FREE ENERGY LOSS ANALYSIS DECOMPOSITION OF THE POWER VOLTAGE CHARACTERISTIC OF AN INTERDIGITATED BACK CONTACT SOLAR CELL

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ABSTRACT: The current voltage (JV) curve decomposition is a very powerful tool for interpreting simulation results but also measurements. However, drawing conclusions from it about power losses by simply multiplying by the solar cell voltage V is firstly incomplete because it overlooks power losses during transport and secondly incorrect because all free carriers in the solar cell do not carry an energy equal to q·V. Transport losses are therefore classically introduced separately through the series resistance that incorrectly assumes a monopolar transport in the solar cell. The two issues are addressed in the recently developed Free Energy Loss Analysis (FELA) leading to the rigorous power voltage (PV) curve decomposition. However, interpretation rules as well as links to the classical approach are still missing to make FELA a useful tool for solar cell development. It is the goal of this paper to make the first steps in this direction by attempting to explain the FELA losses dependence to voltage and comparing them to classically described power losses. Good correlation is shown between recombination current and power loss except at high voltage, and a link is established between FELA majority carrier Joule losses and series resistance losses. The FELA minority carrier Joule losses that are a consequence of collection but also of recombination remain undescribed classically and deserve further investigation.
Keywords: Free Energy loss Analysis, Series resistance, Joule losses, Modeling

1 INTRODUCTION

With the advance of solar cell technology getting closer to the theoretical efficiency limits, loss analysis has a more prominent role than ever. Power or efficiency losses in solar cells can be split into the following two main components.

The optical losses that are the input power not used for electron hole pair generation because the photons are simply not absorbed in the cell (reflection or transmission) or not absorbed for creating electron hole pairs (free carrier absorption). Thermalization losses, the power loss of carriers releasing their excess energy with respect to the bandgap, should not belong to optical losses within the aforementioned definition. However, the semiconductor being given and so its bandgap, this loss can only be affected by modifying the illumination spectrum and thus with purely optical consideration. For this reason we include it in the optical losses leading to the ultimate efficiency which amounts to 40-50% in silicon.

Then come the electrical losses that are the electron (e-) and hole (h+) power not extractible to the external circuit because carriers collide with silicon atoms during thermal motion (entropy losses) or diffusion/drift motion (Joule losses) or simply because the generated carriers recombine (recombination losses).

Recently the free energy loss analysis [1] or FELA emerged to quantify the aforementioned electrical efficiency losses in a rigorous way, however, only from simulation.

Among tools available to interpret simulation results (but also some measurement results), the current (or recombination) loss analysis [2] or the current voltage (JV curve) decomposition is one of the most useful.

For the first time FELA allows the full and rigorous decomposition of the power voltage characteristic (PV curve). Considering that a solar cell is basically an energy conversion device and that its performance is ascertained only in terms of maximum energy conversion ratio (η), FELA is the only rigorous tool that goes to the heart of the problem.

In this respect, understanding the PV curve decomposition as an interpretation tool for simulation, but also for measurement, should reveal itself even more relevant than understanding the JV curve decomposition for solar cell development purpose.

Until now, FELA has been used only to quantify power losses at maximum power point in order to ascertain potential power gain obtained by tuning specific technological parameters.

It is therefore the goal of this paper to make the first steps in describing and understanding the voltage dependence of the power losses described by the FELA but also to attempt to link them to the power losses as they are classically described. We therefore study an interdigitated back contact solar as an example.

2 THEORY AND PHENOMENA DESCRIPTION

Considering that every free carrier carries originally an energy equal to the bandgap (E_g) one can define the total flow of electrical energy available as:

$$\Phi_{Ultimate} = \frac{1}{A}\int_V G \cdot E_g \cdot dV \qquad (1)$$

Where G is the generation, V the solar cell volume and A the solar cell area. Normalizing this energy flow to the optical power impinging the solar cell gives the so called ultimate efficiency.

However, a significant part of this energy will be lost by carrier collision with atoms during random thermal motion. In the thermodynamic formalism this loss is related to entropy and thus decreases by increasing the density of carriers (reducing the numbers of degree of freedom thus increasing order) and by reducing the temperature (reducing thermal energy). While the temperature is given, the density of carriers can be increased by increasing illumination. This is the FELA explanation for the higher efficiency of concentrator cells.

The average part of carrier energy remaining after this process (the free energy) is defined as $\Delta E_f = E_{fn} - E_{fp}$

[1] with E_{fn} and E_{fp} the Quasi Fermi Levels (QFL) of electrons and holes, respectively. Analogously to EQ. 1, the total flow of generated carrier free energy can then be expressed as:

$$\Phi_G = \frac{1}{A}\int_V G \cdot \Delta E_f \cdot dV \qquad (2)$$

The QFL being dependent on carrier density, the total free energy flow will depend on illumination and bias voltage.

Annihilation of an electron hole pair by recombination results in dissipation of its free energy. Analogously to EQ. 2, one can then define the flow of free energy lost by recombination R as:

$$\Phi_R = \frac{1}{A}\int_V \mathrm{R} \cdot \Delta E_f \cdot dV \qquad (3)$$

While recombination occurs in the solar cell volume, it also occurs at surfaces leading to:

$$\Phi_{R,surf} = \frac{1}{A}\int_S \mathrm{R}_{\mathrm{surf}} \cdot \Delta E_f \cdot dS \qquad (4)$$

with S the surrounding surface of the solar cell and R_{surf} the surface recombination rate corresponding to the minority carrier flow toward the surface.

During carrier flow (J_e/q, J_h/q) some carriers will collide with atoms and loose part of their energy in heat. This type of power loss is the classically defined Joule loss in electricity. This classical definition assumes that the carrier movement is only induced by an electric field (gradient of the electrostatic potential) through the drift process. In semiconductors, however, this movement can also be induced by a gradient of carrier concentration (gradient of the chemical potential) through the diffusion process. Both processes could be considered at once by considering the movement to be induced by the gradient of the electrochemical potential (or QFL). This leads to the following expression for the Joule loss for electrons and holes.

$$\Phi_{e,h} = \frac{1}{A}\int_V \frac{\vec{J}_{e,h}}{q} \cdot \nabla E_{fn,p} \cdot dV \qquad (5)$$

This expression is consistent in the framework of bipolar transport in semiconductor [3], but the classical Joule loss is also consistent in the framework of monopolar transport by drift, leading straightforwardly to the concept of series resistance that can be measured. Bridging the gap between both representations is challenging because of different formalisms. This is, however, necessary because though FELA is the only rigorous theory in this context, the series resistance is the only measured parameter and its rigorous interpretation can only be performed within the classical formalism. In establishing this link, we observe that the interpretation is facilitated by considering majority and minority carriers instead of electron/hole discrimination as it will be detailed further in this article.

The total output energy flow is finally obtained by subtracting Joule losses (described by the FELA in the semiconductor and by the classical theory in external metallization) and recombination losses (FELA) to total flow of generated carrier free energy (FELA).

3 GLOBAL CONSIDERATIONS

An interdigitated back contact solar cell was simulated using SENTAURUS TCAD and the FELA quantities where computed for every voltage point leading to the PV curve decomposition shown in Fig. 1.

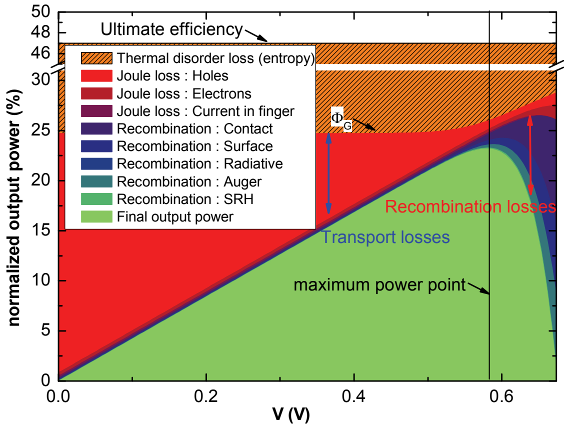

Figure 1: FELA decomposition of IBC solar cell PV curve showing the share of all electrical losses from the ultimate efficiency.

From this decomposition it appears very clearly that transport losses (or Joule losses) are dominant at low voltage while recombination losses dominate at high voltage. Therefore, from the FELA point of view the maximum power can be defined as the voltage where the best compromise is reached between recombination and Joule losses.

At low voltage, the dominant Joule loss contribution originates from minority carriers in the base close to the space charge region as shown in Fig. 2.

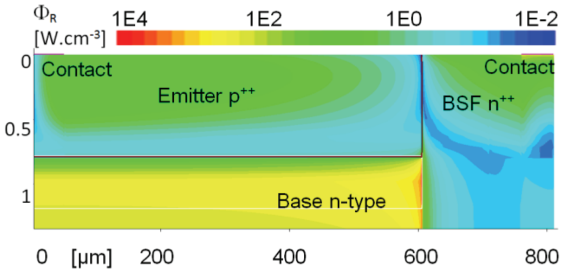

Figure 2: Electron and hole Joule loss power density in the interdigitated part of an IBC solar cell (magnified) at short circuit condition.

Indeed, the collection of minority carriers generated in the bulk reaches a maximum at low voltage, thus inducing a very large gradient of minority carrier density. Moving by diffusion to counteract this large gradient, the minority carriers loose a large quantity of energy by Joule effect as expressed by this FELA result.

The highest power loss density is reached in the base at the edge between emitter and BSF because of a current crowding of both carrier types. Indeed, a fraction of majority carriers (electrons) present under the emitter crowds there in their way to the BSF, while a fraction of minority carriers (holes) present under the BSF crowds there in their way to the emitter.

At high voltage, the dominant loss is recombination at contact, surface and in highly doped areas (Auger) as shown in Fig. 3. Qualitatively, the similarity of this recombination power loss to the recombination current loss lets us think that this loss is almost only dependent on the amount of carriers lost by recombination and not much on the energy of the recombining carriers.

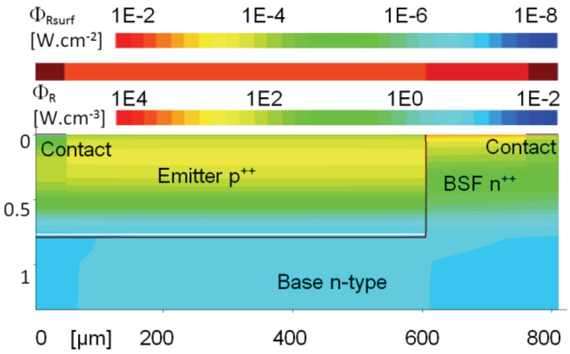

Figure 3: Total recombination power loss density at the surface (top) and in the volume (bottom) of the interdigitated part of an IBC solar cell (magnified) at open circuit condition.

When the junction begins to inject majority carriers to both sides, the recombination rate gets largely increased in the zones where recombination probability is the highest: low lifetime regions in the volume and high surface recombination velocities surfaces at the surface. The loss of electron hole pairs implies the dissipation of their energy that is expressed by this FELA loss.

At maximum power point both aforementioned losses reduce to the best compromise level as shown in Fig. 4.

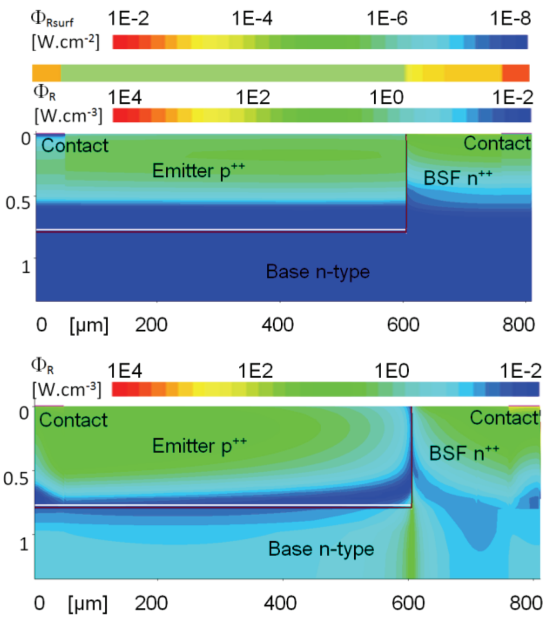

Figure 4: Total recombination power loss density at the surface (top), in the volume (middle) and total Joule loss (bottom) of the interdigitated part of an IBC solar cell (magnified) at maximum power point.

Zones of highest recombination probability reduce activity and collection of almost the same current as in short circuit condition is ensured with a minimal carrier gradient at the junction. One can still observe in the Joule loss map the presence of carrier crowding between emitter and BSF with, however, reduced intensity in comparison to short circuit conditions (Fig. 2).

Interesting is also the almost equal Joule loss power density in the highly doped regions at short circuit conditions (Fig. 2) and at maximum power point (Fig. 4 bottom). This density originates almost entirely from majority carrier Joule losses in both BSF and emitter.

Considering that the solar cell current is almost the same at maximum power point and J_{sc} conditions, the classically described Joule losses (series resistance) would be almost the same for both conditions. This is a first hint for the identification of majority carrier Joule losses to the classically described Joule losses as it will be developed in more detail later in this paper.

4 LINKING FELA LOSSES TO CLASSICALLY DESCRIBED POWER LOSSES

4.1 Rate of generated free energy

As the JV curve can be decomposed classically by a constant generated current (J_{gen}) from which recombination current (J_{rec}) is substracted, just multiplying this JV curve decomposition by the voltage allows converting it classically into a PV curve decomposition. Applied to the generation it gives:

$$\Phi_{G,classical} = V \cdot J_{gen} = V \cdot \mathrm{q} \cdot \frac{1}{A} \int_V G \cdot dV \qquad (6)$$

The comparison between the classically generated power (EQ. 6) with the rate of generated of free energy delivered by the FELA (EQ. 2) is represented in Fig. 5.

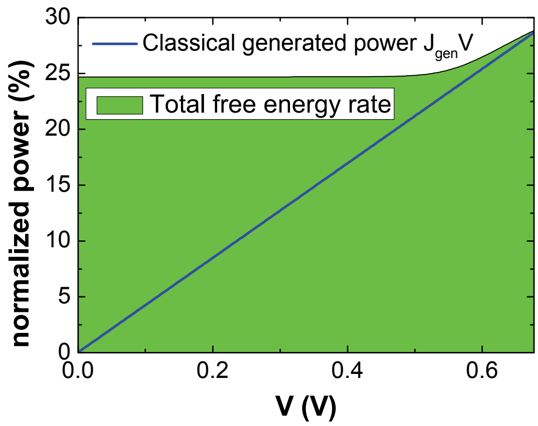

Figure 5: Total rate of free energy generated computed by FELA versus total power generation computed classically.

Comparing EQ. 6 and EQ. 2 one can remark that they are equivalent if ΔE_f would be uniform over the cell and equal to q.V.

The main contribution to Φ_G stems from the bulk because it is the region where most of the solar cell generation occurs. However, in short circuit condition ΔE_f in the bulk, far away from the junction, is imposed only by minority carrier density (in low injection) and thus only by generation (for a given bulk lifetime). The generation being given for the whole PV curve, this value remains constant regardless of the voltage until the junction potential becomes comparable to ΔE_f induced by illumination.

The voltage applied to the cell equals ΔE_f at the junction up to the voltage drop due to series resistance. When ΔE_f at the junction becomes larger than the one induced by illumination in the bulk, the junction tends to impose its ΔE_f to the overall solar cell leading to Φ_G increasing proportionally to V.

However, we observe in Fig. 5 that the increase is smaller probably because the main generation area is on the opposite side of the solar cell and thus influenced only very progressively by the junction ΔE_f.

Finally, we observe that at V_{oc} both theories agree well. Indeed at V_{oc} conditions, the influence of the junction on ΔE_f in the bulk is the largest and there is no significant voltage drop by series resistance. This leads to a homogeneous ΔE_f distribution over the whole solar cell which equals qV, which is the prerequisite for both theories to be equivalent as mentioned before.

4.2 Recombination power losses

Applying the procedure described in the preceding paragraph to the description of recombination one obtains the graph of Fig. 6.

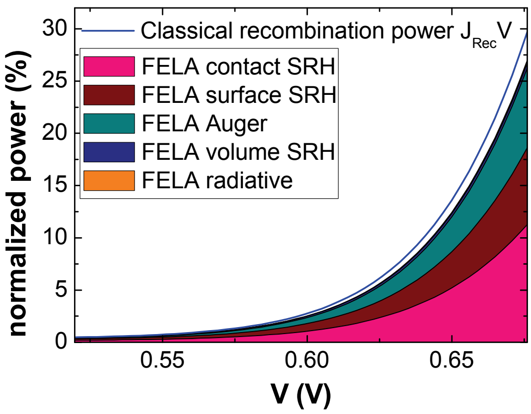

Figure 6: Recombination power loss computed by FELA versus total power recombination loss computed classically.

While the same consideration about the distribution of ΔE_f as in the preceding paragraph could be drawn, here emphasis is given on the fact that the highest active recombination area corresponds also to one of the smallest ΔE_f. This is because a highly recombinative area results in lower minority carrier density which is thus closer to equilibrium value. As ΔE_f can be understood as a measure for the degree of non-equilibrium, the higher the recombination the smaller is ΔE_f. Therefore, the recombination power loss described by FELA increases not as fast as the one described classically.

4.3 Majority carrier Joule losses

In the classical model, the only Joule loss described is the one induced by the series resistance (R_s). This loss can be expressed classically as

$$\Phi_{Joule,Rs} = R_s \cdot J^2 \qquad (7)$$

Having observed previously that the majority carrier Joule loss in the emitter behaves in agreement with the one described classically, we look here for a better correlation by directly comparing a curve proportional to J^2 to the majority carrier Joule loss in the emitter and in the base (the one in the BSF is negligible).

This comparison displayed in Fig. 7 shows a very good correlation tending to support the hypothesis that majority carrier Joule losses computed by FELA could be identified to series resistance power losses as computed classically.

Nevertheless, the classical ways to determine the series resistance (experimentally, from analytical formula and from numerical simulation) use different assumptions which seem difficult to reconcile and to validate. While our previous investigation on this topic [4] concluded that the difference in the estimation of the series resistance between these different methods was small enough to be able to neglect its influence on the final JV curve at maximum power point, a general theory including series resistance in the FELA description is not yet available.

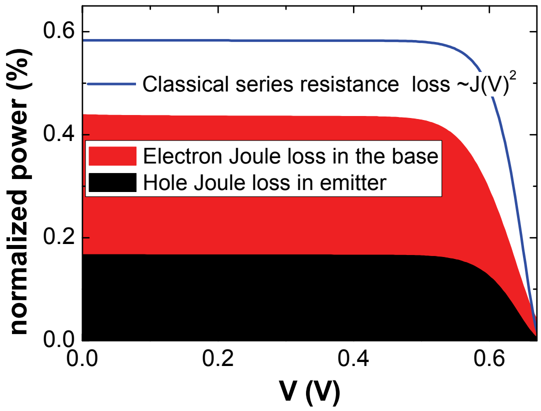

Figure 7: Majority carrier Joule losses in the emitter and base computed by FELA versus the solar cell output current squared (arbitrary scale).

One can finally remark in Fig. 7 that the base contribution does not vanish at V_{oc} conditions. This is probably a consequence of internal current circulation. This loss can, however, not be quantified by the external description of a solar cell (implied by e. g. the two-diode model) where the final output current is 0 and thus the externally seen Joule loss.

4.4 Minority carrier Joule losses

We show in Fig. 8 the most important sources of minority carrier Joule losses in solar cells, which are the base at low voltage and the BSF/emitter at high voltage.

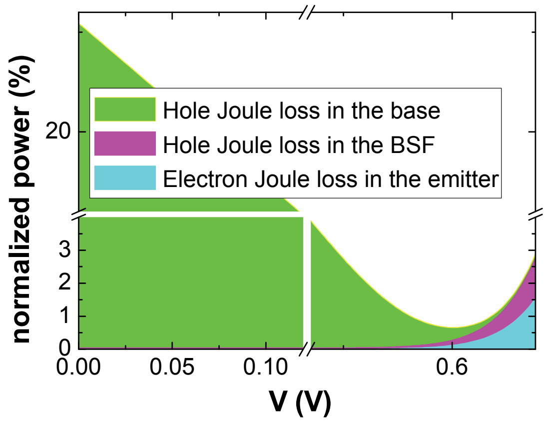

Figure 8: Minority carrier Joule losses in the emitter, BSF and base computed by FELA.

Concerning the minority carriers, their energy can be lost during their transport by diffusion. The minority carrier gradient triggering this diffusion process is induced by the junction at low voltage to ensure minority carrier collection. However, inhomogeneous recombination activity can also induce an inhomogeneity in minority carrier density leading to gradients of carrier density. In such case diffusion transport also occurs and thus minority carrier Joule losses. This effect becomes most significant at high voltage at the contacts explaining the increase of minority carrier Joule losses of the BSF and emitter in this voltage range as shown in Fig. 8.

One can finally remark that the BSF and emitter contribution looks similar, at least qualitatively, to the recombination losses shown in Fig. 6.

The minority carrier Joule losses computed through FELA is peculiar in two ways: 1/ It is the only FELA loss that increases at high and low voltage (though for different reasons) and has a minimum around the maximum power point 2/ It is the only FELA loss that has no presumed counterpart in the classical theory.

5 CONCLUSION AND OUTLOOK

For the first time the full PV curve FELA decomposition has been computed for a solar cell and first steps of interpretation and links to the classical theory have been attempted. FELA allows showing in a much clearer manner that the maximum power point results from the best compromise between recombination and transport losses.

FELA recombination losses are very close to the classically described recombination power losses except at high voltage where recombination reduces ΔE_f.

Concerning transport losses, a very large discrepancy between the approach and the formalism used in the FELA and classically prevents from setting a rigorous equivalence between them. Nevertheless, it was established that in attempting to establish links between them, the FELA Joule losses are more straightforwardly interpretable when expressed in terms of minority and majority carrier Joule losses rather than electron and hole Joule losses.

An almost quantitative link was then demonstrated between majority carrier Joule losses and classically described series resistance Joule losses.

It was shown that minority carrier Joule losses can be induced by diffusion to the collection area at low voltage but also to highly recombinative areas at high voltage making them the only loss of the FELA presenting a minimum around the maximum power point. They seem not to be linked to losses described classically but are linked to collection and recombination: two fundamental processes in solar cells.

Further steps are still required to make this PV curve decomposition a powerful tool to interpret simulation results like the JV curves decomposition. The challenges are first of all of theoretical nature in order to bridge rigorously gaps between the classical representation of power losses and FELA.

Beside the various qualitative links established between both theories, this first attempt showed some peculiarities of minority carrier Joule losses and the absence of its counterpart in the classical theory. These losses therefore deserve further investigation from the theory point of view but also from their possible evaluation by measurement.

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