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ADDRESSING EDGE RECOMBINATION LOSSES IN SHINGLE CELLS BY HOLISTIC OPTIMIZATION OF THE PROCESS SEQUENCE

Alexander Göbel[1,2], Elmar Lohmüller[1], Dirk Wagenmann[1],
Norbert Kohn[1], Marc Hofmann[1], Jonas D. Huyeng[1], Ralf Preu[1,2]
[1]Fraunhofer Institute for Solar Energy Systems ISE, Heidenhofstr. 2, 79110 Freiburg, Germany
[2]University of Freiburg, Department of Sustainable Systems Engineering, INATECH, 79110 Freiburg, Germany
Corresponding author: alexander.goebel@ise.fraunhofer.de

ABSTRACT:
This work focuses on edge recombination losses of cut silicon solar cells, with special attention to shingle cells. We discuss a high-throughput method to form emitter windows by laser ablation of the *p/n*-junction along the cut line. To show the proof of concept, we fabricate symmetrical test structures that reveal a superior surface passivation in the ablation areas. Further, we present results where emitter windows are implemented into our PERC baseline sequence by a single additional structuring step. Shingle cells with emitter window show 83 $\%_{rel}$ less losses in pseudo fill factor *pFF* after thermal laser separation (TLS) compared to cells with full area emitter. Additionally, we introduce an enhancement of the passivated edge technology (PET) by optimizing of atomic layer deposition. We prepared lifetime samples and cut solar cells. We find an increased effective lifetime of the excited carriers by a factor of 1.75. The *pFF* gain for cut solar cells is increased by 24 $\%_{rel}$. In total, our work provides two methods that can save up to 80 % of the power losses in cell cutting by TLS, and the methods are feasible for integration into existing industrial process chains.
Keywords: shingling, edge passivation, emitter window, laser ablation

1 INTRODUCTION AND MOTIVATION

Nowadays, cut solar cells are the standard in the silicon photovoltaics (PV) industry [1], as they reduce electrical losses, which leads to increased module efficiencies [2]. Utilizing silicon solar cells in the form of shingled interconnection presents several advantages. Notably, an expected 10 $\%_{rel}$ increase in module power density [3, 4] and their unobtrusive appearance make them excellent for integrated PV applications [5].

Usually, the cells are cut in the end of the cell's fabrication. This leads to a significant drawback as the new cut edges lack passivation compared to all other surfaces, which causes eventually losses in the energy conversion efficiency [6–8]. Main causes for this are defects at the edges, e.g., dangling bonds or other defects [9].

To reduce the recombination losses that occur at the edges, which are preferably prepared with very little damage, the passivated edge technology (PET) was first introduced on passivated emitter and rear cells (PERC) by Fraunhofer ISE [10, 8] and later demonstrated also on tunnel-oxide passivated contact (TOPCon) [11, 12] and silicon heterojunction (SHJ) solar cells [13, 14]. The PET harnesses two effects by coating the cell's edge with, e.g., AlOx: the chemical and the field effect passivation [15]. The first one saturates open crystal bonds and reduces thereby the amount of crystal defects at the edge. The field effect passivation works by forming stationary charges on the edge, which thus reinforce an imbalance of the free charge carriers near the edge, resulting in fewer recombination pairs of charge carriers.

Dicker has shown that the surface recombination rate is highest at the *p/n*-junction [16]. Despite its small dimension, it causes still most of the edge recombination as has been also simulated by Wöhrle et al. [7]. This leads to an alternative strategy wherein the *p/n*-junction is locally removed along the subsequent separation line through laser treatment. Thus, the severance of the cut *p/n*-junction can be avoided, which is called emitter window. This concept may benefit from the cell's surface passivation that can cover the emitter's edge [17]. Additionally, the current towards the edge is limited [18].

While this approach has been tested on lab scale [19, 17], to the best of the authors' knowledge it has not yet been realized for standard industrial cells. Simulations predict that the emitter window structure is able to shield 80 % of edge recombination losses in the fill factor [20].

In recent studies, we have pursued the emitter window approach by implementing a single additional structuring step into our PERC baseline sequence, revealing proof of successful emitter removal on test structures. Furthermore, this achievement is transferred on cell level showing a significant reduction in losses by the separation step. This novel avenue of exploration holds promise for mitigating edge recombination effects in shingle solar cells. For the PET we pursued an optimization of our processes that leads to improved edge passivation properties.

2 EXPERIMENTAL

2.1 Process sequence PERC

Our process sequence for PERC solar cells is illustrated as flowchart in Fig. 1. As-cut wafers are initially textured, and the emitter is formed by a phosphorous diffusion. Following this, the emitter is locally ablated in the vicinity of the designated separation pathways. This can be done by similar laser equipment as that used for laser doped selective emitter. Therefore, the emitter window in our case refers to all those cells where new cell edges are characterized by an emitter-free area at the end due to separation. The next step is the wet chemical removal of the rear side emitter in a batch process. In this step, any damage caused by the laser ablation on the front side is removed at the same time. The next steps are the passivation of the front and back and the anti-reflective coating (ARC).

The solar cell is finalized by laser contact opening on the backside, screen printing a metallization layout, that is optimized for shingle solar cells, and the contact formation. To obtain shingle solar cells, the full host cells are cut by thermal laser separation (TLS).

Another pair of groups is not treated with the laser, but the PET is applied to the newly formed edges after cutting. The PET consists of two subsequent treatments: application of an AlOx coating by, e.g., plasma enhanced atomic layer deposition (PE-ALD) and its activation through an annealing step [12]. The cut cells are stacked and held tightly during the application of the PET.

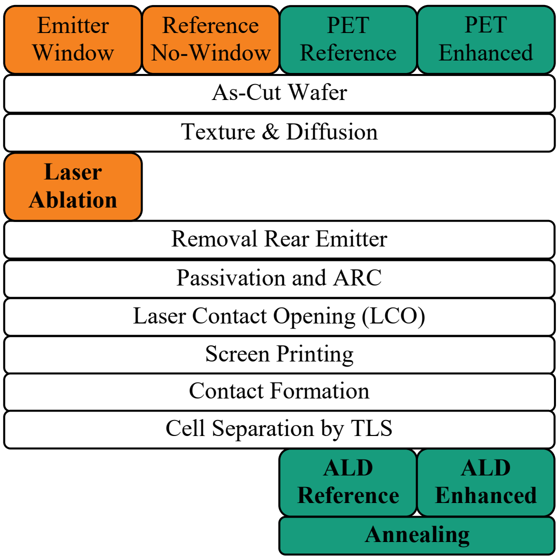

Figure 1: Flow chart of the experimental process flow for PERC solar cells. Two process strategies are evaluated: The emitter windows aim for a suppressed current flow to the edge. Whereas the PET is a very shallow edge damage singulation technology combined with a highly charged dielectric layer passivation.

2.2 Emitter windows

Before utilizing the laser for ablation of the emitter on a complete cell, the process to do so needs to be set up. We fabricate three identical test structures, i.e., n-type wafers are textured and undergo the diffusion for the n+ emitter. Subsequently, laser ablation is performed on both sides of the sample in a pattern similar to a chessboard, creating fields that represent all combinations of ablation and no ablation on the same wafer. The laser emits 532 nm light pulses of about 30 ns duration. A photoluminescence (PL) image of this sample is shown in Fig. 2. Eventually, the effective lifetimes τ_{eff} for all nine fields are measured via quasi steady state photoconductance (QSSPC) from both sides.

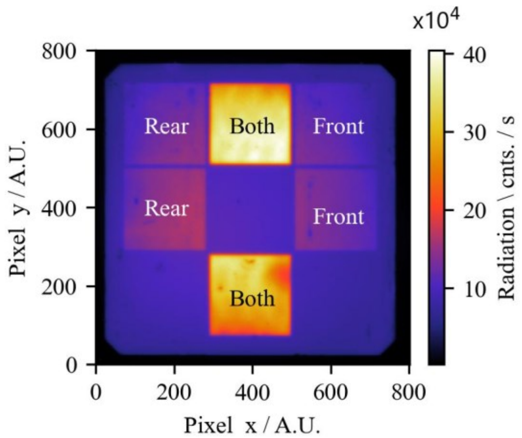

Figure 2: The photoluminescence image reveals a higher amount of radiative recombination in the emitter free fields. By this superior surface passivation, it is found that the emitter is absent, the laser damage in the silicon is etched away and the lateral conductivity is reduced. The labels “Rear”, Front” and “Both” indicate which side of the symmetrical sample is treated with the laser ablation.

For the cells, we use a metallization layout that is designed for shingle cells on M2 wafers. This pattern consists of four full square (fsq) shingle cells and two pseudo square (psq) shingles. After cutting, the fsq shingles have two new edges and the psq shingles have one new edge each. For reference and evaluation of losses caused by cutting, we fabricate twin groups differing only by the emitter ablation. For the ablation, we choose stripes with a width of about 400 µm at the separation line. In the data’s evaluation, we show only the fsq-shingles. The *IV*-data is gathered at an automized cell tester unit.

2.3 Passivated edge technology (PET)

For the optimization of the PET, float-zone silicon (FZ-Si) wafers are used. They suffer only little from impurities and are therefore predestinated for the characterization of the effectiveness of surface passivation layers, such as AlOx. One group of the FZ-Si wafers is coated following our reference recipe, other groups receive variations of the PE-ALD coating process, without changing the layer’s thickness (i.e. cycle time). All groups are annealed equally and the effective lifetimes τ_{eff} are obtained by QSSPC before and after annealing. After evaluation of the results, the reference and the most promising variation (“enhanced”) of the PET are applied to cut solar cells. The gain in the pseudo fill factor *pFF* for one sun illumination is chosen as quantity for the recovery of the cutting losses.

3 RESULTS AND DISCUSSION

3.1 Emitter windows

The samples, shown in Fig. 2, undergo the QSSPC measurement yielding the effective lifetimes τ_{eff} for each field whose data is depicted in the boxplot in Fig. 3. Overall, an increase in effective lifetime is observed for fields with laser treatment. The analysis is simplified by holding the factor for the light in coupling constant. This causes the deviation in τ_{eff} for the areas that have the ablation on one side.

In average an increase from 470 µs (no ablation) to 590 µs (one-side ablation) is observed. Notably, ablation on both sides leads to a lifetime of 960 µs on average which is approximately a doubling in τ_{eff} compared to no ablation. This confirms the successful removal of the emitter by laser ablation without damaging the cell and enables the transfer of our process to shingle solar cells.

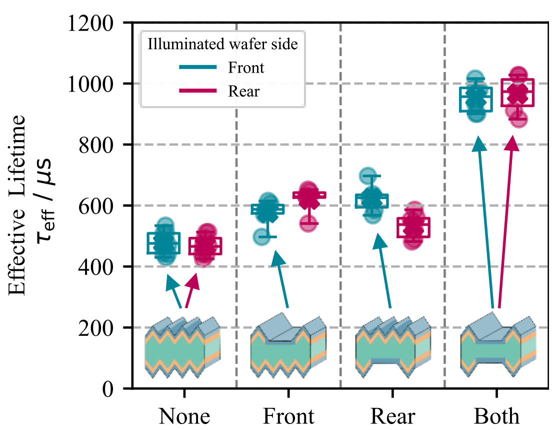

Figure 3: The effective lifetimes τ_{eff} are measured for each test field in both QSSPC configurations. The factor for the light in coupling in not changed.

With the proof of successful removement of the emitter we take complete shingle cells into focus. According to Fig. 1, two almost identical groups of shingles are made. They differ only by having the emitter ablation in the vicinity of the cut edge or being the ordinary case without the window. The light microscopic image of shingle cells with emitter window can be found in Fig. 4, and the scanning electron microscope (SEM) image is presented in Fig. 5.

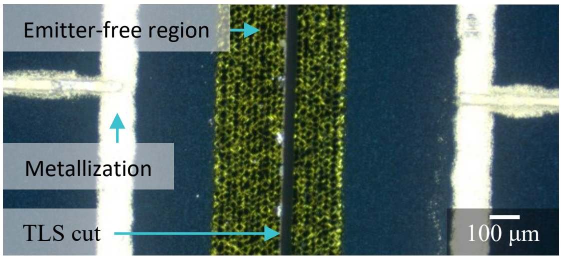

Figure 4: Light microscopic image of two shingle cells side by side with the emitter window after cutting using TLS. The ablation stripe has a width of about 400 µm.

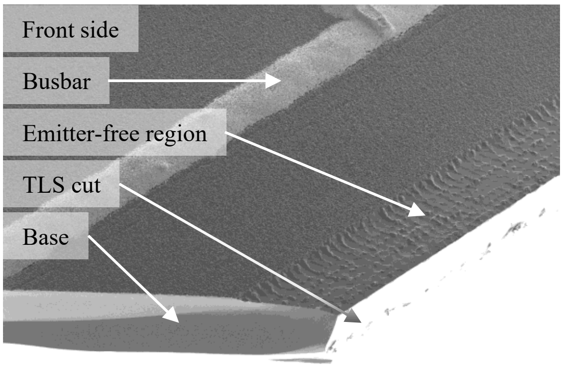

Figure 5: In the SEM image the emitter-free region, made by laser ablation and subsequential etching, is well visible.

Fig. 6 shows the *pFF* for both groups before and after cutting. In the reference group, 1.2 $\%_{abs}$ in *pFF* are lost by separating the cell. The shingle cells with the emitter window lose only 0.2 $\%_{abs}$ in *pFF*. Thus, we find that the use of emitter windows causes only 17 % of the losses in the *pFF* when cut by TLS compared to the reference group.

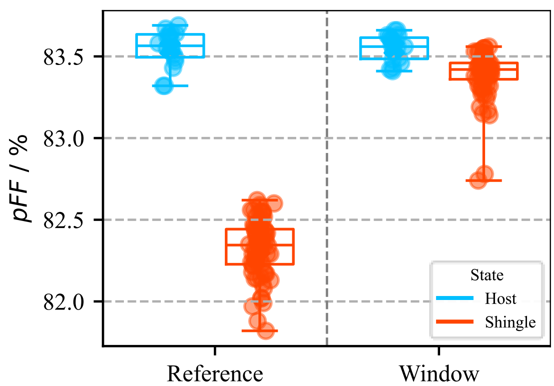

Figure 6: The host cells with the emitter window layout and the reference group start on equivalent *pFF* levels. Post TLS cutting, the shingles with emitter window suffer fewer losses.

An obvious drawback, which is already noticeable at the host level, is the decrease in absolute current for the emitter window group compared to the reference. As a result, we find that the short-circuit current density j_{sc} is 0.24 mA/cm² lower, which compensates for the decreased *pFF* loss in the energy conversion efficiency. Note that we used a quite larger emitter window with 400 µm width for this first trial. Fortunately, when going to a shingling module, only half of the j_{sc} loss come into action due to the principle of shingling.

3.2 Passivated edge technology (PET)

For the investigation of the PET, we measured the τ_{eff} of the FZ-Si samples before and after annealing. The data is illustrated in Fig. 7. In the as-deposited state, no significant difference in τ_{eff} is found for both coatings, averaging 1.5 µs. After annealing, τ_{eff} reaches 2.1 ms for the reference ALD process, while an average of 3.8 ms is achieved for the enhanced process. This result shows a 75 $\%_{rel}$ improvement in effective lifetime.

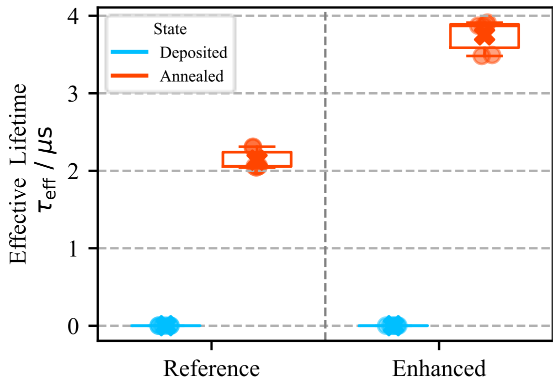

Figure 7: The graph illustrates the effective lifetimes of charge carriers on FZ-Si samples for two implementations of the PE-ALD process. Both coatings underwent the same annealing process.

We applied these encouraging findings to solar cells cut on two sides by TLS. First, we looked at the increased performance from the time just after the cut to after the PET treatment. Second, we examined the overall change in *pFF* from the original cell to the cut cell after passivation.

Fig. 8 displays the increase in *pFF* after applying the PET for both ALD recipes. The data is normalized to the average of the reference run. Our new process results in a 24 $\%_{rel}$ increase in *pFF* recovery. In other words, the edge passivation is almost a quarter more effective than before. The relative improvement is less than the 75 $\%_{rel}$ improvement seen with the FZ-Si samples. The reason for this smaller improvement is that PET can only make up for the losses caused by cutting the cell, which is not limiting the FZ-Si samples. When we include the *pFF* at the host level in our calculations, we find that we can recover up to 80 % of the separation losses regarding *pFF*.

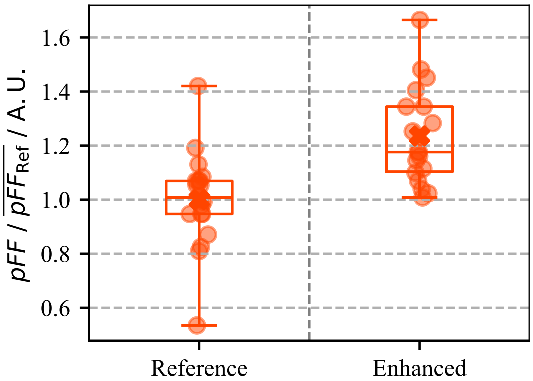

Figure 8: On equal cells that are cut on two sides by TLS the PET was done in two versions. The enhanced process sequence reveals a benefit of 24 $\%_{rel}$ regarding *pFF*.

4 CONCLUSIONS

Our analysis of cut silicon solar cells has revealed significant options for improving cell efficiency and mitigating the effects of edge recombination.

Our experimental data show a notable increase in effective lifetime in cases of ablation, suggesting that laser ablation with subsequent wet-chemical etching can successfully remove the emitter. Furthermore, the reduction of losses in *pFF* when using the emitter window approach highlights the potential of this technique for industry application.

The effectivity of the passivated edge technology (PET) was improved, showing a 75 $\%_{rel}$ rise of the effective charge carrier lifetime on FZ-Si samples. On separated solar cells, our new process enables 24 $\%_{rel}$ more gain, yielding a recovery in *pFF* of up to 80 $\%_{rel}$.

The successful implementation of the emitter window approach and the improvement in the application of PET indicate promising avenues for future research and development in this field.

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