IMPROVED LAYER PROPERTIES COMBINED WITH LIGHT SOAKING ENABLING FOR 23% EFFICIENT SILICON HETEROJUNCTION SOLAR CELLS

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ABSTRACT: Silicon hetero junction (SHJ) cell technology is one of the next generation high efficiency concepts that are currently in the focus of the PV community enabling record efficiencies and increasing in market share. Continuous process improvements along the production chain enable efficiency as well as yield improvements targeting cost reduction and increased market acceptance. This work addresses process improvements in our PV-TEC pilot production environment concerning amorphous silicon (a-Si) and transparent conductive oxide (TCO) layer deposition, and specifically presents a laser-based light soaking treatment enabling cell efficiency gains up to 0.6%$_{abs.}$ All implemented improvements enable for 23% efficiency on full area (244.43 cm^2) SHJ cells. Investigations concerning the impact of the TCO edge exclusion on cell parameters by designated area IV-measurements with varying mask widths indicate that for 3 mm edge exclusion carrier collection and recombination losses which strongly affect J_{SC} and *FF* can be reduced enabling for efficiencies of 23.5%.

Keywords: Silicon hetero heterojunction, light soaking, edge exclusion induced losses

1 INTRODUCTION

Silicon heterojunction (SHJ) cell technology is one of the next generation high efficiency concepts that are currently in the focus of the PV community enabling record efficiencies [1, 2] and increasing in market share [3, 4] Continuous process improvements along the production chain enable efficiency as well as yield improvements targeting cost reduction and increased market acceptance. This work addresses process improvements in our pilot production environment (PVTEC Laboratory) at Fraunhofer ISE concerning amorphous silicon (a-Si) and transparent conductive oxide (TCO) layer deposition and presents a laser-based light soaking (LS) treatment enabling cell efficiency gains up to 0.6%$_{abs.}$.

An optimisation of the a-Si and TCO layer properties is crucial to avoid optical and transport losses in SHJ devices and steadily pave the way for higher efficiencies. Understanding the interplay of the layer properties allows for tuning these step by step.

More and more research comes up to answer the question if light soaking can help to improve the SHJ cell and module efficiency, if the effect is stable over time and which are the physical mechanisms behind. Up till now Kobayashi et al. reported that by light soaking the efficiency of SHJ cells and modules can be improved by 0.3% [5, 6]. The improvements result as open circuit voltage V_{OC} and fill factor *FF* increase and are suggested to originate from a reduced density of recombination active interface states. This contrasts at first sight to the findings that LS induces degradation of thin-film (intrinsic) a-Si:H solar cells which is attributed to the generation of deep defects that act as recombination centers [7] and is referred to as Staebler-Wronski effect (SWE) [8, 9]. Similar behavior as for the bulk a-S:H is observed for the intrinsic a-Si:H/c-Si interface [10, 11]. Capping the intrinsic with a doped a-Si:H layer changes the situation and leads to the reported improvements which are concluded to result in efficiency improvement by shifting the Fermi-level closer to either conduction or valence band and thereby reverting the SWE [5, 6]. Further similar SHJ cell efficiency improvements (0.4-0.7% abs.) have been reported by Hallam and Wright et al. [12, 13] resulting from a “multi-functional post-fabrication process”.

In comparison, our laser-based light soaking approach enables slightly higher efficiency improvements in much shorter time of only a few seconds as presented in [5, 6]. but similar results as reported in [12, 13]. For the light soaking process we applied (ultra-fast) regeneration by laser-based rapid thermal processing [14] and adapted it respecting the lower temperature tolerance of SHJ cells. The process is carried out at high illumination intensity. As an IR laser is used for the process this leads to heating by the radiation. The high illumination intensity leads to high injection and generation conditions resulting in increased carrier mobility. The heating increases the diffusivity of hydrogen. This in turn enables curing of interface defect states at the different interfaces. As the process is ultra-fast and can be carried out either static or within an inline setup it is feasible for industrial integration.

2 APPROACH

Large area (M2, n-type Cz (fabricated by LONGI Green Energy Technology Co., Ltd), base resistivity 3 Ωcm or 1 Ωcm) SHJ solar cells with rear emitter design were fabricated. For alkaline texturing and ozone based cleaning our standard processing was applied. In order to overcome identified absorption and transport losses an optimization of the front and rear side a-Si:H and TCO layers (indium tin oxide ITO) was carried out. The intrinsic and doped a-Si layers were deposited by conductive coupled plasma (CCP) batch PECVD resulting in layers stacks with a thickness (d) ranging between 10-20 nm with variations concerning single layer thickness, composition and doping. ITO layers with approx. d= 75 nm effective thickness on random pyramid texture were deposited with substrate heating via radio frequency (rf) magnetron sputtering whereby H_2 and O_2 percentage were varied. In the first part of the experiments the ITO deposition was carried out at Singulus Technologies AG, in the second part the ITO layers were deposited in-house at Fraunhofer ISE. After

TCO deposition (single layer) screen printing with our reference low temperature silver (Ag) particle based paste (0 busbar (0BB) bifacial design) occurred followed by curing in a convection furnace (t=10 min, T=200°C) and IV-testing (Gridtouch tester unit). Some of the cells were subjected to laser-based light soaking treatment which was optimized with respect to illumination intensity, temperature and time. After light soaking the cells went again to IV-testing.

3 RESULTS

3.1 Baseline full area SHJ cells

Several batches of large area (M2, n-type Cz) SHJ solar cells with rear emitter were fabricated whereby improvements concerning a-Si layer properties (thickness, composition and doping) as well as TCO properties (O_2 and H_2 concentration, with and without H_2) were stepwise implemented.
Table 1 and 2 show the Fraunhofer ISE Callab certified IV measurement results of our best SHJ cells with external ITO layers (Singulus Technologies) and the results of our first batch with internal ITO layers. All cells received light soaking treatment as described in detail in the next section. The measurements were carried out either with a black (non-reflecting) or a golden (reflecting) chuck in total area (ta) configuration.

The cells of the best groups with external TCO achieved maximum efficiency (η) values of 22.6% measured on black chuck (bc) and 23.0% on gold chuck (gc). With internal TCO 22.5% (bc) and 22.8% (gc) were reached.

Table 1: IV data of certified measurement of best cell with external TCO (all total area) after light soaking

Chuck	Area (cm²)	V_{oc} (mV)	J_{sc} (mA/cm^2)	*FF* (%)	η (%)
Black	244.43	739	38.1	80.3	**22.6***
Gold	244.43	741	38.6	80.3	**23.0***

Table 2: IV data of certified measurement of best cell with internal TCO (all total area) after light soaking

Chuck	Area (cm²)	V_{oc} (mV)	J_{sc} (mA/cm^2)	*FF* (%)	η (%)
Black	244.43	741	37.6	80.6	**22.5***
Gold	244.43	742	38.1	80.6	**22.8***

3.2 Impact of light soaking on cell parameters

Finished cells were subjected to light soaking treatment which was optimized with respect to illumination intensity, temperature and exposure time.

To find the best process conditions the "Temperature Gradient Imaging Analysis" (TGIA) method [15] was applied. Therefore a cell precursor prior metallization is treated at certain laser conditions with temperature gradient induced by cooling with air for a single exposure time.
During processing a temperature profile is recorded with an IR camera. Afterwards the temperature profile is correlated with the lifetime calibrated PL images of the entire sample before and after the treatment to determine the best process conditions resulting in the highest delta (Δ) implied open circuit voltage iV_{oc}. Figure 1 depicts a schematic of the static offline laser based RTP setup. Figure 2 exemplarily shows the $\Delta\ iV_{oc}$ plotted against temperature (T) and a magnification for the optimal process condition regime.

It can be seen that until a maximum T value the passivation improves upon the treatment resulting in a positive $\Delta\ iV_{oc}$ presumably due to improved hydrogen passivation. Above the T threshold for a certain process time (t) the hydrogen incorporated in the a-Si layers diffuses not only within the layer stack but rather starts to effuse and the passivation decreases resulting in a negative $\Delta\ iV_{oc}$.

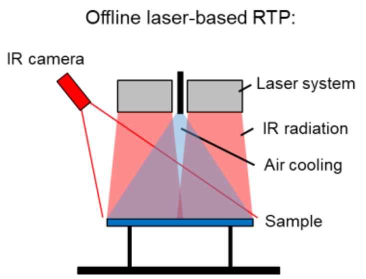


Figure 1: Schematic of static laser based RTP setup

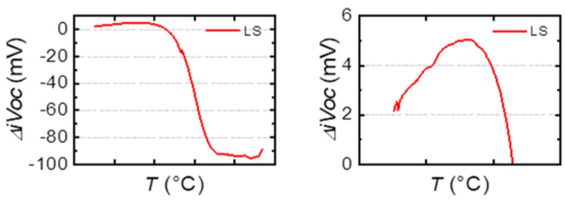
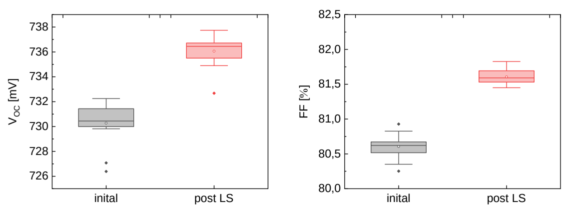


Figure 2: $\Delta\ iV_{oc}$ plotted against temperature (T) (left) and a magnification for the optimal process condition regime determined by TGIA method [15](right).

Applying the optimized laser-based light soaking treatment on SHJ cells leads to an improvement of V_{OC} and FF (driven by R_S reduction) which results in an efficiency (η) gain of 0.4-0.6%$_{abs.}$ (Figure 3). As the J_{sc} is not affected we waive depicting the resulting measurement data.



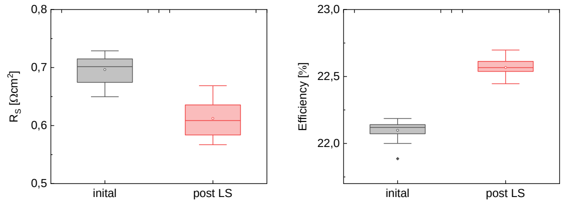


Figure 3: IV parameters in the initial state before and post light soaking (n=14 SHJ cells)

3.2 Impact of edge exclusion

To investigate the further potential of our internal SHJ cells we analyzed imaging data that were recorded in our IV tester. Hereby we observed inhomogeneities concerning the TCO edge exclusion of up to 1.5 mm as depicted in Figure 4. The dark inner area indicates the area covered by the TCO. The green lines indicate the inhomogeneity concerning the distance between the TCO edge exclusion and the wafer edge. The target value of the edge exclusion is expected to be in the range of 1.0 mm to 0.5 mm. Based on these findings we expect an impact on η of the cells driven by recombination and carrier collection losses.

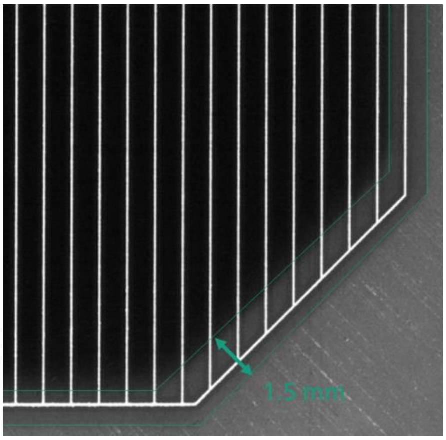


Figure 4: Imaging data of wafer edge, dark inner area indicates TCO covered area until the edge exclusion, the green lines the inhomogeneity concerning the distance between the TCO edge exclusion and the wafer edge.

For detailed analysis of the impact of the edge exclusion we conducted designated area IV measurements with a masked FS in the range (0-20 mm) [16]. Figure 5 pictures the *FF* values obtained by the designated area measurement.

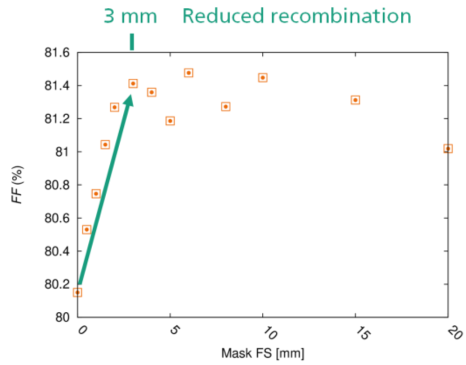


Figure 5: *FF* values obtained by the designated area measurement.

Up to a masked area of 3 mm an improvement of *FF* can be observed indicating that recombination losses occur due to defects close to the wafer edge and direct contacting of the metallization on the a-Si layer stack. With increasing masked area these losses are reduced up to the point where the dark diode area gets larger and recombination increases again as carriers start to be transported into the non-illuminated dark area. This effect of the dark diode area is more pronounced for the $V_{OC.}$ Here with up to 4 mm of masking no impact can be observed as lower recombination of the edge balances the higher recombination of the dark area, for larger edge exclusion, the area of the dark diode dominates and the V_{OC} decreases due to this effect (Figure 6).

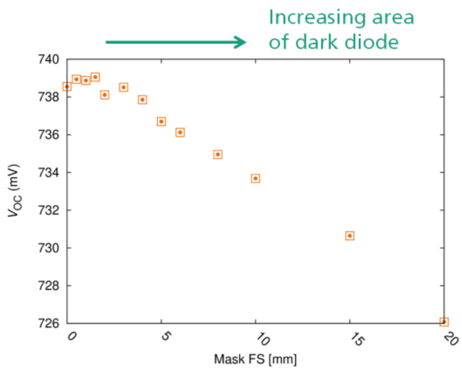


Figure 6: V_{OC} values obtained by the designated area measurement.

The J_{SC} value is also increasing between 0 to 1.5 mm of masked area indicating that carrier collection losses can be reduced (Figure 7).

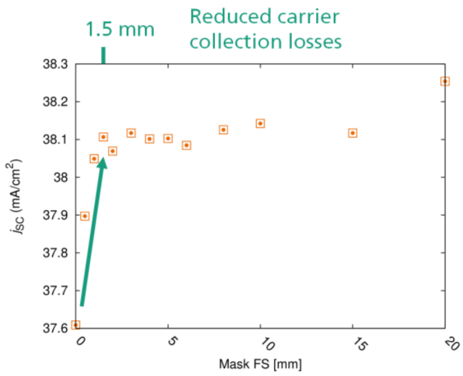


Figure 7: *Jsc* values obtained by the designated area measurement.

For 3 mm masked area a maximum η value of 23.5% can be achieved and shows the potential for further improvements by reducing the edge exclusion (Figure 8).

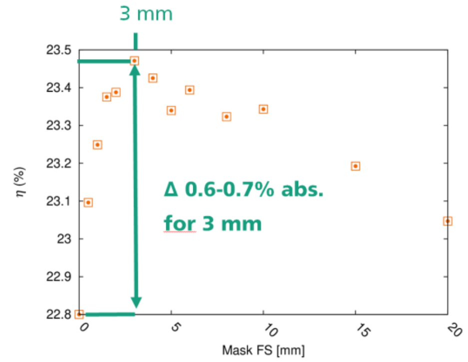


Figure 8: η values obtained by the designated area measurement.

Summing up the impact of the inhomogeneous TCO edge exclusion and wafer edge recombination is very strong. The difference resulting between masked edge relative to the full area is 1.2%$_{abs.}$ (1.6%$_{rel.}$) for *FF*, 0.5 mA/cm^2 (1.4%$_{rel.}$) for J_{SC} and 0.6%$_{abs.}$ (3%$_{rel.}$) for η.

4 SUMMARY AND CONCLUSION

This work presents the actual status of our Fraunhofer ISE PV-TEC SHJ baseline in pilot production environment. All implemented improvements concerning a-Si layer stack and ITO layer optimization as well as the introduction of a laser-based light soaking process enable for 23% efficiency full area (244.43 cm^2) SHJ cells. Investigations concerning the impact of the TCO edge exclusion on cell parameters by designed area IV-measurements with varying mask widths indicate that for 3 mm edge exclusion carrier collection and recombination losses which strongly affect J_{SC} and *FF* can be reduced enabling for a designated area (225.6 cm^2) efficiency of 23.5%. Future work will address further improvements of the SHJ layer stack as well as the edge exclusion. Additionally we will study the stability and transferability of the improvements by light soaking on cell and module level.

ACKNOWLEDGEMENTS

The authors would like to thank all colleagues at the Fraunhofer ISE PV-TEC as well as our project partners. This work was funded by the German Federal Ministry for Economic Affairs and Energy within the research projects “ProSelect“ (contract no. 0324189B).

REFERENCES

References
[1] D. Adachi, J. L. Hernández, and K. Yamamoto, “Impact of carrier recombination on fill factor for large area heterojunction crystalline silicon solar cell with 25.1% efficiency,” *Appl. Phys. Lett.*, vol. 107, no. 23, p. 233506, 2015.
[2] K. Yoshikawa, W. Yoshida, T. Irie, H. Kawasaki, K. Konishi, H. Ishibashi, T. Asatani, D. Adachi, M. Kanematsu, H. Uzu, and K. Yamamoto, “Exceeding conversion efficiency of 26% by heterojunction interdigitated back contact solar cell with thin film Si technology,” *Solar Energy Materials and Solar Cells*, vol. 173, pp. 37–42, 2017.
[3] ITRPV, “International Technology Raodmap for Photovoltaic (ITRPV): 2018 Results,” 2019.
[4] S. K. Chunduri and M. Schmela, “Heterojunction Solar Technology: 2019 Edition,” *TaiyangNews*, 2019.
[5] E. Kobayashi, S. D. Wolf, J. Levrat, G. Christmann, A. Descoeudres, S. Nicolay, M. Despeisse, Y. Watabe, and C. Ballif, “Light-induced performance increase of silicon heterojunction solar cells,” *Appl. Phys. Lett.*, vol. 109, no. 15, p. 153503, 2016.
[6] E. Kobayashi, S. D. Wolf, J. Levrat, A. Descoeudres, M. Despeisse, F.-J. Haug, and C. Ballif, “Increasing the efficiency of silicon heterojunction solar cells and modules by light soaking,” *Solar Energy Materials and Solar Cells*, vol. 173, pp. 43–49, 2017.
[7] H. Dersch, J. Stuke, and J. Beichler, “Light-induced dangling bonds in hydrogenated amorphous silicon,” *Appl. Phys. Lett.*, vol. 38, no. 6, pp. 456–458, 1981.
[8] D. L. Staebler and C. R. Wronski, “Reversible conductivity changes in discharge-produced amorphous Si,” *Appl. Phys. Lett.*, vol. 31, no. 4, pp. 292–294, 1977.
[9] M. Stuckelberger, M. Despeisse, G. Bugnon, J.-W. Schüttauf, F.-J. Haug, and C. Ballif, “Comparison of amorphous silicon absorber materials: Light-induced degradation and solar cell efficiency,” *J. Appl. Phys.*, vol. 114, no. 15, p. 154509, 2013.
[10] S. D. Wolf, B. Demaurex, A. Descoeudres, and C. Ballif, “Very fast light-induced degradation of a - Si:H/ c -Si(100) interfaces,” *Phys. Rev. B*, vol. 83, no. 23, 2011.
[11] E. M. El Mhamdi, J. Holovsky, B. Demaurex, C. Ballif, and S. D. Wolf, “Is light-induced degradation of a-Si:H/c-Si interfaces reversible?,” *Appl. Phys. Lett.*, vol. 104, no. 25, p. 252108, 2014.
[12] B. Hallam, “Defect-Engineered Silicon Heterojunction Solar Cells,” Chengdu, China, Nov. 18 2019.
[13] M. Wright, M. Kim, P. Dexiang, X. Xin, Z. Wenbin, B. Wright, and B. Hallam, “Multifunctional process to improve surface passivation and carrier transport in industrial n-type silicon heterojunction solar cells by 0.7% absolute,” in *15th International Conference on Concentrator Photovoltaic Systems (CPV-15)*, Fes, Morocco, 2019, p. 110006.
[14] A. A. Brand, K. Krauß, P. Wild, S. Schörner, S. Gutscher, S. Roder, S. Rein, and J. Nekarda, “Ultrafast In-Line Capable Regeneration Process for Preventing Light Induced Degradation of Boron-Doped p-Type Cz-Silicon Perc Solar Cells,” in *33rd EU PVSEC*, Amsterdam, The Netherlands, 2017.
[15] Sebastian Roder, Tim Niewelt, Andreas Brand and Jan Nekarda, “Temperature Gradient Imaging Analysis (TGIA) for optimization of an Ultra-Fast boron-oxygen defect Regeneration (UFR),” *in preparation*, 2020.
[16] S. Janke, E.C. Wang, A.B. Morales-Vilches, T. Henschel, A. Cruz Bournazou, R. Schlatmann, B. Stannowski, S. Pingel, A. Moldovan, “Quantifying

& Reducing Edge Losses in Silicon Heterojunction Solar Cells," Marseille, France.