines the segment length where the fingers taper from the widest width to the nominal width.

(11) Edge Gap


Enable rear pattern to define rear metal "fingers" and "busbars". Even if the rear pattern is mostly uniform metal coverage, you might want to nevertheless define the extent of the "finger" layer (which would be the uniform rear aluminium layer) and the position of the "busbars" (which would be the silver solder pads). Disabling the rear pattern forces the rear cell plane to be grounded under the assumption of perfect rear lateral conductance.


If rear pattern is enabled, you can select three different kinds of patterns: a) full area metal contact which resembles that of AI-BSF cells; b) line contact, full area metal which resembles that of PERC or LBSF cells, where there is full area metal coverage on the rear, but the metal-semiconductor contacts are formed in periodic line openings. This option can be used to simulate PERC or LBSF cells, although nowadays it is more common to simulate PERC or LBSF cells using the "full area metal contact" combined with effective parameters calculated by the local contact calculator (see 4.3); c) H-pattern, for bifacial solar cells.
(14) Rear busbar style (for full area metal contact)


If rear pattern is enabled and "full area metal contact" is chosen as the rear metal pattern, then the rear busbar style lets you choose where the solder pads are positioned. If "H-pattern" is chosen, then the rear busbar style options are the same as the front (see number 6).
(15)

Redo/Undo option is available in the Design H-pattern Page.


The H-pattern can be saved as AutoCAD dxf file, for sharing with those from outside. The layers in the dxf file and the shapes follow a convention that is described in section 2.6.

Hit next once you are finished with the H -pattern definition and ready to move on to the meshing page.
(19)

Hit Start Over to return to the front page (the pattern is autosaved).

### 2.5 Meshing Pege



In this page the defined front and rear planes of the solar cell are finely broken down into triangular meshes to implement the network model of the solar cell (see section 1.2). Referring to the screenshot above, going through this page involves little more effort than following the suggested buttons to press (steps 1 4). The page proceeds to mesh the front planes, and then the rear planes.

There is the optional step 0 if you are interested to do minor post editing of the metal grid. In step 2, you also have the option to adjust the fineness of the mesh.

## (optional) Step 0 - Post Editing

Click on the box that says "Click for Post editing", and it will reveal additional options.


You can select from the drop-down list either to edit the "Fingers" layer or the "Busbars" layer.


If you click any of the three buttons "Create Breaks", "Create Extra Rectangles", "Create Extra Terminals", the cursor becomes a cross-hair that allows you to pinpoint locations on the metal pattern, as shown in the above. If you choose "Create Breaks" or "Create Extra Rectangles", then you must aim and click the crosshair on two locations of the pattern to define the opposing corners of a rectangle. In a) "Create Breaks", the layer of interest will contain no metal inside the rectangle that you defined; In b) "Create Extra

Rectangles", the rectangle that you defined becomes an extra metal shape in the layer of interest. In c) "Create Extra Terminals", you must aim and click the cross-hair on one position in the pattern to define an extra solder/probe point.

Alternatively to clicking the buttons and aiming the cross-hairs to define the positions to edit, you can do a more precise job by using commands (see 5.2). For example, in picture d, I type the command "DRAWEXTRAFRONTSHAPE 1-4.68225-7.7-4.67775-7.7-4.67775 7.7-4.68225 7.7" to define an extra metal polygon in the layer 1 (fingers) with vertices at ( $-4.68225,-7.7$ ) $\mathrm{cm},(-4.67775,-7.7) \mathrm{cm},(-4.67775$, $7.7) \mathrm{cm},(-4.68225,7.7) \mathrm{cm}$, resulting in the thin finger that bisects the leftmost two busbars in the picture.

## Step 1 - Analyze Pattern

When you click on this button, Griddler will merge all the shapes in each layer into one, as shown in the above picture e.

Step 2 - Choosing Mesh Detail


Here you can define the mesh detail in the directions tangent to metal, and perpendicular to the metal. After your choice, you can hit Mesh and then check the mesh details by choosing the zoom in button and clicking on the mesh. The above picture shows an example pattern that is meshed using three different mesh detail settings. Generally it is a good idea to have at least 4 nodes along a finger between two busbars (unless you have numerous busbars and very short fingers), and at least 4 nodes between fingers.

## Step 3 - Mesh

When you click on this button, Griddler will mesh the pattern and show it to you like in the above picture.

## Step 4 - OK

After checking the mesh, if you are OK with it, click OK. If not, then go back to step 2 or edit the pattern in step 0.

## 2.6 lmport Auroced dxx

Griddler is not limited to simulating H-pattern designs! You can create your own arbitrary metal pattern using AutoCAD, save it as dxf and import it into Griddler. The screenshots below show how it's done.


In the above, we press "Import AutoCAD DXF" on the front page and a dialog box appears asking us to select a .dxf file. We choose as example, "snowflake3.dxf". Griddler loads this dxf and displays the pattern in the mesh page. As you can see, the pattern consists of a front finger design that is non H-pattern. Specifically it is a roughly $3.8 \times 3.8 \mathrm{~cm}$ unit section of a metal wrap through (MWT) solar cell, where the metal grid resembles a snow flake pattern with the probe point at its center. Griddler is enable to mesh this pattern into an appropriate triangular mesh, and subsequent simulation of the cell voltage shows that the voltage distribution is smooth and continuous which indicates that the mesh is good.

If you are interested in creating your own metal pattern in AutoCAD, be sure to refer to the design rules below. You can also pop up these design rules by pressing the "help" button below the "Import AutoCAD DXF" button on the front page.

## AUTOCAD Design Rules

1. All units are in mm
2. Layers should be named as shown to the right
3. Draw all structures as closed polylines
4. Terminals (front and rear) should be drawn as circles
5. Use PURGE and OVERKILL commands to clean up your drawing 6. Save as AUTOCAD DXF 2013 version. If that doesn't work, try other versions.


### 2.7 Simulation Page



After meshing, Griddler now has converted your cell design into a finite element model that is ready to be simulated. Above we show the Simulation Page and below we illustrate what the various options do.

## (1) Front and Rear Metallization Parameters

This section defines the finger layer, busbar layer, and semiconductor layer (simply called layer) sheet resistances on the front and rear cell planes. For the semiconductor layer, e.g. front emitter plane or rear BSF plane, the sheet resistance is a very commonly quoted unit. For the metal layers, you may use the following equations to convert known resistance units into sheet resistance. If the metal material bulk resistivity is known, use

$$
\rho_{\text {sheet }}=\rho_{\text {bulk }} / t_{\text {layer }}
$$

Where $\rho_{\text {sheet }}$ is sheet resistance, $\rho_{\text {bulk }}$ is bulk resistivity, $t_{\text {tayer }}$ is the metal layer thickness. For instance, $\rho_{\text {bulk }}$ $=3 \times 10^{-8} \Omega \mathrm{~m}$ and $\mathrm{t}_{\text {layer }}=10 \mathrm{um}=1 \times 10^{-5} \mathrm{~m}$ yields $\rho_{\text {sheet }}=3 \mathrm{~m} \Omega / \mathrm{sq}$. If the metal line resistance is known (in units of $\Omega / \mathrm{cm}$ ), use

$$
\rho_{\text {sheet }}=R_{\text {line }} \times w_{\text {line }}
$$

Where $\rho_{\text {sheet }}$ is sheet resistance, $R_{\text {line }}$ is line resistance, $W_{\text {line }}$ is the width of the line. For instance, $R_{\text {line }}=$ $0.333 \Omega / \mathrm{cm}$ and $w_{\text {line }}=60 \mathrm{um}=60 \times 10^{-4} \mathrm{~cm}$ yields $\rho_{\text {sheet }}=2 \mathrm{~m} \Omega / \mathrm{sq}$.

## (2) Wafer Internal Series/Shunt, Temperature, External Series Resistance

By default the wafer internal series resistance and shunt conductance are both set to zero. Nonzero wafer internal series resistance inserts an extra resistor in-between the node and the equivalent circuit shown in section 1.2. Nonzero wafer internal shunt conductance means there is a shunt path presented by the shunt element in the equivalent circuit. The screenshots below illustrate how the cell I-V characteristics change when one raises either the internal series resistance or the internal shunt conductance.


In Griddler 2.5 PRO, the temperature can be adjusted from the default value of $25^{\circ} \mathrm{C}$, and the external series resistance can be set above zero. Both are important for the simulation of modules, as module temperature is typically above room temperature, and a module's cables and interconnections are elements that introduce extra external series resistance.

As shown in the screenshots below, if you choose a temperature different from $25^{\circ} \mathrm{C}$, Griddler 2.5 PRO will offer to adjust the recombination parameters (see point 5) according to


$$
\begin{gathered}
J_{01}(T)=J_{01}\left(25^{\circ} \mathrm{C}\right) \times\left(n_{i}(T) / n_{i}\left(25^{\circ} \mathrm{C}\right)\right)^{2} \\
J_{02}(T)=J_{02}\left(25^{\circ} \mathrm{C}\right) \times\left(n_{i}(T) / n_{i}\left(25^{\circ} \mathrm{C}\right)\right)^{1} \\
n_{i}(T)=9.15 \times 10^{19}\left(\frac{T+273.15}{300}\right)^{2} \exp \left(\frac{-6880}{T+273.15}\right)
\end{gathered}
$$

Where $J_{01}$ and $J_{02}$ are the saturation current densities of the $n=1$ and $n=2$ diodes respectively (saturation current per area values from the $I_{01}$ and $I_{02}$ explained in section 1.2), $T$ is temperature in Celsius, $n_{i}$ is the intrinsic carrier concentration in silicon. The above equations basically mean that the thermal equilibrium carrier concentration, and therefore recombination currents, increase with temperature. This leads to opencircuit voltage ( $V_{o c}$ ) and efficiency drops as temperature rises. The above equations capture most of the negative temperature coefficient in solar cell $V_{o c}$ and efficiency. However Griddler does not model the comparatively minor temperature coefficient in short-circuit current density ( $J_{s c}$ ) that is due to increased absorption of infrared photons as the silicon bandgap decreases with increasing temperature. Griddler also does not make adjustments to the semiconductor sheet resistance due to changes in carrier mobility with temperature.

## (3) Metal Optical Transparency

This is a number that is used to express the ratio between the physical widths of metal fingers and busbars, which defines the contact area, and their "optical widths" which indicate the extent to which they shade the cell from incident light rays. Generally, a finger or a busbar's optical width is less than the physical width, because it is possible for light which impinge on the metal element to scatter into the cell. Shown in the picture below are two possible mechanisms of scattering. In one, the light ray may scatter directly from a facet of the metal element into the cell; in another, which occurs prominently in modules, the light ray may scatter from a metal element facet, then experience internal reflection off the glass-air interface and back into the cell.


The metal optical transparency $=1$ - metal element optical width / metal element physical width. Therefore, the default value of zero means that the optical width is equal to the physical width.

## (4) Current Extraction Method



## Rear Current Extraction <br> Extract current at eac <br> Extract current at each probe point <br> Solder ribbons at probe points, extract current at ribbon ends <br> Full area rear chuck contacting <br> Floating (Voc calculation only)

You can choose where current is extracted to the external circuit, or equivalently where the terminal voltage is applied, for both the front and rear cell planes. The picture below illustrates the difference between the
two most commonly used methods, "Extract current at each probe point" and "Solder ribbons at probe points, extract current at ribbon ends". Choosing "Extract current at each probe point" simulates an I-V testing setup where each probe point is contacted by a pin from I-V testing probe bar. This situation is represented by the top half of the below picture, where the red dots are the connection points to the external circuit. They are also called current extraction points. Choosing "Solder ribbons at probe points, extract current at ribbon ends" simulates a cell which is interconnected to other cells in a module. This situation is represented by the bottom half of the below picture, where the red dots are now at the end of ribbons that draw current from the cell plane down to the edges of the cell. Because current has to flow through an additional element (ribbon) and traverse a longer distance, this current extraction method leads to higher series resistance losses and a lower fill factor, as can be seen from the I-V characteristics.


For the rear cell plane, you can also choose "Full area rear chuck contacting". In this case, it is assumed that every node on the rear plane is grounded, as would be approximately the case if there is an I-V testing stage that makes full area contact to the cell rear side.

Finally, the choice "Floating (Voc calculation only)" is very seldomly used. If you choose this option for either cell plane, that means there is no electrical connection to the external world, and Griddler would prevent you from running the I-V curve. Use this option only if you are interested to simulate open-circuit conditions (e.g. as could be the case in photoluminescence imaging) where you do not want electrical contacts to route current from one part of the cell to another.

## (5) Diode Parameters

In section 1.2 we saw that between the front and rear semiconductor planes is a sandwich layer, where the photovoltaic properties of the solar cell are implemented as an equivalent circuit called the two diode model. As described in that section, the I-V characteristics of the two diode model is

$$
I\left(V_{\text {diode }, i}\right)=I_{L, i}-I_{01, i} \exp \left(\frac{q V_{\text {diode }, i}}{k T}\right)-I_{02, i} \exp \left(\frac{q V_{\text {diode }, i}}{2 k T}\right)-G_{\text {shunt }, i} V_{\text {diode }, i}
$$

Where $V_{\text {diode, }, i}$ is the voltage across the equivalent circuit, $q$ is the elementary charge, $k$ is the Boltzmann constant, $T$ is the cell temperature in Kelvin. $I_{L, i}$ is the light induced current, $I_{01, i}$ and $I_{02, i}$ are the saturation currents of the $\mathrm{n}=1$ and $\mathrm{n}=2$ diodes, and $G_{\text {shunt; }, ~ i s ~ t h e ~ s h u n t ~ c o n d u c t a n c e ~(n o t ~ s h o w n ~ i n ~ t h e ~ a b o v e) . ~ A l l ~}^{\text {a }}$ these current terms scale with the area of the node (which is related to the area of the triangle elements bounding the node), so it is naturally more descriptive to speak in terms of the currents per area or current densities: $I_{L, i} \rightarrow J_{L}, I_{01, I} \rightarrow J_{01}, I_{02, i} \rightarrow J_{02}$. Here the $J_{s}$ refer to current densities. In particular, the saturation current densities related to the two diodes of the equivalent circuit, $J_{01}$, $J_{02}$, take on different values in regions where the wafer is has good surface passivation, as opposed to regions where the wafer has metalsemiconductor contact. Also, in the passivated regions, it is often customary to subdivide the $J_{01}, J_{02}$, into parts which describe recombination currents in the two sides cut by the pn junction. The below picture illustrates an example of these divisions.


Front Diode Parameters


Rear Diode Parameters
1-Sun JL

( $\mathrm{mA} / \mathrm{cm} 2$ )
passivated metal


Region 1 has good passivation on both sides of the wafer. The example cell has a $\mathrm{p}^{+}|\mathrm{n}| \mathrm{n}^{+}$structure, so the pn junction is where the $\mathrm{p}^{+}$emitter meets the n bulk. As said, it is customary to subdivide the $J_{01}$, $J_{02}$, into parts which describe recombination currents in the two sides cut by the pn junction. In this case we attribute $J_{01}=80 \mathrm{fA} / \mathrm{cm}^{2}, J_{02}=10 \mathrm{nA} / \mathrm{cm}^{2}$ to the $\mathrm{p}^{+}$emitter, and $J_{01}=100 \mathrm{fA} / \mathrm{cm}^{2}$ to the base. In Griddler, you can assign the $\mathrm{p}^{+}$emitter values to "Front Diode Parameters" $\rightarrow$ "passivated area" column, and base values to "Rear Diode Parameters" $\rightarrow$ "passivated area" column. Region 2 has metallization contact on the front. We attribute $J_{01}=800 \mathrm{fA} / \mathrm{cm}^{2}, J_{02}=50 \mathrm{nA} / \mathrm{cm}^{2}$ to the emitter side of this region, so in Griddler you can assign these values to "Front Diode Parameters" $\rightarrow$ "metal contact" column. Finally, region 3 has
metallization contact on the rear. We attribute $J_{01}=2000 \mathrm{fA} / \mathrm{cm}^{2}$ to the base side of this region, so in Griddler you can assign these values to "Rear Diode Parameters" $\rightarrow$ "metal contact" column.

Putting it together, we have

$$
\begin{aligned}
& I_{01, i}=J_{01, \text { front }}^{\text {pass }} A_{\text {front }}^{\text {pass }}+J_{01, \text { front }}^{\text {metal }} A_{\text {front }}^{\text {metaltact }}+J_{01, \text { rear }}^{\text {pass }} A_{\text {rear }}^{\text {pass }}+J_{01, \text { rear }}^{\text {metal }} A_{\text {rear }}^{\text {metal contact }} \\
& I_{02, i}=J_{02, \text { front }}^{\text {pass }} A_{\text {front }}^{\text {pass }}+J_{02, \text { front }}^{\text {metal }} A_{\text {front }}^{\text {metantact }}+J_{02, \text { rear }}^{\text {pass }} A_{\text {rear }}^{\text {pass }}+J_{02, \text { rearar }}^{\text {metal }} A_{\text {rear }}^{\text {metal contact }}
\end{aligned}
$$

where $A_{\text {front }}^{\text {pass }}$ is the area of the node which is below front passivation; $A_{\text {rear }}^{\text {pass }}$ is the area of the node which is above rear passivation; $A_{\text {front }}^{\text {metal }}$ is the area of the node which is below front metal; $A_{\text {rear }}^{\text {metal }}$ is the area of the node which is above rear metal.

You'll also notice that under both front and rear diode parameters there are boxes called "1-Sun JL, nonshaded area $\left(\mathrm{mA} / \mathrm{cm}^{2}\right)$ ". These are the light-induced current densities in the unshaded areas of the cell, for front and rear incident light respectively. The total light-induced current of a node is then

$$
\begin{aligned}
I_{L, i}= & \begin{array}{l}
\text { 1Sun } \\
\text { Lonstront }
\end{array} \\
& \text { Suns }_{\text {front }}\left(A_{\text {front }}^{\text {pass }}+A_{\text {front }}^{\text {metal }} \times \text { metal transparency front }\right) \\
& +J_{L, \text { rear }}^{\text {nonhade }} \text { Suns }_{\text {rear }}\left(A_{\text {rear }}^{\text {pass }}+A_{\text {rear }}^{\text {metal }} \times \text { metal transparency rear }\right)
\end{aligned}
$$

 cell, for front and rear respectively; Suns $_{\text {front }}$ and Suns $_{\text {rear }}$ are the intensity of light incident from the front and rear respectively, in units of Suns; and metal transparency front, rear have been described in section point 3 of this section.

## (6) Edge Recombination



The edges of the wafer, or near edge regions of the wafer, in most cases have enhanced recombination. This can be due to a combination of poorer or no passivation near or on the wafer edges, and damage introduced by the edge isolation process. For nodes that are at the wafer edges, the enhanced recombination is represented by two extra $n=1$ and $n=2$ diodes in addition to the diodes whose currents scale with node area. These are drawn in the above picture as big blue diodes. At the edge nodes, the saturation current densities are given by

$$
\begin{aligned}
& I_{01, i}=J_{01, \text { front }}^{\text {pass }} A_{\text {front }}^{\text {pass }}+J_{01, \text { front }}^{\text {metal }} A_{\text {front }}^{\text {metal contact }}+J_{01, \text { rear }}^{\text {pass }} A_{\text {rear }}^{\text {pass }}+J_{01, \text { rear }}^{\text {metal }} A_{\text {rear }}^{\text {metal contact }}+J_{01, \text { edge }} L_{\text {edge }} \\
& I_{02, i}=J_{02, \text { front }}^{\text {pass }} A_{\text {front }}^{\text {pass }}+J_{02, \text { front }}^{\text {metal }} A_{\text {front }}^{\text {metantact }}+J_{02, \text { rear }}^{\text {pass }} A_{\text {rear }}^{\text {pass }}+J_{02, \text { rear }}^{\text {metal }} A_{\text {rear }}^{\text {metal contact }}+J_{02, \text { edge }} L_{\text {edge }}
\end{aligned}
$$

where the enhanced recombination terms are written in red. $J_{01, \text { edge }}$ and $J_{02, \text { edge }}$ are the additional saturation currents per unit length of wafer edge, and $L_{\text {edge }}$ is the edge length of the node.

## (7) Illumination



Referring to point 5 of this section, these are the Sunsiront and Sunsrear terms that appear in the equation of $I_{L, i}$. The above picture shows one example of a bifacial solar cell with illumination of 1 Sun from the front, and 0.2 Sun from the rear.

## (8) Run and Save Buttons



The most often used run button is "Find Jsc Voc MPP" in the above left picture, which prompts Griddler to hunt for the short circuit current density ( $\mathrm{J}_{\mathrm{sc}}$ ), open circuit voltage ( $\mathrm{V}_{\mathrm{oc}}$ ), and maximum power point (MPP)
and related $\mathrm{I}-\mathrm{V}$ parameters (efficiency, fill factor FF, voltage and current at MPP $\mathrm{V}_{\mathrm{mp}}$ and $\mathrm{I}_{\mathrm{mp}}$ ). This is the quickest way to obtain the essential I-V parameters. The above example searched only 6 points to find all these I-V parameters, taking about 12s on a desktop computer.

Next, if you wish to obtain a smooth I-V curve, you can add more calculated datapoints by pressing "JV Sweep" and then choosing an appropriate range and step size. As long as you don't change the pattern or any cell parameters, you can keep adding more datapoints by JV sweep to the already calculated curve.

You can visualize the cell voltage/current density/luminescence intensity by clicking on "Map". This brings up a menu bar that allows you to specify what to map (Diode voltage, Front Voltage, Rear Voltage, Luminescence, Current Density); and at what voltage (below top we show 573 mV which is the voltage at max power; below bottom, we show that you can also type "OC" to simulate at open circuit conditions). Click "Run" to simulate the requested spatial distribution. Click the camera icon to save the image.


After running the I-V curve by either "Find Jsc Voc MPP" or "JV Sweep", click "Report" to save a text summary of some the cell geometry parameters (e.g. wafer area, metal contact area), I-V parameters ( $J_{s c}$, $V_{o c}$, FF, efficiency), loss analysis results (more on that in 2.8), and the I-V curve.


At any moment, click "Save" to save the entire session (cell design pattern and cell parameters). The session files have extension .mat. You can always load sessions by clicking "Load Session" at the front page (see 2.9).


### 2.8 Loss Chart

After running the I-V curve by "Find Jsc Voc MPP", a button called "Loss Chart" appears in the bottom left corner of the I-V curve display. Click on it to reveal a new window that allows you to toggle between four loss analysis charts using radio buttons at the bottom of the window. The first of these is power loss bar graphs, which breaks down in $\mathrm{mW} / \mathrm{cm}^{2}$ the power output at max power point, losses due to shading, recombination, and resistances.


The second and third radio buttons lead to pie charts that break down the proportions of different recombination currents, at maximum power point (MPP) and open circuit (OC) condition respectively, as shown below. The pie chart showing recombination current densities at MPP is in units of $\mathrm{mA} / \mathrm{cm}^{2}$. The sum of the recombination current densities, multiplied by the wafer area, is the actual total recombination current at MPP. The pie chart showing recombination current densities at OC displays the saturation current densities, which are simply the recombination current densities divided by $\exp \left(q V_{o d} k T\right)$. This results in quantities that have typically units of $f \mathrm{~A} / \mathrm{cm}^{2}$, and can be compared on an "apples to apples" basis with the $J_{0}$ terms that appear in section 1.2 , and point 5 of this section.


Finally, the fourth radio button leads to what's called a fill factor drops waterfall diagram. This diagram might take a minute to construct because it is made by simulating a series of scenarios with increasingly higher FF compared to the baseline. Firstly, edge recombination is turned off (if any). Next, the front $J_{01}$ in the passivated area is changed to its median value, if the front $J_{01}$ in passivated area has been given a nonuniform spatial distribution (see 3.1). Then, the $\mathrm{n}=2$ diodes are turned off. Then, the enhanced recombination due to metal contacts is turned off by setting $J_{01}, J_{02}$ in the metal areas equal to the corresponding passivated areas. Then, the shunt conductance is turned off, if any. Finally, at whatever the total $I_{01}$ this last scenario, Griddler calculates the resistance-free ideal fill factor by calculating the I-V curve $I(V)=I_{L}-I_{01}(\exp (q V / k T)-1)$ and obtaining the fill factor of this ideal I-V curve. The gap between the last simulated scenario fill factor and this ideal fill factor, is entirely attributed to series resistance. The proportions of the contributions of different kinds of series resistance to fill factor erosion, is assumed to be equal to the proportions of their contributions to power dissipation at MPP.


### 2.9 Lంad Session

You can always load previously saved .mat session files by going to the front page and clicking "Load Session". Navigate to your file to open it. You can either go to the H-pattern design page to edit the cell design or remesh your pattern, or go straight to the simulation page, as shown below.


### 2.10 L®apn on YouTube (dloprecated)

There are two video channels: one on YouTube and one on Youku. They both host the same instruction and other educational videos related to Griddler, SolarEYE, and simulation of solar cells.


### 3.1 Nonuniform Cell Parameters

Most cell parameters can be given non-uniform spatial distributions. Below we show two examples. In the first, we start with a cell with uniform cell parameters. The below screenshot shows that mapping the front voltage in this case at 500 mV reveals a pretty smooth voltage spatial distribution. Click on the $\mathbb{N}$ button next to "finger contact res" under the Front Metallization section of the simulation page.


A canvas appears which shows the spatial distribution of the front contact resistance, which is right now uniform. Check Enable to turn on non-uniformity, then click "Import pattern". This allows you to choose a picture in either jpg, tif, bmp or txt format. We choose a predrawn txt pattern.


Upon loading the picture, you can see that the canvas shows the spatial distribution described by that picture. If you import a txt file that contains a matrix of values, then the exact values are assigned. If you import jpg, tif or bmp picture files, then the relative values are assigned, and you can define the average value of the contact resistance in the box pointed to in the below screenshot.


Click done to exit the canvas. Now in the simulation page the number inside the box of front finger contact resistance is in blue to indicate that it is non-uniform. Now if we retry mapping the front voltage at 500 mV we see that the voltage spatial distribution is patchy because of the highly nonuniform contact resistance.


In the second example, we first map the front voltage at open-circuit to reveal a pretty smooth voltage spatial distribution. Click on the $\mathbb{N}$ button next to "passivated area J01" under the Front Diode Parameters section of the simulation page.


Again, a canvas appears which shows the spatial distribution of the front passivated area $J_{01}$, which is right now uniform. Check Enable to turn on non-uniformity, then click "Import pattern". This allows you to choose a picture in either jpg, tif, bmp or txt format. We choose a predrawn txt pattern.


Upon loading the picture, you can see that the canvas shows the spatial distribution described by that picture. If you import a txt file that contains a matrix of values, then the exact values are assigned. If you import jpg, tif or bmp picture files, then the relative values are assigned, and you can define the average value of the front passivated area $\mathrm{J}_{01}$ in the box pointed to in the below screenshot.


Click done to exit the canvas. Now in the simulation page the number inside the box of front passivated region $J_{01}$ is in blue to indicate that it is non-uniform. Now if we retry mapping the front voltage at opencircuit we see that the voltage spatial distribution is patchy because of the highly nonuniform recombination.


### 3.2 Cell Parameter Databese (PRO vorsion)

One of the challenges to users of Griddler is understanding what are typical or sensible cell parameters to use to simulate the solar cell. To help you (and ourselves!), over time we have compiled a database of cell parameters and built an interface in Griddler 2.5 PRO that is contextual, easy to use, and automatically updated. As of May 31, 2018, version 6 of the cell parameter database contains more than 400 entries. Here we show one example of its use. In the simulation page below, click on the ? button next to the "metal contact $J_{01}$ " under Front Diode Parameters. The database interface pops up. The top half is an explanation of what "metal contact $J_{0}$ " means, and the lower half is a list of reported or suggested values, alongside description of how these values came about (e.g. value is reported for p-type multi cell on $X$ ohm/sq emitter), as well as the sources and authors of the reported values.


Referring to the series of screenshots below, we can narrow down to results that you are looking for by using search term. For example, if you are working with $n$-type cell, then typing " $n$-type" in the search box narrows down the results to those whose descriptions contain the search word. In this example, we choose the row with the value " $\mathrm{J} 01=1600 \mathrm{fAcm}-2$ ". Upon clicking this row, this value will appear in the box next to "Apply". Clicking on "Apply" will transfer this value into the simulation page in the box "metal contact $\mathrm{J}_{01}$ " under Front Diode Parameters. For certain parameters like metal contact $J_{01}$, some reported values comes paired with other parameters, for example, "J01 = $1800 \mathrm{fAcm}-2, \mathrm{~J} 02=10 \mathrm{nAcm}-2$ ". In this case, choosing this value pair and hitting apply will update both metal contact $J_{01}$ and metal contact $J_{02}$ boxes in the simulation page.

You can also find out the source of reported parameter values by clicking on the "Get Source" button after choosing the value. This will pull up your browser to load the link to the cited journal paper abstract.


## 4 Sola cell Diode Parameters Calculations (PRO Version)

### 4.1 Ovorview

Griddler relies on the user to provide $J_{01}, J_{02}$ parameters as inputs and doesn't perform finite element simulations to solve these recombination currents. Over time we realized the importance to supplement Griddler with calculators or to provide it with a coherent interface to other simulation programs that do solve recombination, base transport, and also optics. Below In this section we will introduce Cell Cross Section Diagram and related windows that ties all these aspects together.


Below we will present the user guide to these windows. If you'll like to understand how Griddler 2.5 PRO does the background calculations, see Appendix A: Mathematical Formulae used in the Cell Cross Sectional Diagram and Base Transport Calculator Pages.

### 4.2 Cell Cross Section Diagram (PRO Version)

In The Griddler 2.5 PRO simulation page, click "Cell Cross Section" in the menu bar to launch the cell cross section diagram.


Let's take a look at the cell cross section diagram. There are buttons that link to front, rear optics, front, rear doped layer calculations. Here you can also define the wafer thickness, bulk lifetime, bulk dopant type. For more definitions, there is a button for you to open up the base transport calculator.


The cell cross section diagram and the base transport calculator (which can be launched either by pressing "Base transport/local contact calculator" in the cell diagram like below, or directly from the Griddler 2.5 PRO menu bar) together forms a web of straightforward, analytical equations that tie together different aspects of the cell cross section (e.g. doped layers, optics, bulk) to produce diode terms that are used in Griddler

1Sun 1 Sun
like $J_{L, f r o n t}^{\text {non shade }}, J_{L, \text { rear }}^{\text {non shade }}, J_{01, \text { front }}^{\text {pass }}, J_{01, \text { front }}^{\text {metal }}, J_{01, \text { rear }}^{\text {pass }}, J_{01, \text { rear }}^{\text {metal }}$ (see 2.6.5).

## 4.3 圆es® Transport Calculator (PRO v@rsion)

In The Griddler 2.5 PRO simulation page, click "Base Transport" in the menu bar to launch the base transport calculator. You can also launch this same page from the cell cross section diagram by clicking "Base transport/Local contact calculator".


The above picture shows the various features of the base transport calculator. We describe them below.

## 1. Simulate Lateral Base Currents

By default this option is turned off. Referring to section 1.2, Griddler is essentially a 2D simulator where current only flows laterally in the top and bottom planes, but not in the "sandwich" layer that is represented by the diodes. Of course, this model does not represent reality perfectly, because electrons and holes can drift and diffuse in the quasi-neutral bulk, and that can manifest in lateral currents. Turning "simulate lateral base currents" on will add these bulk current terms, at the expense of the voltage solver's convergence rate and overall simulation speed.

$$
\begin{aligned}
& \boldsymbol{J}_{\boldsymbol{n}}=q \mu_{n} n \nabla \varepsilon_{f n} \\
& \boldsymbol{J}_{\boldsymbol{p}}=q \mu_{p} p \nabla \varepsilon_{f p}
\end{aligned}
$$

Here, $J_{n}$ and $J_{\rho}$ are the current densities in the bulk, q is the elementary charge, $\mu_{n}$ and $\mu_{\rho}$ are the electron and hole mobilities, $n$ and $p$ are the electron and hole densities, and $\varepsilon_{f n}$ and $\varepsilon_{f p}$ are the electron and hole Fermi levels. There are two important approximations: 1) $\mu_{n}$ and $\mu_{\rho}$ are the equilibrium values; 2) $n$ and $p$ are constant throughout the depth of the wafer.

For most cases, leaving "simulate lateral base currents" off produces accurate I-V results. Let's compare the I-V parameters with this option on (with) or off (without) for a $V_{o c}=669 \mathrm{mV}$ solar cell:

| Comment1 | $\mathrm{Jsc}(\mathrm{mA} / \mathrm{cm} 2)$ | Voc(mV) | FF | Eff | Vmp(mV) | $\mathrm{Jmp}(\mathrm{mA} / \mathrm{cm} 2)$ |
| :--- | ---: | ---: | :--- | :--- | ---: | ---: |
| without | 37.997627 | 669.1464 | 80.76277 | 20.53472 | 572.5797 | 35.863513 |
| with | 37.997627 | 669.3543 | 80.77673 | 20.54465 | 573.0274 | 35.852824 |

The I-V parameters are almost the same in the two cases. The penalty in accuracy of leaving "simulate lateral base currents" off increases as the cell voltage goes up. For example, let's run the I-V parameters of the same cell but at 3.6 Suns instead of 1 Sun illumination:

| Comment1 | $\mathrm{Jsc}(\mathrm{mA} / \mathrm{cm} 2)$ | Voc(mV) | FF | Eff | Vmp(mV) | Jmp(mA/cm2) |
| :--- | ---: | ---: | ---: | ---: | ---: | ---: |
| without | 136.79145 | 702.4682 | 77.84141 | 20.77753 | 578.7787 | 129.236087 |
| with | 136.791451 | 703.4755 | 78.12487 | 20.88309 | 582.1547 | 129.139407 |

Here we can see that the $\mathrm{V}_{\mathrm{oc}}$, FF , and efficiency are all slightly higher if we turn on the lateral base current simulation.

## 2. Wafer Type, Thickness, Resistivity

Changing these parameters will change the base doping level, which influences the equilibrium minority carrier concentration and hence the recombination current densities. See Appendix A.

## 3. Auger and Radiative Recombination

Enabling this will turn on Auger and radiative recombination for silicon (intrinsic recombination). See Appendix A.

## 4. Base Contact Geometry

In this section you can define the geometry of periodic base metal contacts (base usually referring to cell rear). Griddler 2.5 PRO implements analytical equations to solve the base $J_{01}$ for three kinds of periodic base contact schemes as shown below: stripes, circular points arranged in square pattern, and circular points arranged in hexagonal pattern.


## 5. Base Local Contact Resistance

Just like front metal-semiconductor contact resistance, the base periodic contacts may also have nonzero metal-semiconductor contact resistance.

## 6. Bulk Lifetime, Contact SRV, Passivation SRV

Bulk lifetime is the carrier lifetime in the bulk silicon material. Surface recombination velocity (SRV) is a parameter used to describe the strength of recombination current at the cell surface tending to the base (usually the rear). When there is periodic base metal contacts, then there is a different SRV assigned to the contacts, as oppose to the SRV assigned to the passivated surface between contacts.

## 7. Effective Base $J_{01}$ and Effective Contact Resistance

Griddler implements analytical equations (see Appendix A) that takes the base doping, mobility, wafer thickness, base periodic contact geometry, bulk lifetime, contact SRV, passivation SRV, to obtain estimates of the effective base $J_{01}$ and effective base contact resistance. Hitting "Apply" applies the effective base $J_{01}$ is to both passivated area $J_{01}$ and metal contact $J_{01}$ fields under rear diode parameters in the Griddler simulation page; and it applies the effective base contact resistance to the "finger contact res" field under rear metallization.

### 4.4 4 Inmmination Optles (PRO version)

In the cell cross section diagram, click "Front Illumination Optics" or "Rear Illumination Optics" to launch the illumination optics page.


The illumination optics page needs two data: 1) the absorptance in the cell silicon region in the wavelength range $300-1200 \mathrm{~nm}, 2$ ) the illumination spectrum in the same wavelength range. By default, Griddler supplies an arbitrary simulated PERC silicon absorptance curve. You have the option to import or paste another absorptance data to override the default one. The default illumination spectrum is AM1.5G with normalized generation current density of $46.3 \mathrm{~mA} / \mathrm{cm}^{2}$.


Since PRO version 2.50034, Griddler 2.5 PRO will auto-detect whether the imported Si absorptance data contains information about the transmittance into the wafer. The transmittance curve is the fraction of incident light which enters into the silicon bulk. If the imported data is higher than $30 \%$ at 1200 nm , then Griddler assumes this curve is the transmittance. It then calculates the resultant absorptance curve by using light trapping formula (see Appendix A2.2, 2.3). The combination of importing the transmittance curve from external source and Griddler doing the job of calculating absorptance after light trapping is very effective, because light trapping calculations depend on the metallization pattern (since the metallized regions of the cell have different internal reflectance compared to non-metallized regions), as well as the wafer resistivity and doped layers dopant profiles (since the amount of free carrier absorption changes with these parameters). Because Griddler allows the user to change the metallization pattern and dopant profiles, it is better for Griddler to automatically update the light trapping calculations every time any of these aspects are being changed by the user, so that one can readily see how the light-induced current density in the non-shaded areas are influenced by the cell design.

On the other hand, if the imported data is lower than $30 \%$ at 1200 nm , then Griddler assumes this curve is the overall absorptance in the absence of free carrier absorption. It will still make use of light trapping calculations to deduce the absorptance curve after free carrier absorption in the doped regions and in the wafer bulk have been accounted for.


Below we illustrate the workflow of using OPAL2 from PV Lighthouse (a free online calculator) to calculate the transmittance, and then using Griddler to calculate the absorptance curve after light trapping.

Step 1: In the Illumation Optics window, press the OPAL (free) button


Step 2: You'll be directed to the OPAL2 calculator page in PV Lighthouse. Here, you can define the surface morphology, and the antireflection coatings properties, to calculate the light interactions on the light incident side of the wafer.


Step 3: After running the anti-reflection coating calculations, click "RAT data" tab. Copy all the columns as shown.


Step 4: Paste the copied columns into the top box back in the Illumination optics page. In this case, you can see that Griddler auto detects the column called "Transmission", plots it as the green curve, and then runs light trapping calculations to produce the red curve which is the absortance.


Step 5: Click on Light Trapping and a diagram shows up which allows you to adjust the various light trapping parameters, including the internal reflectance at various part so the solar cell, and whether you would like Griddler to account for free carrier absorption at the different doped layers. Here we show the dramatic example where setting the rear side internal reflectance to very low values of 0.1 , results in drastic reduction in the absorptance in the long wavelength region.


Step 6: As per usual, you need to click Apply All in the cell diagram window for the calculated light induced current in the non-shaded region, $\mathrm{J}_{\mathrm{L}}$, to take effect. Ensure that the "Apply lock" is on. This will cause Griddler to automatically rerun light trapping calculations (as well as $J_{0}$ calculations) every time the metallization pattern is changed, and automatically apply the updated JL in the non-shaded region. You can force apply lock by clicking on the lock icon.


### 4.5 Doped Lay@r Calculations (PRO vorsion)

In the cell cross section diagram, click "Calc" next to Emitter, BSF or Metal Recombination to define the doped layer profile and perform cmd-PC1D-6.2 simulations of the doped layer saturation current density $J_{0 e}$ and internal quantum efficiency IQE.


## (1) Import or Define Dopant Profile

You can import the dopant profile in a variety of formats, including tab delimited, comma delimited, space delimited, etc. You can also define the columns that correspond to depth, dopant concentration, and you can choose the unit of each. The background dopant concentration is by default set to the base doping. Check "set constant background conc" to use a flat profile for the opposite dopant concentration. Upon choosing these, Griddler 2.5 PRO will display the junction depth and the sheet resistance.

You can also define the dopant profile as an analytical expression, by clicking on the radiobutton "Define Dopant Profile":


The expressions for the different kinds of profile are:
Uniform: $\quad N(z)=N_{p}$ for $z \leq z_{p}$ and $N(z)=0$ for $z>z_{p}$
Exponential: $\quad N(z)=N_{p} \cdot \exp \left(-\left|z-z_{p}\right| / z_{f}\right)$
Gaussian: $\quad N(z)=N_{p} \cdot \exp \left(-\left(z-z_{p}\right)^{2} / z_{f}^{2}\right]$
Erfc: $\quad N(z)=N_{p} \cdot\left[1-\operatorname{erf}\left(\left(z-z_{p}\right) / z_{f}\right)\right]$
where $N$ is the dopant concentration, $z$ is depth, $N_{p}$ is the peak doping, $z_{f}$ is the depth factor, $z_{p}$ is the peak position.

## (2) User ionization factor at 25C

Altermatt, Schenk, Schmithusen, and Heiser published two papers in 2006 (ref 8-9 of Appendix C) about incomplete ionization as a function of dopant concentration for boron, phosphorus and arsenic, which is widely used. You can select "none" or "phosphorus" if the loaded profile dopant is phosphorus, or between "none", "boron", "arsenic" if the loaded profile dopant is boron.

## (3) Textured, SRV and Doped Layer Bulk Lifetime

Selecting "Surface is textured" sets the surface to textured in PC1D. You must also set the doped layer bulk lifetime ("bulk tau") and emitter surface recombination velocity (SRV) before running the cmd-PC1D6.2 simulation.

## (4) Parameterization for SRV

Different authors have reported empirical trends of emitter SRV when passivated, as a function of the surface concentration. You can write an expression in the form of SRV $=f(x)$ where $x$ is the surface concentration in $\mathrm{cm}^{-3}$, in the formula box provided. For example, writing $S R V=1 e-14^{*} x$ will cause the $\operatorname{SRV}$ to be $1000000 \mathrm{~cm} / \mathrm{s}$ when the surface concentration is $10^{20} \mathrm{~cm}^{-3}$.

You can also press "Use Abbott SRV parameterization (phosphorus only)" which sets
$\operatorname{SRV}=\min \left(10^{\wedge}\left((x / 1 e 20)^{*} 1.5\right)^{*} 4.2 / 1.78,1 e 7\right)$
This is a rough empirical trend that is observed from a study by Abbott and coworkers (M. Abbott, G. Scardera, K. R. McIntosh, A. Meisel, "Simulation of emitter doping profiles formed by industrial $\mathrm{POCl}_{3}$ processes", 39 ${ }^{\text {th }}$ Photovoltaic Specialists Conference (PVSC), 2013), although other groups have published
other empirical trends (e.g. A. Kimmerle, M. Momtazur Rahman, S. Werner, S. Mack, A. Wolf, A. Richter, and H. Haug, J. Appl. Phys. 119, 2016).

## (5) cmd-PC1D-6.2 Calculations for $\mathrm{J}_{0 \mathrm{e}}$ and IQE

Pressing the button "PC1D for $\mathrm{J}_{0 \text { e }}$ and IQE" will prompt Griddler 2.5 PRO to pass the emitter profile and simulation parameters to cmd-PC1D-6.2 to simulate the emitter saturation current density ( $\mathrm{J}_{\mathrm{oe}}$ ) and internal quantum efficiency (IQE). See Appendix C for benchmarking of this cmd-PC1D-6.2 caller to EDNA2, a free online calculator of emitter $\mathrm{J}_{0 \text { e }}$ and IQE.

### 4.6 Application of calculatod Torms to the Griddlor Simulation Pago (PRO v®rslon)

Transfer of calculated terms from the cell cross sectional diagram to the Griddler simulation screen.


Transfer of calculated terms from the base transport calculator to the Griddler simulation screen.


## 5 Efficiency lnppovenent and Connnand Window (PRO version)

There are some routines such as optimization of number of fingers, running multiple cases with one parameter being varied within a certain range, and building efficiency roadmaps (efficiency improvement diagram), that can be easily done by using the commands of Griddler 2.5 PRO. More elaborate routines like running multiple cases with two or more parameters being varied, or parsing a series of dopant profiles in evaluating their effectiveness as solar cell emitters, can be done by stringing together multiple commands in a script. Below we'll show you how to use the efficiency improvement button and some common usages of commands. In Appendix D the full glossary of command is shown.

### 5.1 Efificiency lmprovement Diagram (PRO v®rsion)

The efficiency improvement diagram is a streamlined workflow that allows you to quickly build a roadmap diagram of efficiency progression as different cell parameter improvements are implemented. To access it press "Efficiency Improvement" in the menu bar of the simulation page.


Pressing "Efficiency Improvement" calls up the command window (see 5.2) and triggers it to guide you through the efficiency improvement diagram building process. First, a dialog box appears to ask you to save the present session so that it can be retrieved as the "baseline" case. You may simply use the existing filename.


After you have saved the present session, the command window starts to build a script for the efficiency improvement diagram. The four lines that you see below 1) loads the baseline, 2) runs I-V curve of the baseline, 3) opens a blank file called "summary.txt" and writes the I-V parameters of the baseline into the first row.


Now, go to Griddler and make the first cell parameter change you want to improve the cell. Feel free to make any change of the cell in Griddler. You can even hit "STARTOVER" to go back to the front page and then go to "Design H Pattern" to make some changes to the pattern. You can also open the Cell Cross Section Diagram or Base Transport Window and do some changes there. All of these changes are admissible and will be logged by the command window.

Below I have used the cell parameter database to lookup an improvement for front side finger contact resistance for PERC, and applied it.


The command window will note down this change in the background.


You can make a series of changes to the cell parameter and the command window will log each change sequentially. At the point that you decide it is time to re-evaluate the I-V parameters, go to "Comment" box in the command window and write a description of your changes. Here I write "lower front contact resistance". Hit enter and the command window will note that you would like to run the I-V curve and save the I-V parameters for this case "lower front contact resistance" as a new role in the "summary.txt".


Continue to make other cell parameter changes, giving each change case a new description, entering it into the "Comment" box of the command window, and hitting enter. Repeat this process until you are done with all changes you have in mind. Hit "Play" to run the efficiency improvement process.


Griddler 2.5 PRO will now reload the baseline, run the I-V, make the changes in each case, run the I-V in each case. In each step it will save the I-V parameters in "summary.txt".


When Griddler is finished, it will display an efficiency improvement diagram. You can toggle the radio buttons at the bottom to choose which of the four graphs ( $\mathrm{Jsc}_{\mathrm{sc}}, \mathrm{V}_{\mathrm{oc}}, \mathrm{FF}$, efficiency) you'll like to display. You can also save the screen by pressing "Save".


As well, you can open "summary.txt" to see the actual numbers logged by Griddler for the baseline and improvement cases ran.


To resume normal work, stop the command window from logging your work by hitting the Stop button. You can save this script to rerun the efficiency improvement or share it with colleagues. If you saved this script, you can rerun it later by loading it into the command window. Or hitting "Batch" near the top of this window and load in the script.


### 5.2 Commend WVindow (PRO v®rsion)

### 5.2.1 How to Uso the Command WMindow



Press "Command" in the menu bar of the simulation page to call up the command window. The above picture shows the various features of the command window, which are discussed below.

## (1) Single Commands

Here you can write single commands at a time and Griddler 2.5 PRO will execute them as you enter each. The command is not case sensitive. If you type the first few letters of a command and hit "tab", for example "front", the command windows returns all commands that begin with "front" in the glossary. If you hit the up and down arrows, you can also scroll through previously executed commands.

Type "front" and hit tab....


## (2) Glossory of commands

You can view the glossary by group or by alphabetical order. Clicking on any of the commands brings it to the command line. An explanation window will appear to show you how to use that command.


## (3) Load Scripts

A script is a series of commands written in a text file as rows. To load it and run, press "Batch" in the command window and a dialog box appears where you can choose the file.


In this example we are loading the same script that was used to build the efficiency improvement diagram in section 5.1. As you can see, it consists of a series of commands.

| [ script.txt - Notepad | - | $\square$ | $\times$ |
| :---: | :---: | :---: | :---: |
| File Edit Format View Help |  |  |  |
| LOADSESSION "C: \Griddler2_5_PRO\PERC_example.mat" 1 |  |  | $\wedge$ |
| FINDJSCVOCMPP |  |  |  |
| CLEARFILE "summary.txt" |  |  |  |
| SAVESUMMARY "summary.txt" "base line" |  |  |  |
| FRONTFINGERCONTACTRES 0.11 |  |  |  |
| FINDJSCVOCMPP |  |  |  |
| SAVESUMMARY "summary.txt" "lower front contact resistance" |  |  |  |
| POINTCONTACTSRV 440.000 |  |  |  |
| REARPASSSRV 10.000 |  |  |  |
| CONTACTWIDTH 40 |  |  |  |
| CONTACTPITCH 0.6 |  |  |  |
| CALCEFFECTIVEREARJ01 |  |  |  |
| FINDJSCVOCMPP |  |  |  |
| SAVESUMMARY "summary.txt" "optimized rear local contact" |  |  |  |
| EDGEJ01 0 |  |  |  |
| EDGEJ02 1.72 |  |  |  |
| FINDJSCVOCMPP |  |  |  |
| SAVESUMMARY "summary.txt" "ideally low edge recombination" |  |  |  |
| FRONTJ01METAL 713 |  |  |  |
| FRONTJ02METAL 0 |  |  |  |
| FINDJSCVOCMPP |  |  |  |
| SAVESUMMARY "summary.txt" "lower J01 metal" |  |  |  |
| PLOT "summary.txt" 2 Jsc Voc FF Eff |  |  |  |

## (4) Script Builder

Press "Build" in the command window to reveal the script builder. Turn on "Record" and the command window will record down every action you do in Griddler as a command in the script. Also, once record mode is on, then any command you type here will not be executed, but rather logged as a new line in the script window. Other buttons are explained in the below.


### 5.2.2 Some Us๔ful Commands

There are some commands that an execute actions in Griddler that a single button cannot. Let's look at some commonly used ones.

## 1. OPTIMIZEFRONTFINGERSNUM and OPTIMIZEREARFINGERSNUM

Use these to find the optimium number of front or rear fingers that will maximize efficiency of the cell. The format of the command is

OPTIMIZEFRONTFINGERSNUM \{range from\} \{range to\} \{summary filename.txt\}
For example, the command OPTIMIZEFRONTFINGERSNUM 50200 optimize_front_fingers.txt
Will cause Griddler to repeatedly change the number of front fingers $50-200$, seeking the highest efficiency. For every case, Griddler runs an I-V curve and saves the I-V parameters to optimize_front_fingers.txt. At the end, Griddler will also display plots of $J_{s c}, V_{o c}$, FF, efficiency, against number of fingers.


## 2. FINDJSCVOCMPP

Use this command to run the I-V curve. If you simply type FINDJSCVOCMPP then Griddler will run the IV curve on its present state. If you use the following format

FINDJSCVOCMPP \{parameter to vary\} \{value from\} \{value to\} \{step\} \{summary filename.txt\}

This will cause Griddler to runs many I-V curves, each case varying the desired parameter in the range defined. For instance,

## FINDJSCVOCMPP TEMPERATURE 25505 vary_temperature.txt

will cause Griddler to runs many I-V curves, each case varying the desired parameter in the range 25,30 , $35, \ldots, 50 \mathrm{C}$. For every case ran, Griddler logs the important I-V parameters as a row in the summary text file, here named vary_temperature.txt

At the end, Griddler will also display plots of $J_{s c}, V_{o c}$, FF, efficiency, against the temperature.


## 3. SAVESUMMARY

SAVESUMMARY \{filename.txt\} \{comment\}
Saves the important I-V parameters ( $J_{s c}, V_{o c}$, FF, efficiency, $V_{m p}, J_{m p}$ ) as a single row of numbers in the text file that you specify by the name of \{filename.txt\}. You can add a comment to appear at the left most of the row. For example, in 5.1 we saw that the efficiency improvement diagram script employed commands such as

SAVESUMMARY "summary.txt" "base line"
To record the I-V parameters of the base line case and the improvement cases. Below we show again what the summary.txt file looks like at the end.


### 5.2.3 FOR LOOPS and related commands

You can write for loops and nest them (put one for loop inside another) to flexibly run many I-V curves while systematically changing some cell parameters. Here's an example that combines several useful commands in a for loop. The indentation of lines inside the for loop is not necessary. Griddler will parse the lines with or without the indentation.

DEFINE J02_VALUE 104010
FOR JOe_VALUE 306010
FRONTJ01 J0e_VALUE
FRONTJ02 [J02_VALUE(JOe_VALUE)]
REARJ01 EVAL< $<$ JOe_VALUĒ]*1.5>
REARJ01METAL EVAL<[JOe_VALUE]*1.5>
FINDJSCVOCMPP
SAVESUMMARY Summary.txt FRONTJ01 J0e_VALUE
SAVESESSION test_cell_with_j01=[JOe_VALUE]_j02=[J02_VALUE(JOe_VALUE)].mat NEXT JOe_VALUE

In each iteration of the for loop, four cell parameters change: FRONTJ01 (passivated $J_{01}$ in the front), FRONTJ02 (passivated $J_{02}$ in the front), REARJ01 (passivated $J_{01}$ in the rear), REARJ01METAL (metal $J_{01}$ in the rear). Let's see how each is changed.

First, the values for FRONTJ02 are stored in the first line, DEFINE J02_VALUE 1040 10. The DEFINE command creates an array called J02_VALUE with the values [10, 20, 30, 40] (according to the format start=10, end=40, step=10). Then inside the for loop, the line FRONTJO2 [J02_VALUE(JOe_VALUE)] evaluates the quantity inside the square brackets as J02_VALUE(JOe_VALUE) meaning J02_VALUE(iteration number of the for loop JOe_VALUE). So, in the first iteration of the loop, the quantity int the square bracket is $\operatorname{J02} \operatorname{VALUE}(1)=10$. This value is passed to FRONTJ02. So throughout the four iterations of the for loop, FRONTJO2 is assigned the values 10, 20, 30, 40.

Next, the values for FRONTJ01 are passed directly by the variable of the for loop J0e_VALUE, which takes on the values $30,40,50,60$ (according to the format start=30, end=60, step=10). So throughout the four iterations of the for loop, FRONTJ01 is assigned the values 30, 40, 50, 60.

Finally, the values of REARJ01 and REARJ01METAL are passed inside the for loop using the lines REARJ01 EVAL<[JOe_VALUE]*1.5> and REARJ01METAL EVAL<[JOe_VALUE]*1.5>. The keyword EVAL<mathematical statement> simply asks Griddler to evaluate the mathematical statement inside the < $>$ brackets according to the syntax of MATLAB. So here, EVAL<[JOe_VALUE]*1.5> yields a value of [JOe_VALUE] ${ }^{*} 1.5=45,60,75,90$ throughout the four iterations of the loop.

Inside the for loop, after assigning the cell parameter values, the next lines FINDJSCVOCMPP will run the I-V curve, SAVESUMMARY Summary.txt FRONTJ01 JOe_VALUE will log the I-V parameters (as well as the JOe_VALUE as a comment) of each iteration in Summary.txt. Finally,

SAVESESSION test_cell_with_j01=[J0e_VALUE]_j02=[J02_VALUE(JOe_VALUE)].mat
Saves the session as test_cell_with_j01=30_j02=10.mat, test_cell_with_j01=40_j02=20.mat, test_cell_with_j01=50_j02=30.mat, test_cell_with_j01=60_j02=40.mat for the cases.

If you don't want to define the values of JOe_VALUE and JO2_VALUE in regular interval, an alternative syntax available in the code below.

DEFINE J02_VALUE [5 8 15 40]
FOR JOe_VALUE [30 3542 60]
FRONTJ01 J0e_VALUE
FRONTJ02 [JO2_VALUE(JOe_VALUE)]
REARJ01 EVAL<[JOe_VALUE]**1.5>
REARJ01METAL EVAL<[JOe_VALUE]*1.5>
FINDJSCVOCMPP
SAVESUMMARY Summary.txt FRONTJ01 J0e_VALUE
SAVESESSION test_cell_with_j01=[JOe_VALUĒ]_j02=[J02_VALUE(JOe_VALUE)].mat NEXT JOe_VALUE

Here, DEFINE JO2_VALUE [5 8 15 40] assigns the values 5, 8, 15, 40 into the array J02_VALUE. FOR JOe_VALUE [30 3542 60] assigns the values 30, 35, 42, 60 to JOe_VALUE in the four iterations of the for loop.

Below we show another for loop
FOR DOPANTPROFILENAME [D90_profile E_110_profile F_150_profile]
FOR METALETCHDEPTH_[10 2030 50]

LOADSESSION "E:17-09-15 Griddler 2_5 PRO - PC1DImono_example.mat" 1 IMPORTDOPANTPROFILE 1 "E:\17-09-15 Griddler 2_5 PRO PC1D\[DOPANTPROFILENAME].dop"

DOPEDLAYERSRV 1
EVAL<min(10^(([EMITTERPASSSURFACECONCENTRATION]/1000000000000000000
00)*1.5)*4.2/1.78,10000000)>

DOPEDLAYERLIFETIME 1100
RUNPC1D 1
IMPORTDOPANTPROFILE 2 "E:\17-09-15 Griddler 2_5 PRO -

PC1D\[DOPANTPROFILENAME].dop"
DOPEDLAYERLIFETIME 2100
METALETCHDEPTH 2 [METALETCHDEPTH]
RUNPC1D 2
APPLYFRONTLAYERSHEETRES
APPLYFRONTJL
APPLYPASSEMITTERJ0
APPLYMETALEMITTERJ0
FRONTFINGERCONTACTRES
EVAL<2E20*1/[EMITTERPASSSURFACECONCENTRATION]>
OPTIMIZEFRONTFINGERSNUM 50150 front_fingers_opt.txt
FINDJSCVOCMPP
SAVESUMMARY "2017-09-16_phos_emitter_profile_screening_summary.txt"
[DOPANTPROFILENAME] [METALETCHDEPTH]
EMITTERPASSSURFACECONCENTRATION FRONTFINGERSNUM
EMITTERPASSSRV JUNCTIONDEPTH FRONTLAYERSHEETRES FRONTJL
FRONTJLOSSEMITTER FRONTJLOSSFCA FRONTJ01 FRONTJ01METAL
NEXT METALETCHDEPTH
NEXT DOPANTPROFILENAME

In the above code, you can also pass to the for loop not numbers but strings, in this case FOR DOPANTPROFILENAME [D90_profile E_110_profile F_150_profile] assigns to the variable DOPANTPROFILENAME the values of "D90_profile", "E_110_profile", "F_150_profile". Inside the for loop, the line

## IMPORTDOPANTPROFILE 1 "E:\17-09-15 Griddler 2_5 PRO PC1D\[DOPANTPROFILENAME].dop"

Substitues D90_profile, E_110_profile, F_150_profile in place of [DOPANTPROFILENAME] for iterations $1,2,3$ of the DOPANTPROFILENAME for loop, respectively. This makes Griddler open and import three different dopant profiles in the different iterations of the for loop.

You'll also notice that in the code above, there are two nested for loops. The outer one is for different DOPANTPROFILENAME and the inner one is for different METALETCHDEPTH_. The inner loop variable is used in the line METALETCHDEPTH 2 [METALETCHDEPTH]. This line passes the values of 10, 20, $30,50(\mathrm{~nm})$ to the metal etch depth of the front dopant profile under the metallization, for each of the four iterations of this inner for loop.

Altogether the code will cycle through three different dopant profiles, and for each use four different metal etch depths, to evaluate the $J_{0 e}$ under the passivated region and metal region. For the evaluation of passivated region $J_{0 e}$, the code also uses EVAL to assign an appropriate front SRV that is a function of the emitter surface concentration. The code also uses EVAL to assign an appropriate front metalsemiconductor contact resistance that is a function of the emitter surface concentration. In each iteration, the line OPTIMIZEFRONTFINGERSNUM 50150 front fingers_opt.txt will reoptimize the number of front fingers to each scenario. The resultant I-V parameters for the optimized number of front fingers is then recorded in 2017-09-16_phos_emitter_profile_screening_summary.txt.

### 5.2.4 PMraller FOR LOOPS

You can also use parallel computing mode to execute for loops. Let's see the previous section for loop implemented using parallel for loop:

PARPOOL 3
DEFINE J02 VALUE 104010
PARFOR JOe_VALUE 306010
FRONTJ01 J0e VALUE
FRONTJ02 [J02_VALUE(JOe_VALUE)]
REARJ01 EVAL<[JOe_VALUE]*1.5>
REARJ01METAL EVAL<[JOe_VALUE]**1.5>
FINDJSCVOCMPP
SAVESUMMARY Summary.txt FRONTJ01 J0e_VALUE
SAVESESSION test_cell_with_j01=[JOe_VALUE]_j02=[J02_VALUE(JOe_VALUE)].mat
NEXT JOe_VALUE

The first line PARPOOL 3 asks Griddler to create three parallel processes. The PARFOR JOe_VALUE 30 6010 works exactly like the FOR loop but using parallel processing. Note that you are not allowed to nest PARFOR loops. Any inner loops must be executed using FOR.

## (6) Other Usages of Griddller 2.5 PRO

## 6. 1 Simulaflom of Luminescenco lmago Dxt

Photoluminescence (PL), electroluminescence (EL), and luminescence imaging in general performed at different operating points of the solar cell have proven to be invaluable tools for characterisation. Since 2016-2017, Griddler 2.5 PRO has been used to simulate luminescence image data. Let's review a few examples.

Below are simulations of a cell containing (i) a region of reduced lifetime replicating a grain boundary/dislocation cluster within a region affected by five finger interruptions, (ii) one finger interruption, (iii) two finger interruptions, and (iv) a rectangular region of reduced lifetime centered over a finger. (a) Line scan PL image with vertical cell movement and peak illumination intensity of 2.25 Suns. (b) EL image with 650 mV applied bias. It is an excerpt from Zafirovska's work on using line scan PL imaging to detect finger interruptions and distinguish them from regions of poor lifetime (I. Zafirovska, M. K. Juhl, J. W. Weber, J. Wong, T. Trupke, "Detection of Finger Interruptions in Silicon Solar Cells Using Line Scan Photoluminescence Imaging", IEEE Journal of Photovoltaics, vol 7, pp. 1496 - 1502, 2017). Line scan PL imaging differs from conventional PL imaging through the use of a line scan camera, which works by restricting the field of view to a narrow line spanning the width of a cell. Individual "line" images are continuously captured in sync with linear motion of the cell, and a complete image is formed by combining all of the line images acquired. Since only the narrow field of view is illuminated at any time, line scan PL images appear similar to EL images but with an opposite contrast.


Below are Griddler-simulated images of $V_{\mathrm{d}}$ for (a) EL and (d) mpp, (b) EL-measured and (e) PL-measured $V_{d}$ images for EL and mpp, and $V_{d}$ difference images between measured and simulated data for (c) EL and (f) mpp of a multi-crystalline silicon solar cell.


It is an excerpt from Frühauf's work on extracting the spatial distributions of local two-diode parameters, contact resistance, grid resistance, and emitter resistance of a solar cell, based on spatial data obtained by lock-in thermography, electroluminescence, and photoluminescence imaging (F. Frühauf, J. Wong, J. Bauer, O.Breitenstein, "Finite element simulation of inhomogeneous solar cells based on lock-in thermography and luminescence imaging", Solar Energy Materials and Solar Cells, vol 162, pp. 103-113, 2017).

Below are comparison of luminescence images and corresponding simulations for a monocrystalline solar cell, at different cell operating points as indicated. It is an exerpt from Wong's work on SolarEYE, which is an automated procedure extract the spatial distributions of local two-diode parameters, contact resistance, edge recombination, and metal induced recombination of a solar cell (J. Wong, P. Teena, D. Inns, "Griddler AI: New Paradigm in Luminescence Image Analysis Using Automated Finite Element Methods", IEEE PVSC 2017).


Below we will show an example of luminescence image simulation. We start with the solar cell model that has nonuniform passivated $J_{01}$ on the front side, and nonuniform contact resistance, which was used in section 3.1.

There are some commands that help researchers obtain more precise luminescence images:
INPUTRESOLUTION 1000 - INPUTRESOLUTION sets the resolution of imported images used to define the spatial distribution of parameters. We recommend using 1000 (which will set the resolution to 1000 x 1000 pixels) since most PL images are megapixel resolution, and the derived $J_{0}$ images are also around this resolution.

OUTPUTRESOLUTION 1000 - OUTPUTRESOLUTION sets the resolution of exports of simulated luminescence images from Griddler. We also recommend using 1000.

LUMINESCENCECAL \{ $C$, or filename containing $C$ matrix $\{B$, or filename containing $B$ matrix $\}$
This third command sets the conversion factor between simulated diode voltage in the solar cell to luminescence intensity. Griddler uses the formula

$$
\Phi_{\text {luminescence }}=C\left(\exp \left(\frac{q V_{\text {diode }}}{k T}\right)-1\right)+B I_{L}
$$

Where $\Phi_{\text {luminescence }}$ is the luminescence intensity, $C$ and $B$ are coefficients, $V_{\text {diode }}$ is the diode voltage, $I_{L}$ is the illumination intensity in Suns. By using the LUMINESCENCECAL command, you can set C and B either as single numbers, or as names of text files containing spatial distributions of $C$ and $B$. Here we will use

LUMINESCENCECAL 1e-8 0
Below we show the image process for luminescence intensity, at 1 Sun and 500 mV terminal voltage:


Below we show the image process for luminescence intensity, at 1 Sun and open-circuit:


Press the camera button to store the luminescence image. We recommend saving as text (.txt) as this preserves the numbers without rounding.


If you would like to examine certain areas of luminescence simulations in detail, we also recommend using as high mesh detail as possible to create the mesh. There is also a command to enhance the mesh density in the direction along the metal lines, as shown below. This command needs to be entered before pressing "mesh".


In the above we used the command

## RECTANGLEMESHMASK -2 2040.2

To define within a rectangle with the corners $(-2,2) \mathrm{cm}$ and $(0,4) \mathrm{cm}$, that the mesh density along the metal lines be increased to 0.2 mm spacing. You can see below that after meshing, the defined rectangle area will have the enhanced mesh detail.


Below we compare the exported luminescence image in the rectangle with the corners $(-2,2) \mathrm{cm}$ and $(0,4) \mathrm{cm}$, with and without turning on enhanced mesh detail. You can see in this case the level of details in the latter case is slightly higher.


Exported luminescence image in the rectangle with the corners $(-2,2) \mathrm{cm}$ and $(0,4) \mathrm{cm}$, without turning on enhanced mesh detail.


Exported luminescence image in the rectangle with the corners $(-2,2) \mathrm{cm}$ and $(0,4) \mathrm{cm}$, with enhanced mesh detail

### 6.2 Simulation of Small Siginal AC Rosponse

Both I-V characteristics as well as luminescence characteristics behave differently if the excitation (e.g. illumination, voltage) have temporal variation that brings the solar cell away from steady state. While the Griddler solver is inherently for steady state situations, it is possible to approximate what's called small signal AC response, which is a variation in the cell output that is sinusoidally varying in time, when the
temporal variation in excitation is so a small sinusoid. For example, if the terminal voltage of the cell were $V_{\text {applied }}=V_{D C}+\delta V_{A C} \times \sin (\omega t)$ where $V_{D C}$ is a $D C$ bias, $\delta V_{A C}$ is a small AC bias whose peak to peak variation is less than $\mathrm{kT} / \mathrm{q}, \omega$ is a radial frequency, then one can expect that the terminal current of the cell to be $I=$ $I_{D C}+\delta I_{A C} \times \sin (\omega t+\theta)$ where $I_{D C}$ is a $D C$ current, $\delta I_{A C}$ is a small AC current, $\theta$ is a phase angle. Similarly, the luminescence signal would have a response of this form.

To implement calculations of small signal AC response, the following changes are made in the base transport calculator and luminescence signal calculation. First and most importantly, we define an AC bulk lifetime $\tau^{\star}$ which is a complex number:

$$
\frac{1}{\tau^{*}}=\frac{1}{\tau}+i \omega
$$

The diffusion length is then defined according to $\tau^{\star}$ instead of $T$

$$
L_{d i f f}=\sqrt{D \tau^{*}}
$$

And then is used throughout the equations in Appendix A. Lastly, the luminescence signal calculation is also changed to

$$
\begin{gathered}
\Phi_{\text {luminescence }}=C f(\omega)\left(\exp \left(\frac{q V_{\text {diode }}}{k T}\right)-1\right)+B I_{L} \\
f(\omega)=\frac{L_{\text {diff }}}{W}\left(\begin{array}{l}
\left(1+\frac{S_{\text {eff }} L_{\text {diff }}}{D}\right)\left(\exp \left(\frac{W}{L_{\text {diff }}}\right)-1\right) \\
\\
\left.+\frac{\left(1-\frac{S_{\text {eff }} L_{\text {diff }}}{D}\right)\left(1-\exp \left(\frac{-W}{L_{\text {diff }}}\right)\right)}{\left(1+\frac{S_{\text {eff }} L_{\text {diff }}}{D}\right) \exp \left(\frac{W}{L_{\text {diff }}}\right)+\left(1-\frac{S_{\text {eff }} L_{\text {diff }}}{D}\right) \exp \left(\frac{-W}{L_{\text {diff }}}\right)}\right)
\end{array}\right)
\end{gathered}
$$

This treatment is equivalent to building in the complex diffusion length influence into c .
Below we show a code that will perform AC small signal response analysis. The explanations are provided in the comment lines that begin with \%

```
% load the large area cell file
loadsession 2017-05-19_test_cell.mat 1
FOR edgej01 [0]
    FOR rhoc [0]
        FOR J0e [50]
            FOR REARSRV [0 50 200]
            FOR TAU [2000]
                % sets the region of interest to incorporate entire wafer
                LUMINESCENCEROI -2-2 22
                    % background light is about 0 Suns
                FRONTILLUMINATION O
                    % no sinusoidal light
                    LIGHTPERTURBATION 0
                    % AC bias of 10mV
                    BIASPERTURBATION 10
                    % first we simulate the DC response using the bias light and voltage
```

```
            % first, we specify we are solving in DC mode
            DIFFERENTIALMODE 0
            % we open up the base transport calculator, and calculate effective rear J01 assuming certain
                    bulk lifetime
                    EDGEJ01 [edgej01]
                    FRONTFINGERCONTACTRES [rhoc]
FRONTJ01 [J0e]
REARPASSSRV [REARSRV]
BULKLIFETIME [TAU]
CALCEFFECTIVEREARJ01
% we simulate the DC response with bias of 500mV
MAP 500 4
% we vary the frequency of the AC component from 10Hz to 1000kHz
% 1st argument is the filename to write results to
% 2nd argument (4) means we want to record the PL in the ROI
% 3rd is in the format NUM OF PTS to vary the frequency in a log scale
ACSWEEP 2017-05-19_test_cell_DC500mV_AC10mV_results_tau=[TAU]_rearSRV=
[REARSRV]_frontJ01=[J0e]_contactres=[rhoc]_edge=[edgej01]_peri=[periJ01].txt 4 10
100000050
% background light is about 1 Suns
FRONTILLUMINATION 1
% sinusoidal light
LIGHTPERTURBATION 0.01
% no AC bias
BIASPERTURBATION O
% first we simulate the DC response using the bias light and voltage
% first, we specify we are solving in DC mode
DIFFERENTIALMODE 0
% we open up the base transport calculator, and calculate effective rear J01 assuming certain
bulk lifetime
CALCEFFECTIVEREARJ01
% we simulate the DC response with bias of 500mV
MAP OC 4
% we vary the frequency of the AC component from 10Hz to 1000kHz
% 1st argument is the filename to write results to
% 2nd argument (4) means we want to record the PL in the ROI
% 3rd is in the format NUM OF PTS to vary the frequency in a log scale
ACSWEEP 2017-05-19_test_cell_DC1Sun_AC0_01Suns_results_tau=[TAU]_rearSRV=
[REARSRV]_frontJ01=[J0e]_contactres=[rhoc]_edge=[edgej01].txt 4 10 100000050
NEXT TAU
NEXT REARSRV
NEXT J0e
    NEXT rhoc
NEXT edgej01
```

While the code runs, you'll notice that under ACSWEEP, the simulated image is no longer showing amplitude, but the phase angles as shown below.


After the code finishes, we can open up one of the output text files and see what's inside, below:






AC
excitation
voltage bias







We can also plot for the cases of open-circuit luminescence AC response, the amplitudes and phase versus frequency, as well as the Nyquist plots, for the three different rear SRV values used in the simulation:



### 6.3 Precise Simulations of four wire luV Testing

Real I-V testing uses a four wire configuration where the current source and voltage sense are done separately by different contact pins. To investigate subtleties in the influence of pin contact resistance in such four wire measurement, Griddler 2.5 PRO is capable of inserting sense pins and also to define contact resistance at each pin.

Let's use the example cell below. In the H -pattern design page, use the command DRAWEXTRAFRONTSENSE \{x position (cm)\} \{y position (cm) \} to insert sense terminals on the front plane. You can also use DRAWEXTRAREARSENSE \{x position (cm)\} \{y position (cm)\} to insert sense terminals on the rear plane, but that is not done in this example.


Proceed as normal to mesh the front and rear planes. Then, in the simulation page, you can view the indices of the terminals by the command DISPLAYTERMINALSNUM. The source pins numbers now appear in black and the sense pin numbers appear in blue.


Now, we can assign different pin contact resistance values (in ohms) to each of the pins, as below using the FRONTCONTACTPOINTSRES BYPIN command:


The I-V parameters simulated in this case differs from the default case (no sense pins, zero contact resistance at source pins) very subtly.

| Comment1 | $\mathrm{Jsc}(\mathrm{mA} / \mathrm{cm} 2)$ | Voc $(\mathrm{mV})$ | FF | Eff | Vmp(mV) | $\mathrm{Jmp}(\mathrm{mA} / \mathrm{cm} 2)$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| random_pin_contacts | 34.387015 | 617.36178 | 79.53762 | 16.88522 | 513.445 | 32.886141 |
| no_pin_contacts | 34.387015 | 617.3891 | 79.68929 | 16.91817 | 518.6442 | 32.619993 |

### 6.4 Cells made of Shingles and Cut Wafors

Here we show you how to precisely model cells made of shingles and cut wafers, because the laser cutting needed to split the cell in the end often introduce extra damage on one edge of the cell only. To model this we make use of the commands EDGEJ01 BOTTOM, EDGEJ01 TOP, EDGEJ01 LEFT, EDGEJ01 RIGHT, EDGEJ02 BOTTOM, EDGEJ02 TOP, EDGEJ02 LEFT, EDGEJ02 RIGHT. Let's see an example below.

Below we construct using the H-pattern Design page a shingle cell that is from a wafer cut into fifths. We mesh it and go to the simulation page.


In the simulation page, let's introduce edge recombination only to the bottom edge of the wafer, as that is the edge which is laser cut. We use the command EDGEJ01 BOTTOM 1000 to introduce $1000 \mathrm{fA} / \mathrm{cm}$ to the bottom edge $\mathrm{n}=1$ diodes.


If we press the $\mathbb{N}$ button next to Edge Recombination $J_{01}$, we see that only the bottom edge nodes take on $J_{01, \text { edge }}$ values of $1000 \mathrm{fA} / \mathrm{cm}$.


Similarly, we use the command EDGEJ02 BOTTOM 100 to introduce $100 \mathrm{nA} / \mathrm{cm}$ to the bottom edge $\mathrm{n}=2$ diodes.


Now if we map the open-circuit diode voltages, in the case of no bottom edge recombination and with bottom edge recombination, we see a clear difference. In the latter case there is a lower voltage towards the bottom wafer edge.


If we compare the I-V parameters, in the case of no bottom edge recombination and with bottom edge recombination, we also see a clear difference. In the latter case there is a slightly lower $V_{o c}$ but more importantly, lower fill factor.

| Comment1 | $\mathrm{Jsc}(\mathrm{mA} / \mathrm{cm} 2)$ | Voc(mV) | FF | Eff | Vmp(mV) Jmp(mA/cm2) |  |
| :--- | ---: | ---: | ---: | ---: | ---: | ---: |
| with_bottom_edge_recomb | 37.764091 | 667.2117 | 76.61959 | 19.30557 | 557.5009 | 34.628757 |
| without_bottom_edge_recomb | 37.764149 | 668.8941 | 79.51409 | 20.08543 | 564.7428 | 35.565625 |

### 6.5 Simulating Cracks

Cell crack is a real life problem that occurs in both cell manufacturing, module manufacturing as well as modules in the field. Griddler is the ideal simulation program to easily define and simulate cracked cells. To do so, when you reach the meshing page, you can use the command

DRAWCRACK \{1=thru semi and metal; 2=thru semi only\} ( x y) coordinates in pairs in cm (width) in um e.g. DRAWCRACK 100551
will create a crack in the cell that cuts through both the wafer and the metallization. Below we show an example of a progression of cracks in a cell simulation, its effect on the simulated cell current density and efficiency. The script used to generate the last case is attached below.


OUTPUTRESOLUTION 1000
TITLESCREEN
DESIGNHPATTERN
WAFERTYPE 2
SAVEDXF 8u2he727365ys.dxf
DRAWCRACK 1-1.383966-8.000000-8.000000-0.620690 1
DRAWCRACK $1-5.569620-7.862069-3.679325-5.310345-3.206751-3.793103-3.206751-1.9310341$
DRAWCRACK $1-5.367089-3.517241-3.206751-1.931034-1.2489450 .000000-0.1012662 .3448281$
DRAWCRACK 1 -2.261603-1.034483-4.894515 1.517241 1
DRAWCRACK 1-4.624473 3.517241-4.894515 5.931034 1
DRAWCRACK 1-1.654008 8.000000-1.586498 6.000000-1.046414 4.068966-0.101266 2.344828 1
DRAWCRACK 1 -4.894515 1.517241-5.367089-0.620690 1
DRAWCRACK $1-4.8945151 .517241$-4.624473 3.5172411
DRAWCRACK 1 -8.000000 3.931034 -4.894515 5.931034-1.654008 8.0000001
DRAWCRACK 1-7.054852 4.551724-5.434599 2.7586211
DRAWCRACK 1 - $7.8649797 .379310-5.8396625 .3103451$
DRAWCRACK 1-2.261603-1.034483-1.856540-1.310345-0.438819-0.689655 1.113924 0.206897 8.0000005 .9310341

DRAWCRACK 1-1.248945 0.000000-0.438819-0.689655 1
DRAWCRACK 1 -0.101266 2.3448285 .3670896 .2068971
DRAWCRACK 13.2742622 .0000001 .9240513 .6551721
DRAWCRACK 11.9240513 .6551725 .2320683 .4482761

DRAWCRACK $11.9240513 .655172-0.0337555 .9310341$
DRAWCRACK 11.1139240 .206897 0.506329-2.344828 -0.033755-3.241379 1
DRAWCRACK $10.506329-2.3448285 .974684-7.9310341$
DRAWCRACK 1 - $0.033755-4.5517243 .544304-7.9310341$
DRAWCRACK $15.367089-3.6551728 .000000-6.6896551$
PARSEPATTERN
GOMESH
OKMESH
PARSEPATTERN
GOMESH
OKMESH
REARCURRENTEXTRACTION 3
FRONTCURRENTEXTRACTION 2
FRONTILLUMINATION 1
FINDJSCVOCMPP
REPORT crack_IV_21.txt
FRONTILLUMINATION 0
MAP 7004
FRONTILLUMINATION 1
SAVEPICTURE EL21.txt

### 6.6 Simulating transient solar cell charectoristlcs

High lifetime solar cells may require millisecond time scales to reach steady state in response to an applied voltage. This could cause very significant deviations in the measured I-V characteristics if the voltage sweep rate is too fast for each operating point to be a true steady state. To simulate this behavior, in the simulation screen use either of these commands

## SETSWEEPRATE \{V/s\}

To set a constant voltage ramp rate in V/s for the I-V sweep, or
SETSWEEPTIMING \{filename.txt\}
To load a text file with two columns, each row being a time in seconds and a voltage in V , to determine the sweep rate at different voltages. The latter may be more accurate in describing the sweep rate of I-V testers, which may not be constant voltage ramp rates.

Below is an exaggerated example of a reverse JV sweep performed on a high Voc cell ( $\operatorname{Voc}=741 \mathrm{mV}$ ) with

SETSWEEPRATE 100


### 6.7 Simulating photoluminescence line scans

Line scan photoluminescence is a technique pioneered by BT Imaging. It involves partial illumination of the sample using a narrow width line shaped light source, and typically a line camera that also images at roughly the same location as the illumination. As is typical of line scan imaging, the partial images are then stitched together to form the overall area image of the solar cell.

To perform line scan PL simulation, one can use any of the following commands
LINESCANPL $\{1=$ north south, $2=$ east west $\}$ \{pitch(cm) $\}$

## e.g. LINESCANPL 10.156

North South/east west determines the direction of the light scan. Pitch is the increment of the light/camera ROI. In the above case, the pitch is also the width of the line scan light, as well as the ROI of the line scan camera. The light scan light and the ROI of the line scan camera are collocated.

LINESCANPLMULTIPLECAMERAS $\{1=$ north south, $2=$ east west $\}$ \{pitch(cm \} \{number of line cameras ahead\} \{number of line cameras trailing\} \{line camera pitch (cm)\}
e.g. LINESCANPLMULTIPLECAMERAS 10.156550 .156

In the above, the width of the line camera ROI = line camera pitch may be different from the width of the line scan light = pitch. Optionally, one may define more camera ROIs ahead of trailing the middle ROI. If so, then upon saving the simulated map as txt, multiple txt's will be generated for the stitched image of each ROI.

LINESCANPLMULTIPLECAMERAS $\{1=$ north south, $2=$ east west $\}$ \{pitch(cm $\}$ \{light width(cm)\} \{number of line cameras ahead\} \{number of line cameras trailing\} \{line camera pitch (cm)\}

## e.g. LINESCANPLMULTIPLECAMERAS 10.156550 .156

In the above, the width of the line camera ROI = line camera pitch may be different from the width of the line scan light = light width, which again can be different from the pitch of advance = pitch

LINESCANPLMULTIPLECAMERAS \{Aangle\} \{pitch(cm\} \{light width(cm)\} \{number of line cameras ahead\} \{number of line cameras trailing\} \{line camera pitch (cm)\}

In the above, the direction of the scan can be at any angle
We show below the line scan simulation process using

## LINESCANPLMULTIPLECAMERAS A45 0.156550 .156

Note that the simulation is very slow as it consists of simulating a series of scenarios with the light source advancing between each case. As these simulation progress, the overall cell spatial distribution is shown. When finished, the stitched image is shown.



### 6.8 Simulating hotspots and wafep odge revorse bias breakdown

Griddler can now simulate realistic reverse bias breakdown behavior through the definition of hotspots and wafer edge breakdown. Moreover, the reverse bias breakdown current-voltage characteristics are faithfully emulated in Module simulations if the cell model were input into Module, enabling realistic shading scenarios to be simulated on the module level as well (see Module instruction manual section 4.7).

To define these breakdown behaviours, at the mesh screen, use the following commands
DRAWHOTSPOT $\{\mathrm{x} y\}$ coordinate in cm (radius) in um, (shunt conductance) in $1 / \mathrm{ohm}$, (rev breakdown V) in V , (rev IO) fA, (ideality factor)

DRAWHOTSPOT EDGE \{shunt conductance\} in 1/ohm (rev breakdown V) in V (rev IO) fA (ideality factor)
For example:
DRAWHOTSPOT -4 61000.1 -5 01
DRAWHOTSPOT -9.1 21000 -5 100001
DRAWHOTSPOT EDGE 0101001
Note: to emphasize many hotspots on one edge of the wafer, Use many circular hotspots at different breakdown voltages that are situated close to that wafer edge.


Each time one defines a hotspot or edge breakdown, there will be a confirmation message:


Griddler will concentrate more mesh points around the hotspots:


In the simulation screen, one can now simulate at reverse bias and there is a dropdown menu option to plot the hotspot map. Below are maps of reverse bias at -11 V and -7 V respectively.



One can also do reverse bias I-V trace:


Now, when one saves to REPORT, there will be a record of the hotspot and edge breakdown power dissipation information at the bottom of the report, corresponding to the last case that was ran. Here is an example of the power dissipations at the -11 V bias condition.


## 7 2J Tandlem Solar Cఆll simulation (PRO V®rsion)

### 7.1 Overview

If you're already familiar with the Griddler work flow, then you'll find tandem solar cell simulation to be a very simple and natural extension. A 2 J tandem solar cell model is essentially two regular Griddler cell models stacked together. Conceptually the representation is shown below: Griddler takes the top cell (slicing out the rear metallization), the bottom cell (slicing out he top metallization), and glues them together with the addition of new interlayers.


### 7.2 Quick Guide

Below we will illustrate the process of creating a tandem solar cell model starting with two already-made Griddler cell models, one for the top cell and another for the bottom cell. Once created, the tandem cell model and be saved and then retrieved as zip file.

1. In the Griddler menu, click on Tandem to pop up the tandem settings screen

2. Go to File $\rightarrow$ Load top cell file. Select the top cell Griddler model.

3. The top cell model is loaded into the Griddler main simulation screen. It is also displayed in the tandem settings screen as the top cell.

4. Go to File $\rightarrow$ Load bottom cell file. Select the bottom cell Griddler model.

5. The bottom cell model is loaded into the Griddler main simulation screen. It is also displayed in the tandem settings screen as the bottom cell.

6. Let's study the components of the tandem settings screen more closely.


## 1. Enable Tandem

This is checked by default. If unchecked, then the presently loaded Griddler model will be interpreted as a single cell, and if you run any simulations, it will be simulated as a single cell.

## 2. Edit Top/Bottom Cell

Allows you to toggle between the top/bottom cell inside the Griddler main simulation screen, so you can edit each (don't forget to save).

## 3. Top Cell Position

If the top cell is smaller than the bottom cell, then you can select its relative position overlaying the bottom cell. User is responsible for ensuring that the top cell is entirely contained in the area of the bottom cell!

## 4. Interlayer Sheet Resistance and Contact Resistance

Griddler takes the top cell (slicing out the rear metallization), the bottom cell (slicing out he top metallization), and glues them together with the addition of new interlayers. You can define the sheet resistance of these interlayers here, as well as the contact resistance across their connection to each other. As with most Griddler parameters, you can also clicked the blue N button to define non-uniform spatial patterns for each of these parameters.

## 5. Front/Rear Illumination

With tandem solar cells, you can define the illumination separately for the top cell, bottom cell, as well as the parts of the bottom cell that are not stacked with the top cell (in the case where the top cell is smaller than the buttom cell). In the case where each of these areas illumination is different, be sure to uncheck the "Make Equal" checkbox first.

## 6. Front/Rear Current Extraction Method

The current extraction method popup menus are now moved to the tandem settings screen (they are greyed out in the Griddler main simulation page).

## 7. Photon Coupling J01

Photon coupling is also called luminescence coupling or photon recycling. It refers to the phenomenon where radiative recombination in the top cell can generate significant flux of photons into the bottom cell, whereupon they are absorbed and become photogenerated current. Griddler currently implements a simple treatment in which
q (photon flux emitted from top cell to bottom cell in units of $\mathrm{cm}^{-2} \mathrm{~s}^{-1}$ ) $=$
(Photon coupling $\left.\mathrm{J}_{01}\right) \times\left(\exp \left(q \mathrm{q}_{\mathrm{Jtopcel}} / \mathrm{kT}\right)-1\right)$
Where q is the elementary charge, Vstopcell is the junction voltage of the top cell, and T is the temperature.
7. There are also slight changes in the Griddler main simulation screen when tandem mode is enabled. At the bottom, there is no longer space where you can enter the illumination (that has been moved to the tandem settings screen). In its place is a box where you can define the 1 -Sun $\mathrm{J}_{\mathrm{sc}}$ value of the bottom cell in the non-overlapping area (in the case where the top cell is smaller than the bottom cell).

8. As before, simulations can be ran in the Griddler main simulation screen. If tandem mode is enabled, then the results corresponding to tandem solar cell are shown.

9. One can save the entire tandem cell session as a zip file, and retrieve it later by File $\rightarrow$ Open tandem file (.zip)


## Appendix A: Matheemetical Formulee used in the Cell Cross Sectional Diagram and Rese Transport Calculator Pages

In Griddler 2.5 PRO, the cell cross sectional diagram and the base transport calculator serve as interfaces to cmd PC1D 6-2, external calculators of cell transmittance/absorptance like OPAL2 and the wafer ray tracer offered by PV Lighthouse, and they also implement a collection of useful equations which calculate various current density and recombination parameters. This section covers these equations so that the user understands how Griddler works out the numbers.


## A.1 Limitations

Many calculations rely on the properties of silicon material at temperature of 25C. They include the mobility of electrons and holes, optical absorption coefficient, free carrier absorption coefficient, intrinsic recombination rates, and doped layer properties like saturation current density ( $\mathrm{J}_{0 \text { e }}$ ), sheet resistance, and internal quantum efficiency (IQE). Therefore the calculators are only accurate for silicon at 25C. In the Griddler main simulation screen, it is possible to change the temperature, and the saturation current densities Jo's will be adjusted according to the intrinsic carrier concentration $n_{i}(\mathrm{~T})$ (See 2.7.2). While doing so will approximate cell behavior at non-standard temperatures, it is not a rigorous treatment. In any case, Griddler does not attempt to completely capture the temperature-dependence of all cell properties, as it would necessitate consideration of a multitude of factors like defect energy levels, etc, which are anyway beyond the scope of the simulation program.

## A.2 Light induced current density in the non=shealed region

## A. 2.1 Ovorvlew

The cell cross sectional diagram shows clearly the formula leading to this term (cell cross section diagram, box 1).

$$
\begin{equation*}
J_{L}=J_{S i} \text { absorption }-J_{\text {loss,FCA }}-J_{\text {loss,emitter }}-J_{\text {loss,base }} \tag{1}
\end{equation*}
$$

Where $J_{L}$ is the light induced current density (in the non-shaded region). In the cross section diagram box 1, an additional offset current density is also included in the equation, which allows the user to bring the calculated $J_{L}$ to agreement with experiment. The offset term is arbitrary and will not be covered here. In practice, using the offset term is still meaningful because it still allows the user to explore the relationship between $J_{L}$ and changing cell parameters.

## A.2.2 Absorption Current Denstyy in the Absence of Free Cartier Absorptlon

$$
\begin{equation*}
J_{\text {Si absorption }}=q \int_{0}^{\infty} A_{S i, n o F C A}(\lambda) \Phi(\lambda) d \lambda \tag{2}
\end{equation*}
$$

$J_{S i ; a b s o r p t i o n ~}$ is the rate of photons absorbed in the solar cell active material, per unit area of non-shaded region, times the elementary charge, in the absence of free carrier absorption. Here, $q$ is the elementary charge, $\lambda$ is the wavelength, $\Phi(\lambda)$ is the photon flux per unit wavelength $\left(\mathrm{cm}^{-2} \mathrm{~s}^{-2} \mathrm{~nm}^{-1}\right)$, representing the incident spectrum. $A_{\text {si,no }{ }^{\text {FCA }}}(\lambda)$ is the spectral absorptance in the cell active material in the absence of free carrier absorption.

In the Griddler PRO versions before 2.50034, $A_{\text {Si,no } F C A}(\lambda)$ is always directly imported from other external calculation programs through the Illumination Optics window. Since PRO version 2.50034, Griddler 2.5 PRO will auto-detect whether the imported Si absorptance data contains information about the transmittance into the wafer. The transmittance curve is the fraction of incident light which enters into the silicon bulk. If the imported data is higher than $30 \%$ at 1200 nm , then Griddler assumes this curve is the transmittance. It then calculates the resultant absorptance curve in the absence of FCA by using the light trapping formula.
$A_{S i, n o ~ F C A}(\lambda)=T \frac{\left(1-T_{1}\right)+T_{1} R_{b 1}\left(1-T_{2}\right)+T_{1} T_{2} R_{b 1} R_{f 1}\left(1-T_{n}\right)\left(1+R_{b n} T_{n}\right)}{1-R_{b n} R_{f n} T_{n}{ }^{2}}$
Where $T$ is the transmittance, and the remaining parameters in the right hand side of equation 3 are light trapping parameters in a model first published by Basore [1]. The diagram below illustrates the factors Griddler considers in calculating these different parameters. Without diving into the details, the
morphologies on both sides of the wafer (either planar or pyramid texture), the internal reflectance at the metallic regions and non-metallic regions, as well as the layout of the metal grids on both sides of the wafer, all figure into the determination of $T_{1}, T_{2}, T_{n}, R_{f 1}, R_{f n}, R_{b 1}, R_{b n}$.


## Ao2.3 Loss off Current Density in the Prosence of Free Canrier Absorption

Griddler calculates the absorptance curve with FCA by using a very similar light trapping formula as equation 3:
$A_{\text {Si,with } F C A}(\lambda)=$
$T T_{0} \frac{\alpha_{B B}(\lambda)}{\alpha_{F C A}(\lambda, z)+\alpha_{B B}(\lambda)} \frac{\left(1-T_{1} \prime\right)+T_{1} \prime R_{b 1} \prime\left(1-T_{2} \prime\right)+T_{1} \prime T_{2} \prime R_{b 1} \prime R_{f 1^{\prime}}\left(1-T_{n^{\prime}}\right)\left(1+R_{b n} \prime T_{n} \prime\right)}{1-R_{b n^{\prime}} R_{f n^{\prime}} T_{n^{\prime}} \prime^{2}}$
Here, the primed terms $\mathrm{T}_{1}{ }^{\prime}, \mathrm{T}_{2}$, $\mathrm{T}_{\mathrm{n}}{ }^{\prime}, \mathrm{R}_{\mathrm{f} 1}$, $\mathrm{R}_{\mathrm{fn}}$, $\mathrm{R}_{\mathrm{b} 1^{\prime},}, \mathrm{R}_{\mathrm{bn}}$ ' are different from their unprimed counterparts by accounting for the free carrier absorption in the wafer bulk and in the doped regions (if they are defined and if user has checked the box indicating the absorption in these regions shall be considered). The extra term $T_{0}$ is the transmittance through the incident light side doped layer after accounting for free carrier absorption, and $\alpha_{B B}$ is the band to band absorption coefficient [2]. $\alpha_{F C A}(\lambda, z)$ is the free carrier absorption coefficient taken from ref 3:
$\alpha_{F C A}(\lambda, z)=C N \lambda^{\gamma},\left\{C=1.80 \times 10^{-9}, \gamma=2.18\right\}$ for $\mathrm{p}-\mathrm{Si},\left\{C=1.68 \times 10^{-6}, \gamma=2.88\right\}$ for $\mathrm{n}-\mathrm{Si}$
For $\lambda>=1000 \mathrm{~nm}$ and
$\alpha_{F C A}(\lambda, z)=0$
For $\lambda<1000 \mathrm{~nm}$
where N is the dopant concentration in $\mathrm{cm}^{-3}, \lambda$ wavelength is given in cm , and the unit of $\alpha_{F C A}$ is always in $\mathrm{cm}^{-1}$. Equation 5 is applied regardless of the dopant concentration N , across the solar cell, although ref 3 states that it is applicable to dopant range of $10^{18}-5 \times 10^{20} \mathrm{~cm}^{-3}$.

After this, the current density loss due to free carrier absorption is

$$
\begin{equation*}
J_{l o s s, F C A}=q \int_{0}^{\infty}\left(A_{S i, n o ~ F C A}(\lambda)-A_{S i, w i t h ~ F C A}(\lambda)\right) \Phi(\lambda) d \lambda \tag{6}
\end{equation*}
$$

## A.2.4. Loss of Current Donsity duo to lmporfect Emiter collecton

$$
\begin{equation*}
J_{\text {loss,emitter }} \approx q \int_{0}^{600 \mathrm{~nm}} A_{S i, n o ~ F C A}(\lambda) \Phi(\lambda)\left(1-I Q E_{0}(\lambda)\right) d \lambda \tag{7}
\end{equation*}
$$

Joss, emitter represents the rate at which photogenerated carriers in the emitter layer recombine. In equation 7, $I Q E_{0}(\lambda)$ denotes the internal quantum efficiency as defined by the ratio of collected carriers to photogenerated carriers, for a cell with a long base and very long base diffusion length. $I Q E_{0}(\lambda)$ is calculated by cmd PC1D 6-2 [4]. Note that the term $A_{S i, n o ~ F C A}(\lambda)$ is used for convenience---rigorously this term should be $A_{B B}(\lambda)$, the absorptance which leads to band-to-band transition (electron-hole pair generation) in the case that free carrier absorption is also considered. However as the integral in equation 7 spans from 0600 nm of wavelength, where free carrier absorption is insignificant, it can be assumed that $A_{S i, n o ~ F C A}(\lambda)=$ $A_{B B}(\lambda)$. The choice of integration in the $0-600 \mathrm{~nm}$ range is arbitrary. At 600 nm , the penetration depth of light in silicon is about 2.41um, which is deeper than most emitter layers in practice. For most decent emitters the $I Q E_{0}(\lambda)$ past 600 nm is close to 1 . However, for very poor emitters, $I Q E_{0}(\lambda)$ past 600 nm can still be significantly lower than 1 , and equation 7 will underestimate the actual imperfect emitter collection loss.

## A22.5 Loss of Current Density due to lmporfect Bese Collectlon

$$
\begin{equation*}
J_{\text {loss,base }}=q \int_{0}^{\infty} \int_{0}^{W} g(\lambda, z)\left(1-f_{c}(z)\right) d z d \lambda \tag{8}
\end{equation*}
$$

Jloss,base represents the rate at which photogenerated carriers in the base recombine. In equation $8, g(\lambda, z)$ is given by equation 4 , and $f_{c}(z)$ is the base collection efficiency, representing the ratio of collected carriers to photogenerated carriers at depth $z$. In terms of the recombination parameters in the base, $f_{c}(z)$ is given by

$$
\begin{equation*}
f_{c}(z)=\cosh \left(\frac{z}{L_{D}}\right)-\frac{S_{e f f} L_{D} / D \cosh \left(w / L_{D}\right)+\sinh \left(w / L_{D}\right)}{S_{e f f} L_{D} / D \sinh \left(w / L_{D}\right)+\cosh \left(w / L_{D}\right)} \sinh \left(\frac{z}{L_{D}}\right) \tag{8a}
\end{equation*}
$$

if the pr junction is at the front. If the pn junction is at the rear then

$$
\begin{equation*}
f_{c}(z)=\cosh \left(\frac{w-z}{L_{D}}\right)-\frac{S_{e f f} L_{D} / D \cosh \left(w / L_{D}\right)+\sinh \left(w / L_{D}\right)}{S_{e f f} L_{D} / D \sinh \left(w / L_{D}\right)+\cosh \left(w / L_{D}\right)} \sinh \left(\frac{w-z}{L_{D}}\right) \tag{8b}
\end{equation*}
$$

$w$ is the thickness of the cell, $L_{D}$ is the minority carrier bulk diffusion length, $D$ is the minority carrier diffusion coefficient, $S_{\text {eff }}$ is the effective rear surface recombination velocity (if pn junction is at front; it is the effective front surface recombination velocity if the pn junction is at the rear), whose expression will be given further below.

## A.3 Bese Saturation Recombination Current Density

## A.3.1 Ov®rview

The total recombination current density in the base is given by

$$
\begin{equation*}
J_{\text {recombination,base }}=J_{01, \text { base }} \exp (q V / k T)+J_{02, \text { base }} \exp (q V / 2 k T) \tag{9}
\end{equation*}
$$

where $V$ is the local diode voltage, $T$ is the temperature, $k$ is the Boltzmann constant. $J_{01, \text { base }}$ and $J_{02, \text { base }}$ are the saturation current densities of the diodes with ideality factors $n=1$ and $n=2$ respectively, in what's commonly known as a two diode model of the solar cell. The calculators only provide linear equations that calculate $J_{01, \text { base }}$. In the cell cross sectional diagram, if the checkbox "Use rear $J_{0}$ base by local contact calculator" is checked, then

$$
\begin{equation*}
J_{01, b a s e}=\frac{q n_{i}^{2} D}{N L_{D}} \frac{S_{e f f} L_{D} / D \cosh \left(w / L_{D}\right)+\sinh \left(w / L_{D}\right)}{S_{\text {eff }} L_{D} / D \sinh \left(w / L_{D}\right)+\cosh \left(w / L_{D}\right)} \tag{10}
\end{equation*}
$$

$n_{i}$ is the instrinsic carrier concentration of silicon [5], $N$ is the dopant concentration in the base. In this case $J_{01, \text { base }}$ applies everywhere in the Griddler base layer (rear if pn junction is on the front; front if pn junction is on the rear). If the checkbox "Use rear $J_{0}$ base by local contact calculator" is unchecked in Fig 1, then Griddler uses

$$
\begin{align*}
& J_{01, \text { base }, \text { pass } 1 D}=\frac{q n_{i}^{2} D}{N L_{D}} \frac{s_{\text {pass }} L_{D} / D \cosh \left(w / L_{D}\right)+\sinh \left(w / L_{D}\right)}{s_{\text {pass }} L_{D} / D \sinh \left(w / L_{D}\right)+\cosh \left(w / L_{D}\right)}  \tag{11a}\\
& J_{01, \text { base,met } 1 D}=\frac{q n_{i}^{2} D}{N L_{D}} \frac{s_{\text {met }} L_{D} / D \cosh \left(w / L_{D}\right)+\sinh \left(w / L_{D}\right)}{s_{\text {met }} L_{D} / D \sinh \left(w / L_{D}\right)+\cosh \left(w / L_{D}\right)} \tag{11b}
\end{align*}
$$

$J_{01, \text { base,pass1D }}$ applies to the regions in the Griddler base layer which is over a passivated region, and $J_{01, \text { base,mettD }}$ applies to the regions in the Griddler base layer which is over a metallized region.

## A 3.2 Effective surfece recombliation velocity Sen ln the cese of locally comtactod surfaces

For surfaces with periodic local contacts, the surface recombination velocity (SRV) at the contacted region is typically higher than at the non-contacted region (which are passivated). Saint-Cast and co-workers have provided analytical formulae for the resultant effective SRV if the local contact geometry were parallel stripes, or an array of circular dots arranged in square or hexagonal fashion [6]
$S_{\text {eff }}=\left((1-f) S_{\text {pass }}+S_{\text {met }} f\left(\frac{r_{\text {spr }} S_{\text {pass }} f+1}{r_{\text {spr }} S_{\text {met }} f+1}\right)\right) \times\left[\left(1+\frac{L_{D}}{D} \tanh \left(\frac{w}{L_{D}}\right)\right)\left(S_{\text {pass }}-\left((1-f) S_{\text {pass }}+\right.\right.\right.$
$\left.\left.\left.S_{\text {met }} f \frac{r_{\text {spr }} S_{\text {pass }} f+1}{r_{\text {spr }} S_{\text {met }} f+1}\right)\right)\right]^{-1}$
$f$ is the fraction of metal contacted area, $S_{\text {pass }}$ is the SRV of the noncontacted (passivated) region, $S_{\text {met }}$ is the SRV of the contacted region, $r_{\text {spr }}$ is the dark spreading resistance given by

$$
\begin{equation*}
r_{s p r}=\frac{1}{D}\left(\frac{A}{2 \pi a} \operatorname{atan}\left(\frac{2 w}{a}\right)+W(1-\exp (-w / 2 p))\right. \tag{13}
\end{equation*}
$$

for dot contacts, with $a$ being the radius of the dot contacts, $w$ being the cell thickness as before, p is the half of the distance between the centers of two contacts, A is the area of collection for one contact.

$$
\begin{equation*}
r_{s p r}=\frac{1}{D}(p \gamma(a) / 2+w(1-\exp (-w / 2 p)) \tag{14}
\end{equation*}
$$

for stripe contacts, with $\gamma$ defined to be

$$
\begin{align*}
& \gamma(a)=\frac{1}{\pi} \ln \left(2 \frac{\sqrt{\cosh (\pi a / 4 w)}+1}{\sqrt{\cosh (\pi a / 4 w)}-1}\right) \text { if } \quad \tanh (\pi a / 4 w) \leq \frac{1}{\sqrt{2}}  \tag{15a}\\
& \gamma(a)=\pi\left[\ln \left(2 \frac{\sqrt{\cosh (\pi a / 4 w)}+1}{\sqrt{\cosh (\pi a / 4 w)}-1}\right]^{-1} \text { if } \frac{1}{\sqrt{2}} \leq \tanh (\pi a / 4 w) \leq 1\right. \tag{15b}
\end{align*}
$$

## A.3.3 Conversion betwoon besc surfece dos and SRVs

The quantity $J_{0 \text { passivated,BSF }}$ in the cell cross sectional diagram, box 2 is linked to rear passivation SRV in the base transport calculator, box 4 . Similarly the quantity $\mathrm{J}_{0, B S F, \text { metal contact }}$ is linked to contact SRV. These two pairs of quantities are linked by the equations

$$
\begin{align*}
& J_{0, \text { passivated }, B S F}=\frac{q n_{i}^{2}}{N} S_{\text {pass }}  \tag{16a}\\
& J_{0, \text { metal }, B S F}=\frac{q n_{i}^{2}}{N} S_{\text {met }} \tag{16b}
\end{align*}
$$

If the cell cross sectional diagram is used to calculate $J_{0, \text { passivated,BSF }}$ or $J_{0, \text { metal,BSF }}$ by running cmd-PC1D 62 computation on the BSF layers, then the values of $S_{\text {pass }}$ and $S_{\text {met }}$ will be updated in the base transport calculator page using equations 16 . Conversely, if the values of $S_{\text {pass }}$ or $S_{\text {met }}$ is altered in the base transport calculator page, then the cell cross sectional diagram updates $J_{0, p a s s i v a t e d, B S F}$ and $J_{0, \text { metal,BSF }}$ using equation 16.

## Aas Auger and Radiative Recombination

See formulation by Richter and Glunz [9]. Auger and radiative recombination constitute the intrinsic recombination process that sets an upper limit to silicon solar cell efficiency. In Griddler, it is assumed that the fermi level splitting is constant and equal to the value at the junction, throughout the thickness of the silicon wafer.

## A.5 Bese resistance due to current crowdingy, lateral current flow, and Contact rosistance at local contects

## A.5.1 Ovorvicw

The base resistance (related to the field "effective rear contact resistance" in the base transport calculator, box 4) consists of three components

$$
\begin{equation*}
R_{s, \text { base }}=R_{s(\text { lat })}+R_{s(\text { crowd })}+R_{s(\text { contact })} \tag{17}
\end{equation*}
$$

$R_{s(l a t)}$ refers to the lateral flow of current in the base, $R_{s(\text { (rowd })}$ refers to the resistance encountered in the vicinity of a local contact, where the current density increases towards the contact point. $R_{s(\text { contact })}$ refers to the contact resistance at the contact point itself.

## A.5.2 Calculatfon of the offectivo roar contect resistance

$R_{s, \text { base }}$ is in units of $\Omega \mathrm{cm}^{2}$. If the Griddler base geometry is full area metal, then $R_{s, b a s e}=\rho_{c, \text { eff }}$ where $\rho_{c, \text { eff }}$ is the effective grid contact resistance, which is the value in the field "effective rear contact resistance" in the base transport calculator box 4 . If the Griddler base geometry is a grid instead, then $\rho_{c, \text { eff }}=R_{s, b a s e} / f$ where $f$ is the finger area contact fraction.

## A.5.3 国se resistance due to current crowdling

Both Cuevas [7] and Saint-Cast and coworkers [6] have derived expression for the resistance due to current crowding to a local contact. The former is calculated via [7]

$$
\begin{align*}
& R_{S(\text { crowd })}=\rho \int_{w}^{0} \frac{A}{A_{\text {crowd }}(x)} d x  \tag{18}\\
& A_{\text {crowd }}(x)_{\text {point }}=\pi a^{2}+\pi^{2} a(w-x)+2 \pi(w-x)^{2}  \tag{19}\\
& A_{\text {crowd }}(x)_{\text {linear }}=2 a+\pi(w-x) \times 1 \mathrm{~cm} \tag{20}
\end{align*}
$$

The latter is calculated simply via [5]

$$
\begin{equation*}
R_{S(\text { crowd })}=D \rho r_{s p r} \tag{21}
\end{equation*}
$$

where $r_{s p r}$ is as defined in equations 13 and 14. If the base transport calculator, box 4, if the radio button "calculate $\mathrm{R}_{\mathrm{s}, \text { ligh" }}$ is on, then equations $18-20$ are used. If the radio button "calculate $\mathrm{R}_{\mathrm{s}, \text { dark" }}$ is on, then equations 13-14, 21 are used (see A.4.6).

## A.5.4 Base resistance du( to leteral current flow

For dot contacts [8],

$$
\begin{equation*}
R_{S(\text { lat })}=\rho \frac{A}{2 \pi w}\left[\frac{r_{\max }^{2}}{r_{\text {max }}^{2}-r_{\text {min }}^{2}} \ln \left(\frac{r_{\max }}{r_{\min }}\right)-\frac{1}{2}\right] \tag{22}
\end{equation*}
$$

where $\rho$ is the base resistivity, w is the cell thickness, A is the area of collection for one contact. $r_{\max }=$ $\sqrt{A / \pi}$ and $r_{\text {min }}=a+w \pi / 4$ where $a$ as before is the radius of the dot contacts. For stripe contacts, we use based on resistive power dissipation

$$
\begin{equation*}
R_{S(l a t)}=\frac{\rho s(s-2 a)}{12 w} \tag{23}
\end{equation*}
$$

where s is the pitch of the contacts and a is the half width of the stripe contacts.
If the Griddler base geometry were a grid, then the Griddler simulation itself will also model lateral current flow to the grid fingers. Therefore in this case it would be a kind of "double counting" if the effective rear contact resistance also considers the base lateral current induced resistance. So, in this particular case, the base transport calculator will subtract out a term similar to equation 19 , where $s$ is the pitch of the grid and a is the half width of the fingers as defined by Griddler.

## A.5.5 回®s® resistance du® to contect resistance తt local contacts

This term is very simply

$$
\begin{equation*}
R_{S(\text { contact })}=\frac{\rho_{c}}{f} \tag{24}
\end{equation*}
$$

where $\rho_{c}$ is the specific contact resistance, and $f$ is the contact area fraction.

## 

In the base transport calculator, box 4, there is the option to select $R_{s, \text { light }}$ vs $R_{s, \text { dark. }}$. The former refers to the resistance encountered by the current flow pattern when the solar cell is illuminated, that is, with photogenerated current density that is fairly uniform throughout the cell plane. The latter refers to the resistance encountered by the current flow pattern when the solar cell is forward biased in the dark. In the base transport calculator, the following work flow is used:

If calculate $R_{s, \text { dark }}$ is chosen:

1. $R_{s(l a t)}$ is set to zero.
2. $R_{s(\text { crowd })}$ is calculated using equations 13-14, 21.
3. $R_{s(\text { contact })}$ is calculated using equation 24.

If calculate $R_{s, \text { light }}$ is chosen:

1. $R_{s(l a t)}$ is calculated using equations 22-23.
2. $R_{s(\text { crowd })}$ is calculated using equations 18-20.
3. $R_{s(\text { contact })}$ is calculated using equation 24.
4. If the Griddler base geometry were a grid, then the Griddler simulation itself will also model lateral current flow to the grid fingers. Therefore in this case it would be a kind of "double counting" if the effective rear contact resistance also considers the base lateral current induced resistance. So, in this particular case, the base transport calculator will subtract out a term similar to equation 18 , where $s$ is the pitch of the grid and a is the half width of the fingers as defined by Griddler.
5. The resultant $R_{s, \text { light }}$ cannot be lower than $R_{s, \text { dark. If that is not the case, then }} R_{s, \text { dark }}$ is used.

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## Appendlx B: Compartson of Griddler 2 to Gridsim and the simple two diode model

Griddler 2 is a finite-element model (FEM) simulator which is an implementation of the network model of solar cell as interconnected diodes. Griddler 2 meshes the solar cell front and rear planes into nodes and triangular elements. It then calculates the front and rear voltage at each node, after specifying the photocurrent received by each node, and the voltages at terminal nodes on the front and rear planes. The solution of the spatially dependent voltages on the cell front and rear planes, is consistent with the current flow pattern for a given cell metallization geometry. Therefore, Griddler 2 is generally more accurate than simple power loss formulae in calculating the ohmic power dissipation due to lateral current flows in the cell planes. Simple power loss formulae assumes a certain current flow pattern which involves two approximations: 1) each node is a current source with the same current density, 2 ) in the case of an H pattern metallization, current flows in a perpendicular path to the nearest metal finger, then parallel to the finger to the nearest busbar. Both approximations break down after the solar cell terminal voltage has risen past the maximum power point, or when the metallization plane is not an H-pattern (e.g. full area metallization in the cell rear). In theory, because the simple power loss formulae assumes a certain solution for the current flow, thereby enforcing a constraint, then according to the energy minimization principle, it must necessarily overestimate the ohmic power dissipations, though the degree of overestimation may be small for certain scenarios. Griddler 2 is also generally more accurate than the two diode model representation of a solar cell at calculating the terminal voltage, because it is able to capture the lateral currents and voltage variations in the cell planes.

In theory, the simple power loss formulae in calculating ohmic power dissipations become accurate when its approximations are robust. These conditions are met when 1) the terminal voltage is well below the maximum power point, when the diodes have not "turned on" and therefore each node may indeed have almost identical current density; 2) the cell metallization plane is constructed such that the current flow pattern is closely resembling the approximated one. Therefore, in special cases where these circumstances are met, the simple power loss formulae should be reasonably accurate, and its calculations serve as sound basis of comparison for Griddler 2.

On the other hand, the two diode model becomes accurate if the cell planes are highly conductive, such that voltage variations along the cell planes are minimized. Under this circumstance, the voltage at each node may be taken to be the terminal voltage, and all the nodal diodes are well approximated to be in parallel. Then in this case, the two diode model should be reasonably accurate in calculating the terminal voltage, and its calculations serve as sound basis of comparison for Griddler 2.
B.1 Comparison of Griddler 2 to GridSim 5.3 in calculating ohmic powor dissipations

Table I. Ran cases and calculated power dissipations

|  | $\begin{aligned} & N \\ & \frac{1}{0} \\ & 3 \\ & \varepsilon \end{aligned}$ |  |  |  |  |  |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  |  |  |  |  |  |  |  |  |  |  | $\xrightarrow{\text { ¢ }}$ |
|  |  |  |  |  |  |  |  |  |  | $\begin{aligned} & \hat{o} \\ & \stackrel{\rightharpoonup}{\text { N }} \end{aligned}$ |  |  |
|  |  |  |  |  |  |  |  |  |  | $\begin{aligned} & 0 \\ & 0 \\ & \text { U } \\ & \text { oj } \end{aligned}$ | $\begin{aligned} & 0 \\ & 0 \\ & 0 \\ & 0 \\ & 0 \\ & 0 \end{aligned}$ |  |
|  |  |  |  |  |  |  | $\begin{aligned} & \text { or } \\ & \hline 0 \\ & \vdots \\ & \hline \end{aligned}$ |  |  |  |  |  |
|  |  |  |  |  |  |  | $\begin{aligned} & \stackrel{\infty}{\sim} \\ & \underset{\sim}{0} \\ & 0 \end{aligned}$ |  | $\begin{aligned} & \underset{\sim}{\aleph} \\ & \underset{\sim}{0} \end{aligned}$ |  |  |  |
|  |  | $\begin{aligned} & \frac{\varepsilon}{n} \\ & \frac{0}{0} \\ & \hline \end{aligned}$ |  |  |  | $\begin{aligned} & \stackrel{\otimes}{0} \\ & \underset{\sim}{7} \end{aligned}$ |  | $\begin{aligned} & \hat{\text { on }} \\ & \stackrel{\rightharpoonup}{7} \end{aligned}$ |  |  |  |  |
|  |  | $\begin{array}{\|l\|} \hline \frac{1}{2} \\ \hline \overline{0} \\ \hline i \end{array}$ |  |  |  | $\begin{aligned} & \underset{\sim}{7} \\ & \underset{\sim}{7} \end{aligned}$ |  | $\begin{aligned} & \infty \\ & \underset{\sim}{7} \\ & \underset{\sim}{\circ} \end{aligned}$ |  |  |  |  |
|  | $\begin{aligned} & N \\ & \frac{1}{2} \\ & 3 \\ & E \end{aligned}$ | $\begin{aligned} & \frac{\varepsilon}{n} \\ & \frac{0}{0} \\ & \hline \end{aligned}$ |  | $\begin{aligned} & \stackrel{n}{m} \\ & \underset{\sim}{m} \\ & \hline \end{aligned}$ | $\stackrel{\substack{n \\ \\ \underset{\sim}{m} \\ \hline}}{ }$ |  |  |  |  |  |  |  |
|  |  | $\begin{array}{\|l\|} \hline \frac{9}{9} \\ \hline 0 \\ \hline 0 \\ \hline \end{array}$ |  | $\begin{aligned} & \stackrel{\infty}{\sim} \\ & \underset{\sim}{\mathrm{N}} \end{aligned}$ | $\begin{aligned} & \text { N} \\ & \text { N} \\ & \text { ò } \end{aligned}$ |  |  |  |  |  |  |  |
|  |  |  |  |  | $\begin{aligned} & \text { N} \\ & \underset{\sim}{\infty} \\ & \text { O- } \end{aligned}$ |  |  |  |  |  |  |  |
|  |  |  |  | 0 <br> $\underset{\sim}{n}$ <br>  | 0 <br>  <br>  |  |  |  |  |  |  |  |
|  | $\begin{aligned} & \text { n } \\ & E \\ & 3 \\ & E \\ & E \end{aligned}$ | $\begin{array}{\|l\|} \hline \frac{\varepsilon}{\vec{n}} \\ \dot{0} \\ \hline \end{array}$ | $\begin{aligned} & \stackrel{n}{N} \\ & \underset{N}{N} \\ & \text { on } \end{aligned}$ |  |  |  |  |  |  |  |  |  |
|  |  | $\begin{array}{\|l\|} \hline \frac{9}{0} \\ \frac{0}{0} \\ \hline 0 \end{array}$ | $\begin{aligned} & \underset{\sim}{\sim} \\ & \underset{\sim}{\sim} \end{aligned}$ |  |  |  |  |  |  |  |  |  |
|  | $\begin{aligned} & \stackrel{\rightharpoonup}{E} \\ & \frac{5}{3} \\ & \vdots \end{aligned}$ |  | $\begin{aligned} & \hat{N} \\ & \underset{\sim}{\infty} \\ & \underset{\sim}{0} \end{aligned}$ |  |  |  |  |  |  |  |  |  |
|  |  | $\begin{aligned} & \frac{1}{2} \\ & \frac{0}{0} \\ & i 0 \end{aligned}$ | $\begin{aligned} & \text { y } \\ & \text { Nin } \\ & \text { No } \end{aligned}$ |  |  |  |  |  |  |  |  |  |
|  |  |  |  | $\begin{aligned} & \stackrel{\rightharpoonup}{\overleftarrow{N}} \\ & \text { ஸ̀ } \end{aligned}$ | g ஸ゙ | $\begin{aligned} & n \\ & \stackrel{n}{\infty} \\ & +\infty \\ & + \end{aligned}$ | $\begin{aligned} & \text { n } \\ & \stackrel{0}{\infty} \\ & +\dot{+} \end{aligned}$ | $\begin{aligned} & \text { n } \\ & \stackrel{0}{\infty} \\ & +\underset{\sim}{2} \end{aligned}$ | $\begin{aligned} & \text { n} \\ & \stackrel{0}{\infty} \\ & \underset{\sim}{+} \end{aligned}$ |  | ¢ |  |
|  |  |  | 8 <br> $\stackrel{8}{7}$ <br>  |  | Q + in | $\begin{aligned} & \infty \\ & \underset{\infty}{\infty} \\ & \underset{\sim}{\infty} \end{aligned}$ | $\underset{\sim}{\underset{\sim}{\infty}} \underset{\substack{m \\ \rightarrow}}{ }$ | $\begin{aligned} & \underset{\sim}{\sim} \\ & \underset{\sim}{\infty} \\ & \underset{\sim}{n} \end{aligned}$ | $\begin{aligned} & \underset{\sim}{N} \\ & \underset{\sim}{\infty} \\ & \underset{\sim}{n} \end{aligned}$ | $\begin{aligned} & \text { ol } \\ & \stackrel{\circ}{\infty} \\ & \text { on } \end{aligned}$ | O on $\infty$ 0 |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |

GridSim version 5.3 is an excel implementation of the simple power loss formulae for an H -pattern front grid solar cell, written by A. Mette with small changes by M. Hoerteis. Table I compares the relevant ohmic power dissipations calculated by GridSim and Griddler 2. For each row of Table I, the left column refers to the particular H-pattern geometry and settings of the Griddler 2 file. Each of the ran cases are chosen to ensure that the approximated current flow pattern by the simple power loss formulae conforms closely to the actual.

For each H-pattern, Griddler 2 generated the mesh using the coarsest mesh settings available. This is intentionally done to test whether Griddler 2 is sufficiently accurate using the coarsest mesh settings. For finer mesh settings, it is expected that Griddler 2 should improve in accuracy.

It can be seen that all ohmic power dissipations calculated by the two models agree to within $6.5 \%$ relative for the tested cases.

Concurrently, it can be seen that the optical shading calculations by Gridder 2 and GridSim are also in excellent agreement, to within $1.5 \%$ relative for the test cases.

## B.2 Comparlson of criddler 2 to Two dlode model in calculating opon-circult voltages

Table 2. Ran cases and calculated open-circuit voltages

|  | Suns | Front Side |  |  |  | Rear Side |  |  |  | Edge Recombination |  | Internal Shunt | Griddler | Hand Calc* |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | Passivated Area |  | Metal Contact |  | Passivated Area |  | Metal Contact |  |  |  |  |  |  |
|  |  | J01 | J02 | J01 | J02 | J01 | J02 | J01 | J02 | J01 | J02 |  | Voc | Voc |
|  |  | (fA/cm2) | ( $\mathrm{nA} / \mathrm{cm} 2$ ) | (fA/cm2) | ( $\mathrm{nA} / \mathrm{cm} 2)$ | (fA/cm2) | ( $\mathrm{nA} / \mathrm{cm} 2)$ | (fA/cm2) | ( $\mathrm{nA} / \mathrm{cm} 2)$ | (fA/cm2) | ( $\mathrm{nA} / \mathrm{cm} 2)$ | (ohm-cm2) | (mV) | (mV) |
| case1 | 0.1 | 200 | 10 | 600 | 50 | 0 | 0 | 200 | 20 | 0 | 0 | 0 | 568 | 566 |
| case2 | 1 | 200 | 10 | 600 | 50 | 0 | 0 | 200 | 20 | 0 | 0 | 0 | 640 | 639 |
| case3 | 0.1 | 200 | 0 | 600 | 0 | 0 | 0 | 200 | 0 | 0 | 0 | 0 | 586 | 588 |
| case4 | 1 | 200 | 0 | 600 | 0 | 0 | 0 | 200 | 0 | 0 | 0 | 0 | 647 | 645 |
| case5 | 1 | 200 | 0 | 600 | 0 | 0 | 0 | 200 | 0 | 1000 | 0 | 0 | 635 | 634 |
| case6 | 0.1 | 200 | 0 | 600 | 0 | 0 | 0 | 200 | 0 | 1000 | 0 | 0 | 576 | 574 |
| case 7 | 0.1 | 200 | 10 | 300 | 50 | 0 | 0 | 200 | 10 | 1000 | 200 | 0 | 541 | 540 |
| case8 | 1 | 200 | 10 | 300 | 50 | 0 | 0 | 200 | 10 | 1000 | 200 | 0 | 624 | 622 |
| case9 | 1 | 200 | 10 | 600 | 50 | 0 | 0 | 200 | 20 | 0 | 0 | 100 | 635 | 633 |
| case10 | 0.1 | 200 | 10 | 600 | 50 | 0 | 0 | 200 | 20 | 0 | 0 | 100 | 366 | 365 |

The two diode model takes as the diode light-induced current to be the summation of the nodal light-induced currents. It also takes as the saturation current densities to be the summation of the nodal saturation current densities. Namely,
$\mathrm{J} 01=\mathrm{J} 01$, front passivated area $\times(1-\mathrm{f}$ front metal $)+\mathrm{J} 01$, front metal contact $\times \mathrm{f}$ front metal +J 01 , rear passivated area $x(1-f$ rear metal) +J 01 , rear metal contact x f rear metal +J 01 ,edge $\times$ Ledge / A wafer
$\mathrm{J} 02=\mathrm{J} 02$,front passivated area $\times(1-\mathrm{f}$ front metal) +J 02 ,front metal contact f front metal +J 02 , rear passivated area $x(1-f$ rear metal $)+J 02$,rear metal contact $x$ frear metal +J 02 ,edge $\times$ Ledge / A wafer

Each of the ran cases are done when the lateral conductance of the cell front and rear planes are maximized.

It can be seen that all open-circuit voltages calculated by the two models agree to within $1-2 \mathrm{mV}$.


Griddler 2.5 PRO is equipped with a cell cross sectional diagram with an interface to cmd-PC1D-6.2 [1] for doped layer saturation current density $J_{o e}$ calculations, as well as internal quantum efficiency (IQE) calculations. cmd-PC1D-6.2 and PC1Dmod 6-2 are command line executed and graphic user interface versions of a fast, one-dimensional semiconductor device simulator written at the Institute for Energy Technology (IFE) Norway. It is open source and freely available for download. Another well known free calculator of silicon solar cell emitter Joe and IQE is EDNA2 [2], developed and hosted online by PV Lighthouse. The authors and collaborators of a previous version of cmd-PC1D-6.2 (v6.1) have compared the $J_{o e}$ calculations between cmd-PC1D-6.1 and EDNA2, for a variety of Gaussian shaped boron and phosphorus silicon emitter profiles, and found good agreement between the two calculators [3]. In this section, we will compare both $J_{o e}$ and IQE calculations between cmd-PC1D-6.2 and EDNA2 (v2.5.5), for a variety of boron and phosphorus silicon emitter profiles that we select from electrochemical capacitance voltage (ECV) measurements. Specifically, the cmd-PC1D-6.2 results are obtained by running the Griddler 2.5 PRO (v2.50021) interface, so the comparison is between the Griddler 2.5 PRO (v2.50021) cmd-PC1D6.2 Caller and EDNA2 (v2.5.5).

Table I. Parameters used in the two calculators

|  | Griddler 2.5 PRO (v2.50021) <br> lmd-PC1D-6.2 Caller | EDNA2 (v2.5.5) |
| :--- | :--- | :--- |
| Background phosphorus doping <br> when simulating boron profiles | $2.0 \times 10^{15} \mathrm{~cm}^{-3}$ | $2.0 \times 10^{15} \mathrm{~cm}^{-3}$ |
| Background boron doping when <br> simulating phosphorus profiles | $8.0 \times 10^{15} \mathrm{~cm}^{-3}$ | $8.0 \times 10^{15} \mathrm{~cm}^{-3}$ |
| Auger recombination | Richter 2012 [4] | Richter 2012 [4] |
| Emitter bulk lifetime | 100 us | 100 us |
| Specified voltage | 0.55 V | 0.55 V |
| Carrier Mobility | Klaassen 1992 [5,6] for sheet <br> resistance, Schindler 2014 [7] for <br> Joe | Klaassen 1992 [5,6] |
| Carrier Statistics | Fermi Dirac | Fermi Dirac |
| Dopant lonization | Altermatt 2006 [8,9] | Altermatt 2006 [8,9] |
| Band gap narrowing | Yan and Cuevas 2013 [10,11] | Schenk 1998 [12] |
| Emitter bulk E field | Poisson equation | Quasi-neutral approximation |

Table I compares the simulation parameters used by the two calculators. The two calculators have some differences in the modelling procedure. For example, EDNA2 assumes that the emitter is quasi-neutral, while cmd-PC1D-6.2 solves the electric field inside the emitter. The two calculators also use different methods to calculate bandgap narrowing.

A variety of boron and phosphorus emitter profiles have been fed to both calculators. When simulating boron profiles, the phosphorus base doping of the cell is set to $2.0 \times 10^{15} \mathrm{~cm}^{-3}$, and when simulating phosphorus profiles, the boron base doping of the cell is set to $8.0 \times 10^{15} \mathrm{~cm}^{3}$. The bulk SRH lifetime of the emitter is always set to 100us. The surface recombination velocity (SRV) for each case is set to different values and is recorded down in Tables II and III.

## C.2 Boron Emittor Calculations

Table II below compares the sheet resistance, $\mathrm{J}_{0 \text { e }}$ and IQE at the wavelengths $300,350,400,450 \mathrm{~nm}$, obtained by the two calculators. the column EMITTERPASSSRV shows the front SRV that was used in the simulations.

Table II. Sheet resistance, Joe and IQE obtained by the two calculators



Figure 1. Graphical plots of the results in Table II. In each plot the grey line indicates perfect agreement.
Figure 1 above plots the results obtained by the two calculators. The agreement is generally very good. Average fractional deviations between the two calculators are $0.17 \%, 6.8 \%, 0.18 \%, 0.21 \%, 0.3 \%, 0.57 \%$, for the sheet resistance, $J_{0 e}$, IQE300, IQE350, IQE400, IQE450, respectively. Therefore, the two calculators can be used interchangeably for boron emitters for practical intents.

## C.3 Phosphorus Emittor Calculatlons

Table III below compares the sheet resistance, $J_{0 e}$ and IQE at the wavelengths $300,350,400,450 \mathrm{~nm}$, obtained by the two calculators. the column EMITTERPASSSRV shows the front SRV that was used in the simulations.

Table III. Sheet resistance, $\mathrm{J}_{0 \mathrm{e}}$ and IQE obtained by the two calculators



Figure 2. Graphical plots of the results in Table III. In each plot the grey line indicates perfect agreement.
Figure 2 above plots the results obtained by the two calculators. The agreement is generally very good except for IQE. Average fractional deviations between the two calculators are $0.3 \%, 2.8 \%, 6.0 \%, 4.5 \%$, $21 \%, 26 \%$ for the sheet resistance, $J_{0 e}$, IQE300, IQE350, IQE400, IQE450, respectively.

Therefore, the two calculators can be used interchangeably for phosphorus emitters sheet resistance and $J_{0 e}$ calculations for practical intents. For IQE calculations the agreement is also good enough to yield very similar $J_{s c}$ results.

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