Studying edge losses in silicon heterojunction solar cells

Pradeep Balaji
Solar Power Laboratory,
Arizona State University,
Tempe, AZ, 85284 - USA
pradeep.balaji@asu.edu

Stuart Bowden
Solar Power Laboratory,
Arizona State University,
Tempe, AZ, 85284 - USA
sgbowden@asu.edu

André Augusto
Solar Power Laboratory,
Arizona State University,
Tempe, AZ, 85284 - USA
augusto@asu.edu

***Abstract*— In this manuscript we study the impact of edge losses in silicon heterojunction solar cells. The edge of the cells may play a larger role due to the large diffusion length of the carriers and the presence of a high conductive layer in this type of architecture. We fabricate silicon heterojunction solar cells with different areas and masking schemes to evaluate the impact of the edge on the open-circuit voltage. We measured lower open-circuit voltages on cells which have larger ratio of cell perimeter-to-area but have similar lifetimes and similar implied characteristics. The solar cell with 6 cm^2 shows open-circuit voltage 7 mV lower than the cell with 150.3 cm^2. Electroluminescence and photoluminescence imaging are used to evaluate the diffusion of carriers at the edges of the cells. We show the out diffusion of carriers at the edges of the cell which demonstrates the cell is affected by the surroundings.**

Keywords—silicon, edge recombination, open-circuit voltage loss

I. Introduction

Edge recombination impacts the performance of solar cells significantly and has been studied in various works [1,2]. Edge recombination is particularly large for silicon heterojunction (SHJ) solar cells due to the large diffusion length of minority carriers and the presence of a high conductive layer [3]. Edge recombination affects small area SHJ solar cells more significantly [4] and generally record efficiencies reported on SHJ are measured on large area solar cells [5]. In this paper we analyze the edge effects by fabricating SHJ solar cells with different areas and masking schemes to evaluate the changes in open-circuit voltage (V_{OC}). We complement our study by modeling the edge recombination using PC3D [6]. We demonstrate that solar cells with the same implied factors, implied open-circuit voltage (iV_{OC}), implied fill factor (iFF), show different pseudo fill factors (pFF) and open-circuit voltage for different cell areas after metallization.

II. Experiment

Silicon heterojunction samples were fabricated on n-type Czochralski (CZ) wafers, with a starting thickness of 200 µm and a bulk resistivity of 3 - 4 Ωcm. The wafers were thinned and textured to 40 µm using alkaline wet etching and followed by an acidic cleaning process [7]. Plasma enhanced chemical vapor deposition (PECVD) was used to deposit intrinsic and n/p-doped hydrogenated amorphous silicon (a-Si:H) layers, forming a p-i/c-Si/i-n stack. The effective minority carrier lifetime was measured using a Sinton photoconductance decay lifetime tester (WCT-120). The iV_{OC} was calculated from the lifetime measurement.

Indium tin oxide (ITO) of different areas was deposited on both front and rear surfaces using sputtering. A silver contact was sputtered on the rear side. Front contacts were screen printed with silver paste. All the cells were annealed for 30 mins at 200 ºC. A Sinton FCT-450 flash tester was used to measure the I-V curves of the solar cells. Electroluminescence (EL) and photoluminescence (PL) imaging are used to evaluate the diffusion of carriers at the edges of the cells.

III. Results and Discussion

A. SHJ device results

We manufactured SHJ solar cells with two different areas and similar effective lifetimes and implied I-V parameters. These cells underwent the same manufacturing process, and the only difference is the ratio of cell perimeter-to-area, Tab. 1, which is achieved by depositing different ITO areas. The area surrounding the cells is passivated. We used 40 µm thin wafers in this work as the V_{OC} increases with decreasing wafer thickness, making any changes in the voltage more discernable [8]. The 150.3 cm^2 cell shows a smaller gap between iV_{OC} and V_{OC} than the 6 cm^2 cell. The larger cell also shows higher pFF.

Table 1: Comparison of SHJ solar cells of different areas but with similar effective minority carrier lifetimes at an injection level of 3×10^{15} cm^{-3}.

Area (cm^2)	*Perimeter /Area (cm^{-1})*	*τ_{eff} (µs)*	*iV_{OC} (mV)*	*V_{OC} (mV)*	*iFF (%)*	*pFF (%)*
150.3	0.31	1440	764	747	83.7	82.4
6	1.63	1432	764	740	83.7	80.8

[1] τ_{eff} is the effective minority carrier lifetime.
[2] Area is approximated to the first decimal point.

A voltage loss of 20 mV is seen between the iV_{OC} and the V_{OC} measured on the final SHJ solar cell, as seen in Tab. 1. A certain percentage of loss in V_{OC} can be attributed to the damage induced by sputtering which results in the loss of surface passivation [9,10].

In this work, we try to quantify the contribution of edge losses to the total voltage losses in the SHJ solar cell. Electroluminescence images are used to find the periphery of the SHJ solar cell up to which the injected carriers diffuse, Fig. 1. A single linescan of the EL image is shown in Fig. 2. Each pixel intensity of the image is directly proportional to the carrier density of SHJ solar cell [11]. It can be noticed that the injected carriers are diffusing at least 4.5 mm from the edge of the device.

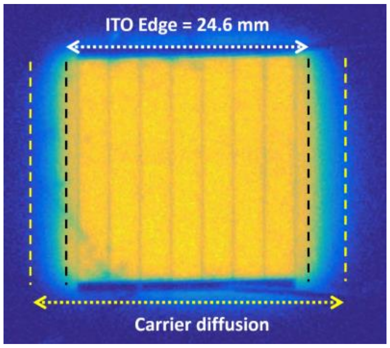

Fig. 1. EL image of 6 cm^2 SHJ solar cell under a bias voltage of 0.530 mV. It can be noticed in the image that carriers are diffusing outside the ITO and metal contact region.

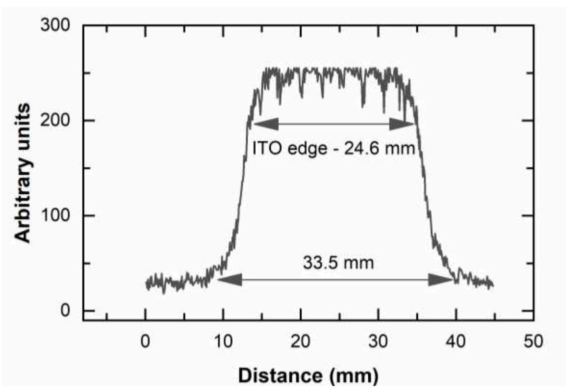

Fig. 2. A linescan of the EL image obtained from Fig. 1. The y-axis represents the pixel intensity of the EL image in arbitrary units. This shows the spread of the carriers at the edges. The 6 cm^2 device has minority carriers that diffuse atleast 5 mm from the edge of the device on each side.

B. *Photoluminescence imaging at short-circuit condition*

Photoluminescence imaging of solar cells at short-circuit conditions can also be used to measure the diffusion of carriers at the edge of the cell area. PL counts (C_{PL}) are directly proportional to the np-product and thus related to the diode voltage (V_d) as:

$$C_{PL} \propto np \propto n_i^2 \exp\left(\frac{qV_d}{kT}\right) \quad (1)$$

where n_i is the intrinsic carrier concentration, k is the Boltzmann constant, n and p are the electron and hole concentration and T is the temperature [12]. Figure 3 (a), (c) represents a PL image of the 6 cm^2 device and 150.3 cm^2 device under short-circuit conditions respectively. Fig. 3 (b), (d) is a representative linescan of PL intensity across the devices respectively and we see carriers diffusing at least 5 mm for both cases when compared to the edge of the ITO layer on the device. The section of the PL linescan till the edge of the ITO, is proportional to the V_{OC} measured when the entire substrate is illuminated. When using a measurement mask, there is diffusion of carriers along the edges which we are assuming, in our preliminary hypothesis, to be proportional to the diffusion of carriers at the edges under short circuit conditions. The loss of voltage due to the diffusion of carriers around the edge of the solar cell is estimated using the ratio of the PL intensities as:

$$\frac{\log(\bar{C}_1)}{\log(\bar{C}_2)} \propto \frac{V_{unmasked}}{V_{masked}} \quad (2)$$

where $\bar{C} = \sum_{k=0}^{n} C_k$, is the average of all the pixel counts for the area under consideration. At this point in time we are still working on the details of this hypothesis, and a more definitive analysis will be addressed in a future publication.

Measured V_{OC} values for a 6 cm^2 square SHJ solar cell with and without masking is 725 mV and 735 mV respectively. Using the ratios within the PL linescan as described above, Fig. 2(b), we calculated a V_{OC} 725 mV for a masked measurement of the device. Measured V_{OC} values for a 150.3 cm^2 pseudo-square SHJ solar cell with and without masking is 742 mV and 739 mV respectively. Using PL linescan, Fig. 3(d), we calculated the voltage to drop to 739 mV. A voltage drop of 12 mV was calculated from PL for 6 cm^2 and 3 mV for 150.3 cm^2 area SHJ solar cell which are close to the measured values, Tab. 2. These results are a good indication that smaller cells that have larger cell perimeter-to-area ratio, have larger edge recombination [13].

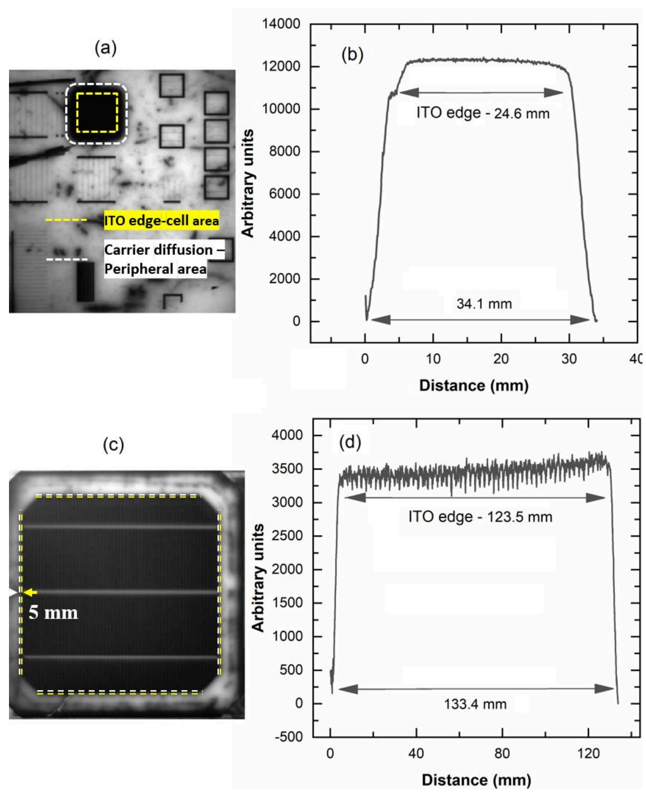

Fig. 3. (a) PL image of 6 cm^2 SHJ solar cell under short circuit condition. (b) Representative PL intensity linescan across the 6 cm^2 device which shows minority carriers diffuse at least 5 mm from the edge of the device. (c) PL image of 150.3 cm^2 SHJ solar cell under short circuit condition. (d) Representative PL intensity linescan across the 150.3 cm^2 device has minority carriers that diffuse at least 5 mm from the edge of the device. It is to be noted that PL linescans have undergone translational transformation.

TABLE 2: COMPARISON OF VOLTAGE LOSSES IN SHJ SOLAR CELLS WITH DIFFERENT CELL PERIMETER-TO-AREA RATIO .

Cell area (cm^2)	*Perimeter/ Area Ratio (cm^{-1})*	*ΔVoc (I-V) Exp. (mV)*	*ΔVoc (PL) Est. (mV)*
150.3	0.31	3	3
6	1.63	10	12

Exp. – Experiment; *Est.* – Estimated from PL images;

C. Modeling results

As previously addressed, one of the methods to understand the voltage losses due to edge recombination is to measure the I-V characteristics of solar cells with and without an optically opaque mask. We use a three-dimensional device simulation software: PC3D to evaluate the edge recombination parameter [6]. When measuring solar cells with a mask there is recombination of light generated carriers into the region around the solar cell. The goal of the model is to quantify that recombination with PC3D. We modeled the recombination for cells that are 6 cm^2 as the effect is more pronounced here. The modeled device is pictured below, Fig. 4. To get a similar result in 2D we can model an infinitely long solar cell which is 1 cm wide. It would then have the same ratio of cell perimeter-to-area. The bulk lifetime is set to 3 ms and a surface saturation current density (J_0) of 5 fA/cm² for each side. The base resistivity is 3-Ωcm n-type. Series resistance (R_s) is not considered in this model currently. ITO sheet resistance is set to 70 Ω/sq and since it is under a contact it will make minimal difference to the V_{OC}. Further details for simulation parameters for the ITO layer can be found here [14].

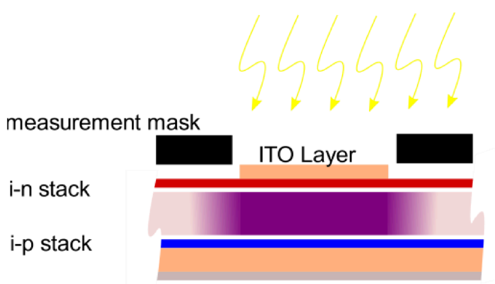

Fig. 4. The ITO layer defines the cell area. Outside the cell area the surface is passivated with the n-type/intrinsic a-Si:H stack on the front and p-type/intrinsic a-Si:H at the bottom. The purple area represents the excess carriers, which will leak out of the illuminated area and decline to zero at infinity.

The model shows that as we scan across from the center of the device from left to right the intensity reduces by 95% at a distance of 1cm from the device, Fig. 5. The simulation predicts a loss of 5 mV and the experimental results show a loss of 10 mV for a 6 cm^2 area solar cell between masked and unmasked measurements. At the moment, we are working on the model to represent more accurately the boundary conditions of the experimental cells.

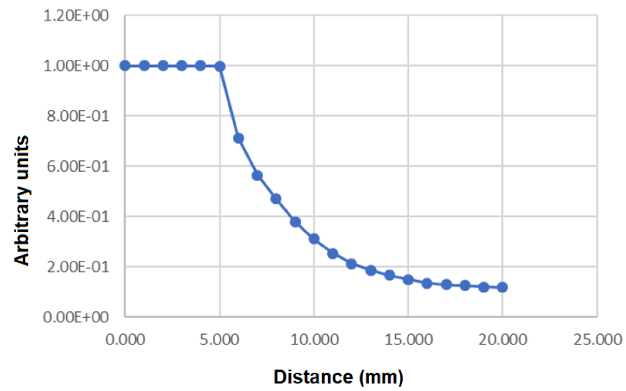

Fig. 5. Linescan of the electroluminescence edge obtained from PC3D. The y-axis represents the intensity of electroluminescence which is directly proportional to excess minority carrier density.

IV. CONCLUSIONS

In this manuscript we present the current status of our study to identify the impact of edge losses on open-circuit voltage in silicon heterojunction solar cells. We demonstrate that the edge losses decrease with the decrease in the ratio of cell perimeter-to-area. A change in the cell area from 6 cm^2 to 150.3 cm^2 led to a voltage gain of 7 mV. When measuring voltage with and without a mask, a difference of 10 mV is seen for 6 cm^2 SHJ solar cells. This reduces to 3 mV for an area of 150.3 cm^2. We demonstrate that PL imaging at short-circuit conditions is a promising technique to quantify the voltage losses from the edge of solar cells.

REFERENCES

[1] K. R. McIntosh and C. B. Honsberg, "The Influence of Edge Recombination on a Solar Cell's IV Curve", 16th European Photovoltaic Solar Energy Conference. 2000.

[2] N. Jensen, U. Rau, R. M. Hausner, S. Uppal, L. Oberbeck, R. B. Bergmann, & J. H. Werner, " Recombination mechanisms in amorphous silicon/crystalline silicon heterojunction solar cells," Journal of Applied Physics, 87, no. 5, pp. 2639-2645, 2000.

[3] S.Y. Herasimenka, W. J. Dauksher, & S. G. Bowden, "> 750 mV open circuit voltage measured on 50 µm thick silicon heterojunction solar cell," Applied Physics Letters, 103, no. 5, pp. 053511, 2013.

[4] K. Rühle, M.K. Juhl, M.D. Abbott, L.M. Reindl and M. Kasemann, "Impact of edge recombination in small-area solar cells with emitter windows," IEEE Journal of Photovoltaics, 5(4), pp.1067-1073, 2015.

[5] K. Yoshikawa, H. Kawasaki, W. Yoshida, T. Irie, K. Konishi, K. Nakano, T. Uto, D. Adachi, M. Kanematsu, H. Uzu and K. Yamamoto, "Silicon heterojunction solar cell with interdigitated back contacts for a photoconversion efficiency over 26%," Nature energy, vol. 2, no. 5, pp.17032, 2017.

[6] P. A. Basore, PC3D, http://www.pc3d.info/, 2020.

[7] S.Y. Herasimenka, W. J. Dauksher, C. J. Tracy, J. Lee, A. Augusto, H. Jain, K. Tyler, Z. Kiefer, P. Balaji, S. G. Bowden and C. Honsberg, " Front-and rear-emitter screen printed silicon heterojunction solar cells with> 20% Efficiency," Proceedings of the 31st European Photovoltaic Solar Energy Conference, pp. 761-764, 2015.

[8] A. Augusto, P. Balaji, J. Karas, and S. G. Bowden, "Impact of substrate thickness on the surface passivation in high performance n-type solar cells," In 2018 IEEE 7th World Conference on Photovoltaic Energy Conversion (WCPEC)(A Joint Conference of 45th IEEE PVSC, 28th PVSEC & 34th EU PVSEC), pp. 2792-2794. IEEE, 2018.

[9] P. Balaji, W.J. Dauksher, S.G. Bowden and A. Augusto, "Development of 40 µm thin flexible silicon heterojunction solar cells," 2018 IEEE 7th World Conference on Photovoltaic Energy Conversion (WCPEC), (A

Joint Conference of 45th IEEE PVSC, 28th PVSEC & 34th EU PVSEC, pp. 2100-2103, June 2018.

[10] A. Augusto, S. Y. Herasimenka, R. R. King, S. G. Bowden and C. Honsberg, "Analysis of the recombination mechanisms of a silicon solar cell with low bandgap-voltage offset," Journal of Applied Physics, 121(20), p.205704, 2017

[11] O. Breitenstein, A. Khanna, Y. Augarten, J. Bauer, J. -M. Wagner, and K. Iwig, "Quantitative evaluation of electroluminescence images of solar cells," Phys. Status Solidi (RRL), vol. 4, pp. 7, 2010.

[12] T. Trupke, B. Mitchell, J. W. Weber, W. McMillan, R. A. Bardos, & R. Kroeze, "Photoluminescence imaging for photovoltaic applications", Energy Procedia, vol. 15, pp. 135-146, 2012 .

[13] P. P. Altermatt, G. Heiser and M. A. Green, "Numerical quantification and minimization of perimeter losses in high-efficiency silicon solar cells," Progress in Photovoltaics, no. 4, pp. 355-367, 1996.

[14] D. Alonso-Álvarez, A. Augusto, P. Pearce, L. Ferre Llin, A. Mellor, S. G. Bowden, D. J. Paul, and N. Ekins-Daukes, "Thermal emissivity of silicon heterojunction solar cells," Solar Energy Materials and Solar Cells, 201 110051, 2019.