

Can SCAPS simulate a solar cell under ‘bifacial illumination’?

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Questions:

1. Is there a possibility that we might synchronously illuminate both the sides at same time with this software?
2. Can we take IV data from bifacial illumination?
3. ... and more similar questions, all recent...

1. Short answer

No, SCAPS can “do” only illumination from one side. To simulate a solar cell under ‘bifacial illumination’, there are two options:

1. Simulate twice an IV curve, once with light from left, yielding $I_{\text{from left}}(V)$, and once with light from right, yielding $I_{\text{from right}}(V)$, and then just “add” the results, as will be detailed below. This is however an approximation, as also explained below.
2. Or: Simulate the illumination part yourself. This is: illuminate the cell with two-sided or whatever illumination conditions in an own (or another, optical) program, and calculate the eh -generation profile $G(x)$ in the cell. Then, input this $G(x)$ profile in SCAPS (see Manual), and do the electrical simulation with SCAPS.

2. First strategy: adding IV simulations, $I_{\text{from right}}(V)$, $I_{\text{from left}}(V)$... and $I_{\text{dark}}(V)$

As said, this strategy is an approximation, and it relies on the linearity of the solar cell. The assumptions for linearity are:

1. The total current $J(V)$ is a linear superposition of a contribution of the voltage and a contribution of the illumination
2. The dark current $J_{\text{dark}}(V)$ depends only on applied voltage V , but not on the illumination conditions
3. The light current $J_{\text{light}}(V)$ depends on illumination conditions, but not on the applied voltage V . Also, when the illumination intensity P (in suns, or in Wm^{-2} or whatever) is varied for a same spectral distribution of the illumination, the light current J_{light} is proportional to P . And finally, when there is illumination by multiple sources, the contributions of these sources to the light current can be simply added.
4. Thus, under applied voltage and under illumination, the J - V law of this ideal, linear solar cell is:

$$J(V) = J_{\text{dark}}(V) + J_{\text{light}}(P) \quad (1)$$

Non-linearity can occur when the dark current is dependent on illumination; or when the light current is dependent on voltage (the term ‘voltage dependent collection efficiency’ has been invoked often ...). And there is a variety of physical mechanisms that can cause more or less severe non-linearity...

In the present case of bifacial illumination, there are two set-ups for illumination, one ‘from right’, and one ‘from left’, we have, always under the assumption of linearity:

$$J_{\text{from right}}(V, P_{\text{right}}) = J_{\text{dark}}(V) + J_{\text{light, from right}}(P_{\text{right}}) \quad (2)$$

and

$$J_{\text{from left}}(V, P_{\text{left}}) = J_{\text{dark}}(V) + J_{\text{light, from left}}(P_{\text{left}}) \quad (3)$$

... and note that the same dark current $J_{\text{dark}}(V)$ is appearing in both Eqs. (2) and (3).

And when both illuminations, from left and from right, are simultaneously present, thus under ‘bifacial illumination’, we have, always for the linear cell:

$$\begin{aligned} J_{\text{bifacial}}(V, P_{\text{right}}, P_{\text{left}}) &= J_{\text{dark}}(V) + J_{\text{light, from left}}(P_{\text{left}}) + J_{\text{light, from right}}(P_{\text{right}}) \\ &= J_{\text{from right}}(V, P_{\text{right}}) + J_{\text{from left}}(V, P_{\text{left}}) - J_{\text{dark}}(V) \end{aligned} \quad (4)$$

We stress that Eq. (4) only holds for linear cells, as defined above.

You can do the addition and subtraction of Eq. (4) yourself, with an external program. For example, you can copy/paste the IV data of three simulations in an Excel sheet (once on dark, once with illumination from right, once with illumination from left), and then do the algebraic addition there, and finally all that is necessary: displaying the resulting IV curve $I_{\text{bifacial}}(V)$ in a nice graph, and derive the efficiency parameters η , J_{sc} , V_{oc} and FF yourself.

You can also let SCAPS do this job (thus do the addition/subtraction, display of resulting IV , and calculation of the efficiency parameters) in a SCAPS script. An example of such script will be given below.

3. Second strategy: add two generation profiles $G_{\text{from left}}(x)$ and $G_{\text{from right}}(x)$

This strategy is more correct, since it does not depend on the assumption of linearity (of the electrical solar cell properties). The first step is to obtain the generation $G_{\text{bifacial}}(x)$ (in particles/m³/s) and put this table in a valid SCAPS generation file. For a valid G - x file format, see the SCAPS User Manual, and the example `.gen` files delivered with SCAPS. You can obtain the bifacial generation $G_{\text{bifacial}}(x)$ in whatever way you like:

1. You can use any own, or external optical program that can calculate $G_{\text{bifacial}}(x)$ with possibly much more optical sophistication than what is implemented in the SCAPS internal optical model (see our User Manual). You then have to transform the output of your optical program into a valid SCAPS generation file (in particular, mind the units, these are μm for position x , and $\text{m}^{-3}\text{s}^{-1}$ for generation G). The best results would be obtained when your optical program would use the same x -mesh as SCAPS, if not SCAPS will interpolate, at the cost of accuracy. Also, each time you are changing something essentially for the optics, e.g. the thickness of a layer, you will have to redo all this. Fortunately, the cooperation between SCAPS and external programs can be facilitated by the SCAPS script (that is, alas, not so easy to use...).
2. Or, you can use the SCAPS internal optical model, that is rather coarse, see Manual. Then run one simulation under illumination from right (a simulation at the working point voltage $V = 0$ V is enough, no IV simulation is needed), and save the generation $G(x)$ from the Generation/Recombination panel. Then do so for illumination from left. Then add the two generations obtained as:

$$G_{\text{bifacial}}(x) = G_{\text{from right}}(x) + G_{\text{from left}}(x) \quad (5)$$

The validity of adding generation profiles is much more general than is the validity for adding electric currents, as only the optics need to be linear. That is generally the case, except for e.g.

- (optical) non-linear materials, not often to be expected in solar cells (unless some weird materials under very concentrated light??)
- Optical absorption dependent on carrier densities, such as free carrier absorption, absorption via defects (IPV effect),... not that common.

Again, doing two simulations (illumination from right and from left), saving the optical generation profiles $G(x)$, adding them, saving them as a valid SCAPS generation file, and then set the light source to ‘from generation’ and load this file... can be automated by the SCAPS script. Though, for first try-outs, you might well test this strategy out ‘manually’ in e.g. Excel.

4. A SCAPS script illustrating these two strategies

4.1 What you need

You will need:

- SCAPS \geq 3.3.09 of December 2020, because the script makes use of many script variables (not only using the six letters x, y, ... z of earlier versions, but 26 letters, from a to z).
- The script file `bifacial.script`.
- The definition files `simple pn bifacial.def` and `simple pn bifacial donor defects in p-layer.def`.
- Finally, the script will create a generation file `bifacial generation.gen` on your disk, in the [SCAPS]/generation directory.

4.2 Set-up of the two definition files for this illustration

We start from `simple pn.def` (this definition file is really advised as a starting point for about everything!). In this set-up, the p -layer is thicker, and more weakly doped than the n -layer, that is thinner and more heavily doped. It is thus clear that the ‘normal’ (thus, the best) side of incidence for the illumination is from the n -side, thus from right. Thus, we have set the side of light incidence to ‘from right’. In a bifacial illumination set-up, the cell is simultaneously illuminated from the left, thus from the p -side. The p -layer is not too thick (less than a diffusion length L_n), and the left (p -) contact is really well passivated ($S_n = 1$ cm/s), so this cell will almost equally well perform under both sides of illumination incidence. To see at least some difference between both sides, we made the p -contact ‘only a little bit passivated’, and have set $S_n = 10^4$ cm/s. Also, we modified the absorption model of both layers (clicked off the sqrt-model, clicked on the power law 1 (with $n_1 = 1$), and the sub-bandgap law. In this way the $\alpha(\lambda)$ curve is falling more gradually (less abruptly) to zero for wavelengths above the band gap wavelength. We kept the defect in the p -layer, but increased the defect density N_t with a factor 10, and decreased the capture cross sections σ_n and σ_p with a factor 10. This does not change anything when the defect is ‘neutral’, as it is in `simple pn.def`. The problem definition with the changes described above is saved as `simple pn bifacial.def`. When the defect type in the p -layer is changed from ‘neutral’ to ‘simple donor’, the file is saved as `simple pn bifacial donor defects in p-layer.def`.

4.3 The script `bifacial.script`

This script is abundantly commented, so study it, and run it. It contains multiple times the command `show scriptvariables`, sometimes active, sometimes out-commented (when the line starts with `'//'`). Make all of these active (thus removing the double slash), and if necessary add more of them. When the script variables panel appears, you can study at ease what has been done since the previous display of this panel, and above all, you have the opportunity to stop the script execution. When all is running to your expectations, you can remove all, or most of these `show scriptvariables` commands. This is a highly advised practice (see Manual)! Also, keep the Manual at hand for explanation on the SCAPS script commands. And it is better to get thoroughly acquainted with all aspects of SCAPS, before you dive into scripting... and this usually takes some time... With all these advices, we hope that you will be able to understand this script, up to a level that you can do your own additions/modifications/... and that we can now directly jump to the results of the script, that illustrates the above sections.

4.4 Illustrations

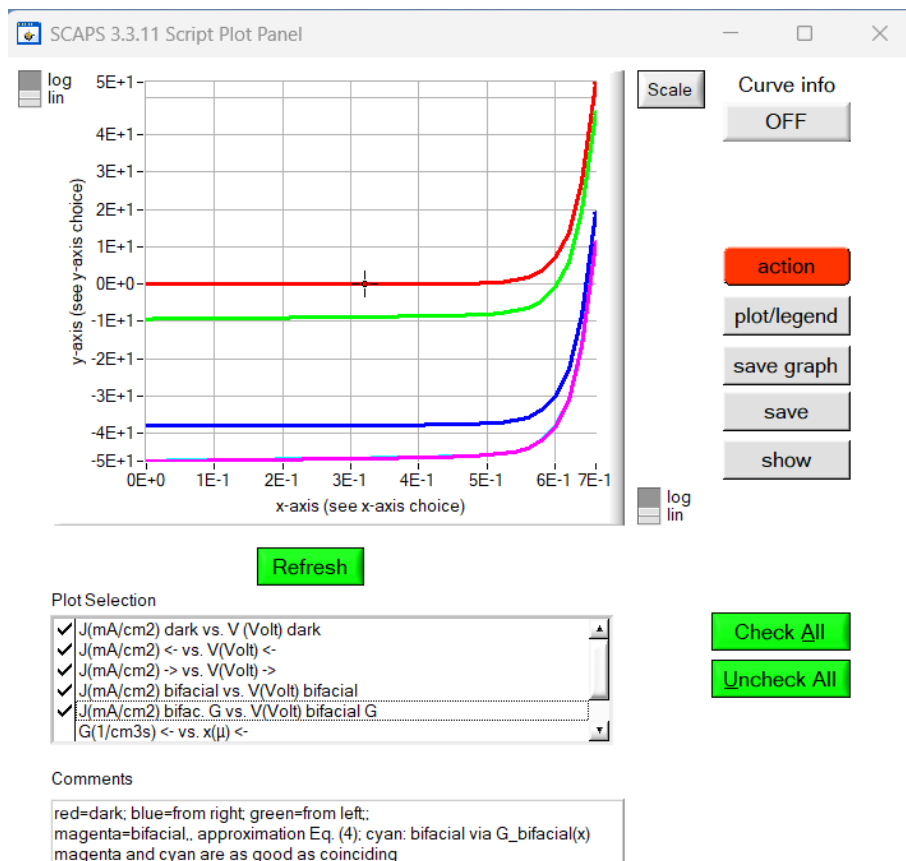


Fig. 1 Resulting *IV* curves of the script `bifacial.script`, for the problem `simple pn bifacial.def`. The color code is explained in the comments field. This is a cell where linear superposition as in Eq. (4) holds: the magenta and cyan curves coincide really well; and, the two one-sided *IV* curves (blue and green) are (by eye) true vertical translations of the dark *IV* curve (red).

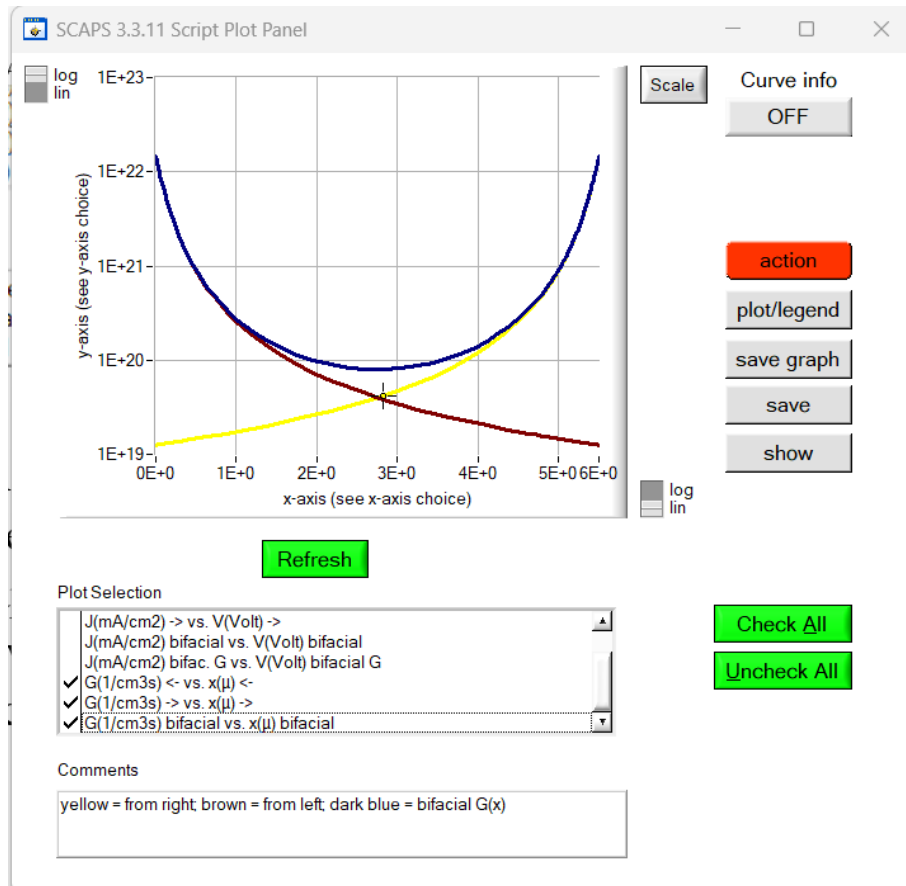


Fig. 2 Resulting generation profiles $G(x)$ by the script *bifacial.script*, for the problem *simple pn bifacial.def*. The color code is explained in the comments field. Note that the illumination intensity from left is the same as from right in this illustration. This is not realistic: illumination from the back side, here left, will usually be (much) lower than illumination from the front side (here right), and also usually have a different spectrum.

We can thus conclude that linear superposition, thus application of Eq. (4), holds for the problem *simple pn bifacial.def*, where the p -layer has neutral defects. Not much is needed to break this simple linearity: it is sufficient to give the defect in the p -layer a charge type (here single donor). This is illustrated in the figure below.

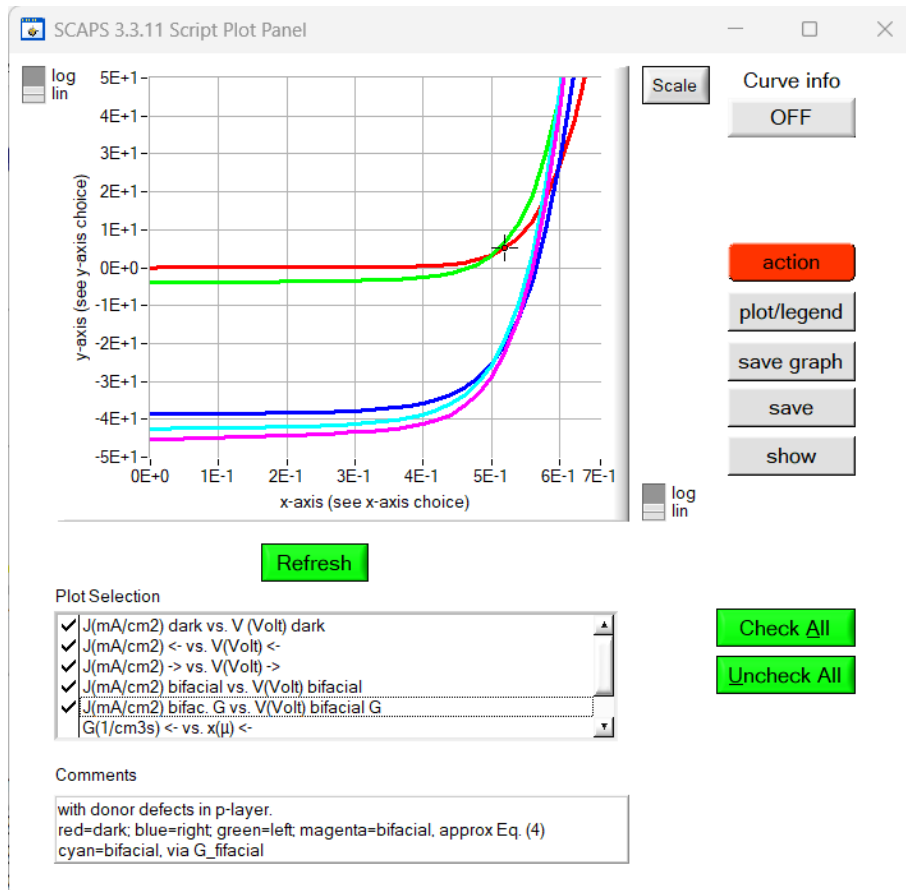


Fig. 3 Resulting IV curves of the script *bifacial.script*, for the problem *simple pn bifacial donor defects in p-layer.def*. The color code is explained in the comments field. This is a cell where linear superposition as in Eq. (4) does not hold: the magenta and cyan curves do not coincide; and, the two one-sided IV curves (blue and green) are (at sight) clearly not just vertical translations of the dark IV curve (red). As explained, the cyan curve (via $G_{\text{bifacial}}(x)$) is to be trusted more than the magenta one (application of approximation Eq. (4)).

4.5 Final remarks

- The simple approximation of Eq. (4) is often valid for simple cells. One then can easily get the bifacial IV curve by linear combination of the dark IV , and the one-sided IV 's with illumination once from right and then from left.
- However, slight complications in cell physics can break this linearity, and then the only way (in SCAPS, at present) is to calculate bifacial generation profile $G(x)$ with an external program, or, when one is satisfied with the coarse optical model of SCAPS, one can do it within SCAPS.
- All actions needed to study bifacial cells can be automated by a suitable SCAPS script, and some effort...
- Note that the summation equations (4) and (5) are only seemingly simple. When one has all IV curves in a tabulated form, as is the case in SCAPS and all other numerical programs, a summation element per element (as done in our script) can only be done if all $I-V$ tables have exactly the same set of V -values. This is the case in our script, but it is the responsibility of the user to keep an eye on this. When not all V -tables are identical, interpolation will be involved

in the implementation of Eq. (4)... And the same story about G - x tables and the application of Eq. (5)...

- The illumination conditions used here in the illustrations are much too idealistic: we assumed that identical light (both its spectrum and intensity) is incident both at the front (here right) side and on the rear (here left) side. This was mainly chosen for my ease, but it is not realistic.
- One should realize that there is some problem with the definition of the “efficiency” of a bifacial cell: should one relate the cell’s electrical output power just to the incoming light power at the front side? Or the summed optical power incident on front and rear side? I have no point of view in this matter. Perhaps that whole bifacial mania is about total output power, not so much about efficiency.

Marc Burgelman, Gent, 29-12-2023