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► **To cite this version:**

V Giglia, Jordi Veirman, Renaud Varache, B Portaluppi, S Harrison, et al.. Influence of Edge Recombinations on the Performance of Half-, Shingled- and Full Silicon Heterojunction Solar Cells. 37th European Photovoltaic Solar Energy Conference and Exhibition, Sep 2020, online, France. pp.282-285. hal-02983770

HAL Id: hal-02983770

<https://hal.science/hal-02983770v1>

Submitted on 30 Oct 2020

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INFLUENCE OF EDGE RECOMBINATIONS ON THE PERFORMANCE OF HALF-, SHINGLED- AND FULL SILICON HETEROJUNCTION SOLAR CELLS

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ABSTRACT: Full size silicon heterojunction solar cells (SHJ) made on the pilot line at CEA-INES reach efficiencies (η) up to 24.5%. However, photoluminescence pictures of such cells reveal that the cell edges are the site of a significant recombination activity. Therefore, mitigating recombination at the edges can in principle represent an interesting path to unlock higher η . This challenge is all the more important for cells with a high perimeter/area ratio and/or cut edges, such as half-cells and shingled cells obtained by cutting from full size cells. For such technologies, 1) the edges resulting from cutting are cleaved while 2) the remaining edges typically feature a gap where TCO is missing due to TCO masking. To our knowledge, cell edge effects for different SHJ cell configurations (full, half or shingled) have been little addressed, are poorly understood, and guidelines for efficient edge treatment are therefore still missing. The results of our investigations reveal that the native passivation quality of the cell edges is significant, which leads to a remarkably low 0.15% loss in efficiency. On the contrary, our work on the half- and shingled-cells revealed that the repassivation of the cut edges could be an efficient lever for increasing such cells efficiencies.

Keywords: Heterojunction, Edge effects, Recombinations, Simulation

1 INTRODUCTION

One of the prerequisites for the manufacturing of SHJ cells is to ensure an efficient passivation of the monocrystalline silicon (*c*-Si) wafer surfaces. The depositions of hydrogenated amorphous silicon (*a*-Si:H) layers on both the front and the back side of the *c*-Si wafer provides very high passivation quality leading to open circuit voltages (V_{oc}) greater than 735mV. The passivation quality, which can be assessed by photoluminescence, can be significantly impacted at the cell edges (plummeting signal), because of non-desired carriers recombinations occurring at the cell edges [1]. These recombinations are often assumed to be due to the low passivation level of the edges. While the effects of the edge recombinations on silicon homojunction solar cells performances have been addressed [2], the quantification of edge-induced performance losses for SHJ cells is only partial.

According to the international technology roadmap for photovoltaic predictions [3], the SHJ market share is expected to strongly increase within the next ten years. Furthermore, because the reduction of the dimensions of the cells embedded in modules allows to reduce the resistive losses, half-cells and shingled-cells market shares are expected to outstrip that of full size SHJ cells. However, for such cells, the ratio perimeter/surface is increased and so is the criticality of edge effects-induced performance losses.

In this context, an original simulation code for Silvaco (ATLAS), taking into account the effects of recombinations at the cell edges, was developed. The simulations were used in order to propose a quantification of edge-induced performance losses for as-produced CEA SHJ cells, as well as half- and shingled cells.

2 EXPERIMENTAL AND SIMULATION DETAILS

2.1 Experimental details:

All SHJ cells in this work are rear junction[4], busbarless cells. Busbarless metallization scheme was chosen in order to ease the establishment of the modeling structure thanks to the high symmetry level of such cell configuration. The SHJ busbarless cells were fabricated on the CEA-INES pilot production line, based on *n*-type Cz monocrystalline substrates (M2 format, PSQ 156.75 × 156.75 mm², Longi). The $I(V)$ measurements were carried out an in-line solar simulator by Pasan SA, with perpendicular wires grids.

2.2 Simulation details

Simulations were run using the ATLAS package from Silvaco. The simulated structure (see Fig.1) is based on that presented in [5] including (*i/n*) *a*-Si:H stack on the front side of the (*n*) *c*-Si wafer and (*i/p*) *a*-Si:H stack on its rear side. The (*n*) *c*-Si substrate and its *a*-Si:H layers are sandwiched between ITO layers. Finally, a metallization grid is implemented with the same density as that of actual cells. The parametrization of each layer is based on characterizations carried out on M2 cells from the CEA-INES pilot line baseline at the time of this study.

Because of practical limitations regarding the mesh size, only small structures can in principle be simulated precisely. As a consequence, an entire cell can not be simulated from only one simulation structure. In order to overcome this limitation, the cells were divided into 3 specific unit cells (Fig.1). For instance, a half-cell can be decomposed into (Fig.1):

- A core unit cell (without any edge effect)
- A native edge cell, representing the edge of the cells as they are produced. In this case, the ITO is masked on the rear side and the edge recombination are taken into account with the implementation of an interfacial defect density D_{it1} at the edge.
- A cut edge unit cell. In this structure, the rear side of the cell is fully covered by the ITO. For this unit cell, edge recombinations are taken into account with the implementation of D_{it2} .

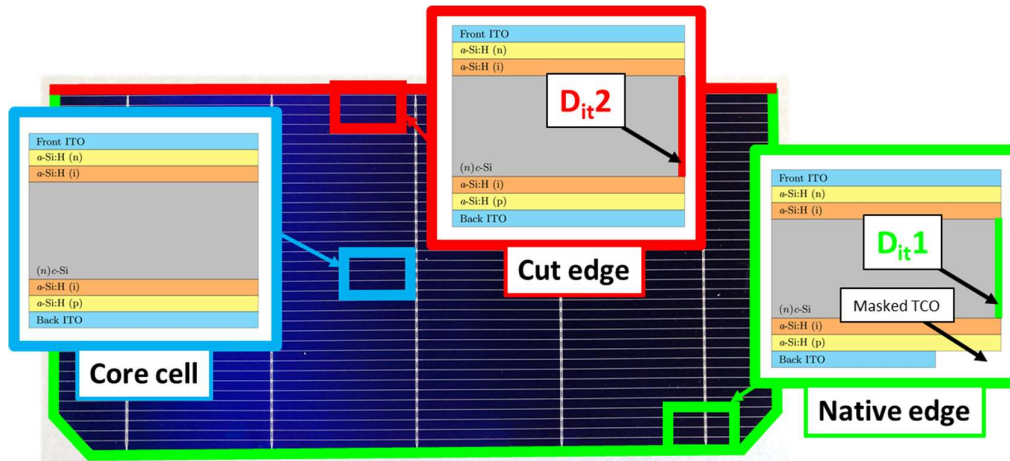


Figure 1: Representation of the splitting of a half-cell into a core unit cell, a native edge unit cell and a cut unit cell.

Then an area-weighted association of these cells was performed in order to reconstruct an entire cell. To this aim, the unit cells were associated in parallel and for each bias voltage, the area-weighted sum of their currents was extracted allowing to reconstruct the full cell $I(V)$ curve.

With this simulation protocol, the simulation of entire cells including edge losses is made possible whatever the cell format and geometry. A pre-requisite however, is the knowledge of D_{it1} , the D_{it} associated with the recombination at native cell edges. It is the purpose of the next section to determine its value for CEA cells.

3 QUANTIFICATION OF THE PASSIVATION QUALITY FOR AS-PRODUCED CELL EDGES

In order to quantify the passivation level of as-produced cell edges, $I(V)$ measurements were performed on ten SHJ cells from the CEA-INES pilot line. Subsequently, the cell edges were softly abraded with a wet sanding paper so that any existing layer on the edges was removed. This raised the c -Si D_{it} on the cell edges to 10^{14} cm^{-2} (as many as the surface density of silicon atom). Then $I(V)$ measurements were performed on these cells with abraded edges. In order to ensure complete removal of any pre-existing layer, the abrasion protocol was repeated until $I(V)$ losses were stabilized. As shown in Fig.2 a slight 0.13%abs. η reduction was observed after abrasion, which was fairly constant among all cells. Along with these measurements, simulations were run by associating a core cell with four native edges in order to simulate a full size cell including the native edges. The edge D_{it} was set as a variable ranging from 0 cm^{-2} (perfectly passivated edge) and 10^{14} cm^{-2} (bare silicon edge). The variation of the simulated cell η as a function of the edge D_{it} is plotted in Fig.3. predicted efficiency variation resulting from this D_{it} sweep is relatively narrow, around 0.3% abs. only.

Building on our experimental result, it can be seen that if one places the observed 0.13%abs reduction in η after abrasion on that figure, the as-produced cell edge passivation quality can be numerically well reproduced by implementing $D_{it1} = 3 \times 10^{10} \text{ cm}^{-2}$ on the native cell edges. Unexpectedly, the passivation quality on as-produced edges is far better than the bare silicon case. Fig.2 further tells us that this native edge passivation prevents from an additional 0.13%abs η loss. Furthermore it can be noticed

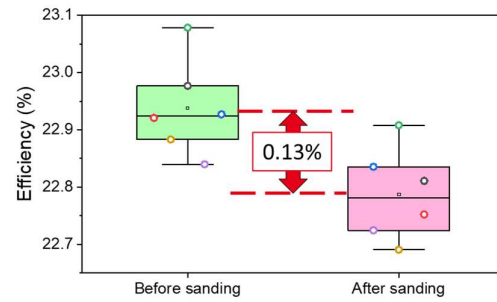


Figure 2: M2 full size cell efficiency before and after the four edges were depassivated. Each colored circle corresponds to a specific cell.

that a perfect edge passivation would allow only a 0.15%abs. η rise from the native edge case. In other words, the native edge-induced η losses are estimated to 0.15%abs. This is much lower than worst case estimations for PERC and TopCon cells in [6], which would by extrapolation to SHJ cells give edge induced losses (no edge passivation) approaching 1% abs. for full size M2 cells. This result suggest that the achievable gain by engineering the edge on full cells is low on CEA technology and may not be worth it.

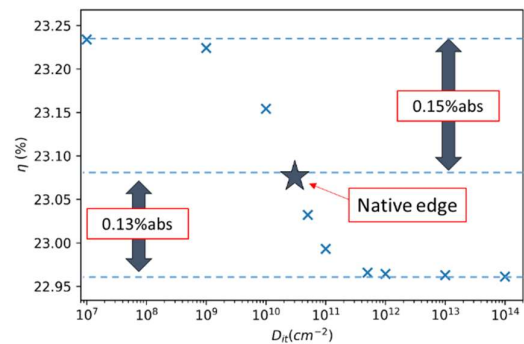


Figure 3: Full size cell efficiency as a function of the implemented D_{it1} .

With a view to confirm the validation of our cell edge passivation quality quantification, we have generated a simulated photoluminescence (PL) profile extracted from the integrated radiative recombination rate calculated by Silvaco. This profile was compared to a PL profile extracted from a PL picture shot on an as-produced cell (Fig.4.). The very good agreement between the simulated and measured PL profiles supports the fact that the implementation of native edge $D_{it} = 3 \times 10^{10} \text{cm}^{-2}$ well describes the edge effects.

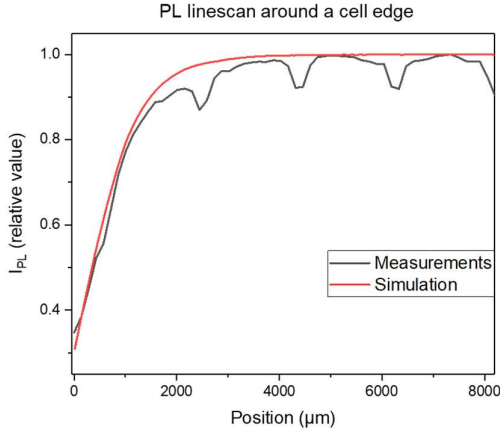


Figure 4: Comparison of an experimental and simulated photoluminescence profile at a native cell edge. The simulated profile was calculated with $D_{it} = 3 \times 10^{10} \text{cm}^{-2}$

Transmission electron microscopy (TEM) analysis were also performed on cell precursors to investigate the origin of the passivation on the edges. The analysis of the TEM pictures reveals that uniform and conformal $a\text{-Si:H}$ layers are present on the edges. Even if the edge $a\text{-Si:H}$ layers are approximately 50% thinner than that on the cell front & back surfaces, their presence clearly promotes the existence of a significant edge passivation quality as measured on our as-produced cells.

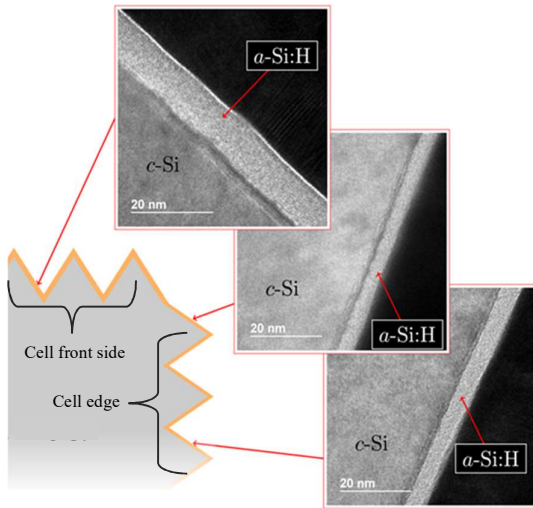


Figure 5: Transmission electron microscopy observation on the cell front surface and the cell edge : a residual, thin $a\text{-Si:H}$ layer can be observed on the edge

4 INFLUENCE OF CELL CUTTING ON SUB CELLS η

As D_{it1} , the D_{it} to implement in order to simulate the cells native edges, is now known, the influence of the cutting of entire cells into half-cells and shingled-cells can be addressed. As exposed in Fig.1, a cut edge can be associated to the core and the native edge unit cells. In order to simulate the influence of the cutting induced losses, the cut edge D_{it} was set to that of bare silicon known to be around 10^{14}cm^{-2} . Through a direct application of the protocol presented in section 2.2, Fig.2, the efficiencies of half-cells and shingle cells were simulated and then compared to that of the M2 full size from which they were obtained (see Table.1). It appears that the cutting-induced efficiency losses are very important and highlight the criticality of this topic.

D_{it2}	η (%)		
	Full size cell	Half-cell	Shingled-cell
10^{14}cm^{-2}	23.07	22.87	22.21
$3 \times 10^{10} \text{cm}^{-2}$		22.99	22.62

Table 1: Comparison of a simulated full size cell efficiency and the efficiencies of the half- and shingled-cells obtained from this cell before ($D_{it2} = 10^{14} \text{cm}^{-2}$) and after ($D_{it2} = 3 \times 10^{10} \text{cm}^{-2}$) the cut edge passivation was set to the same level as that of native edges.

In the case of the shingled-cell, the cutting induces a 0.9%abs additional edge induced η loss. Other simulations were performed with a cut edge passivation at the same level as that of native edges in order to address an achievable passivation quality. To this aim D_{it2} was set at the same value as D_{it1} (see Table.1). This allowed to divide by a factor of 2, the sub-cells edge-induced losses. This means that, the cut edge repassivation for half- and shingled-cells would allow to importantly reduce the cells cutting-induced losses. Thus, unlike entire cells, the cut-edge repassivation beneficial effects would be a very efficient lever to use in order to increase the cut cells efficiencies.

5 CONCLUSION

In this paper an original simulation code on the basis of that presented in [5], the additional implementation of edge interfacial defect density equal to $3 \times 10^{10} \text{cm}^{-2}$ was shown to faithfully describe the cell edges behaviour. Among the studies carried out for the determination of the D_{it} value to implement in order to describe the edge effects, two results must be highlighted. Firstly, the abrasion of as-produced cells edges induced a 0.13%abs. η drop. This illustrates that the edge native state prevents from 0.13%abs. η edge-induced losses. The second unanticipated result was the 0.15% η drop between the case of a perfectly passivated cell edge and a native edge. This demonstrates that the non-directional PECVD deposition of $a\text{-Si:H}$ layers brings an indirect benefit to the cell efficiency by significantly repassivating the cell edges. Consequently, the native edge repassivation is not an efficient lever to use in order to increase SHJ cells efficiencies. On the contrary, the bare silicon cut edges of half- and shingled-cells offers a large potential passivation

improvement. In order to provide guidelines for repassivation processes requirements, our current studies are focused on a correlation between the implemented edge D_{it} and the corresponding carriers effective lifetimes. In a coming paper, the simulation code will be used for the description of the cutting-induced losses in cut-cells performances losses. The physics involved in these losses will be discussed on the basis on simulation results.

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