Erschienen in: Proceedings of 32nd EU PVSEC. - München : WIP, 2016. - S. 858-862. - ISBN 3-936338-41-8
http://dx.doi.org/10.4229/EUPVSEC20162016-2AV.3.39

INVESTIGATIONS ON LASER FIRED CONTACTING AND ANNEALING OF RST SILICON PERC-TYPE SOLAR CELLS

Benjamin Albrecht[a], Yves Patrick Botchak[a], Fabrice De Moro[b], Philipp Keller[a], Giso Hahn[a]
[a]Department of Physics, University of Konstanz, 78457 Konstanz, Germany
[b]Solarforce SA, 1 rue du Dauphin, 38300 Bourgoin-Jallieu, France

Author for correspondence: benjamin.albrecht@uni-konstanz.de Tel.: +49 7531 882082, Fax: +49 7531 883895

ABSTRACT: The Ribbon on Sacrificial Template (RST) casting process is a kerf-loss free direct wafer casting method, which enables the production of silicon ribbon wafers below 100 µm thickness for thin solar cells. But the thinner the cell, backside passivation is all the more important. In our lab-type PERC solar cell process, the back contact is realized by laser fired contacts (LFC). In this study the influence of different LFC parameters on back side passivation is shown, based on lifetime samples made of standard 1 Ohmcm FZ wafers. With the best parameter set, surface recombination velocity $S_{eff,LFC}$ of 34.1 cm/s is possible with reasonable contacting. Beside backside passivation, an improvement of bulk lifetime of RST material was achieved by different surface passivation and annealing steps. These improvements resulted in a new effective lifetime record for RST material of 39.6 µs (measured by QSSPC).

Keywords: Annealing, Laser Fired Contacts, Lifetime, Passivation, Ribbon Silicon

1 INTRODUCTION

The Ribbon on Sacrificial Template (RST) casting process [1] enables the production of silicon ribbon wafers down to 50 µm thickness for thin solar cells. It is a kerf-loss free direct wafer casting method which means that energy-intensive silicon material can be saved. But the thinner the cell, backside passivation is all the more important. In our lab-type PERC solar cell process [2], the back contact is realized by laser fired contacts (LFC). Single side metalized and LFC contacted FZ lifetime samples showed that the standard LFC parameters, used by us up to now, damage backside passivation significantly.

In this study new LFC parameter sets are studied on single side metalized and LFC contacted 1 Ωcm p-type FZ lifetime samples (sec. 2.1, 3.1). Minority carrier lifetimes are measured before metallization and after LFC by TR-PLI [3] (time resolved photoluminescence imaging). Double side metalized and LFC contacted contact resistance samples are produced in parallel to measure contact resistances of the LFCs.

Beside backside passivation, improvement of bulk quality is very important for RST material to reach higher cell efficiencies. P-gettered and one-time H-passivated 1 - 3 Ωcm, 50 – 80 µm thick, p-type RST wafers from different batches, produced by the company Solarforce SA (France) [4], show typical bulk lifetimes of 15 – 30 µs. These wafers are used in this study for further treatments.

In the first RST experiment (sec. 2.2, 3.2), RST wafers are surface passivated with either SiN_x:H via PECVD (plasma-enhanced chemical vapor deposition) or Al_2O_3 via ALD (atomic layer deposition) and are annealed up to 3 h at 400 °C in N_2 atmosphere. Lifetimes are measured several times in between via QSSPC (quasi-steady-state photo conductance) measurements. Standard 1 Ωcm FZ wafers are processed in parallel to determine S_{eff} and use it to calculate τ_{bulk} for the RST wafers.

The second RST experiment (sec. 2.3, 3.3) is about multi-passivation of RST material with Al_2O_3. One passivation step includes Al_2O_3 deposition (ALD) and 1 h annealing at 400 °C in N_2 atmosphere. Multi-passivation comprises three passivation steps with etching off the passivation layer in between. Lifetimes are measured after each step via QSSPC.

The third RST experiment (sec. 2.4, 3.4) comprises all annealing steps which are used in our solar cell process [2] to establish electrical contacting on front and rear side of the solar cell. But only rear side contacting was realized, so that lifetime measurements with TR-PLI [3] could be applied after each step. Compared to the first (annealing) experiment, also low temperature annealing (70 – 170 °C) and annealing with Al present is applied here.

2 EXPERIMENT

2.1 Optimisation of LFC parameters

To find out LFC parameter sets which damage surface passivation as little as possible but still enable reasonable electrical contact, single side LFC contacted lifetime samples and double side LFC contact resistance samples are produced in parallel.

For this investigation 250 µm thick, 5x5 cm² 1 Ωcm p-type FZ wafers are used. At first, all wafers receive a wet chemical cleaning, are symmetrically coated with 37.5 nm Al_2O_3 by ALD and are annealed for 60 min at 400 °C in N_2 atmosphere. TR-PLI [3] is used to determine $\tau_{eff,Al2O3}$. τ_{bulk} was assumed to 3,800 µs for all 1 Ωcm FZ wafers and the surface recombination velocity $S_{eff,Al2O3}$ was calculated.

The LFC lifetime samples are then coated on the backside with 2 µm Al via EBPVD (e-beam evaporation), are LFC contacted with a 1064 nm laser (pitch 0.5 mm and different pump current/frequency sets) and annealed for 40 min at 350 °C in N_2 atmosphere. TR-PLI [3] is used to determine τ_{eff} of LFC lifetime samples.

The LFC contact resistance samples are coated on both sides with 2 µm Al by EBPVD and LFC contacted with the same LFC parameter sets as the LFC lifetime samples. 4 point probe resistivity measurements are used to calculate the resistance R_{LFC} of one LFC point. An optical microscope is used to measure diameters of the

LFC points additionally.

2.2 Annealing experiment on RST material

This experiment (400 °C for all annealing steps, τ_{eff} measured with PCD) examines the effect of annealing after passivation of RST wafers with Al_2O_3 (ALD) compared to SiN_x:H (PECVD) on τ_{bulk}. Standard FZ wafers are processed in parallel to determine S_{eff}, so that τ_{bulk} of RST wafers can be calculated from τ_{eff} (assuming that S_{eff} for FZ and RST wafers is equal).

All wafers receive a $POCl_3$ diffusion, are coated with 75 nm SiN_x:H via PECVD on the front side, and are fired in a belt furnace to enhance τ_{bulk} before SiN_x:H and emitter are etched off. A standard wet chemical cleaning followed before the wafers are separated into two groups.

Both groups contain three subgroups: FZ samples, RST batch 1 and RST batch 2. Each subgroup contains four wafers. RST batches vary in resistivity (batch 1: 1 – 2 Ωcm; batch 2: 2 – 3 Ωcm) and some crystallization parameters. The first group is coated with 37.5 nm Al_2O_3 (ALD) on both sides and is annealed for a total of 3 h. Four τ_{eff} measurements are performed in between. The second group is passivated with 37.5 nm SiN_x:H (PECVD) on both sides, annealed for 3 h, fired and annealed a total of 2 h more. Four τ_{eff} measurements are performed after firing. Then, SiN_x:H is etched off and the samples are coated also with 37.5 nm Al_2O_3 (ALD) and annealed for 30 min. τ_{eff} is measured again to compare both groups with the same passivation layer.

2.3 Multi-passivation of RST material

In this investigation some samples of the annealing experiment are processed further. The other samples have received only the standard treatment before (P-gettering, PECVD SiN_x:H-coating, firing, Al_2O_3 surface passivation (ALD) and 1 h annealing at 400 °C). All samples have exactly one Al_2O_3 surface passivation before this experiment.

In this experiment all samples receive three Al_2O_3 surface passivation steps in addition, one after the other. One passivation step includes etching off the old Al_2O_3 passivation, new Al_2O_3 deposition (ALD) and 1 h annealing at 400 °C in N_2 atmosphere. Lifetimes are measured after each step via QSSPC.

2.4 Low temperature annealing, Al metallization and LFC on RST material

This experiment comprises all annealing steps which are used in our solar cell process [2] to establish electrical contacting on front and rear side of the solar cell. But only rear side contacting was realized, so that lifetime measurements with TR-PLI [3] can be applied after each step.

RST samples with different history are used. Some have been used already for the experiments 2.1 and/or 2.2, the others received only the standard treatment before (P-gettering, PECVD SiN_x:H-coating, firing, Al_2O_3 surface passivation (ALD) and 1 h annealing at 400 °C).

To establish front side contacting, a photolithography process is used in our solar cell process [2]. This includes different annealing steps: 30 min at 170 °C, 1 h at 70 °C and a ramp from 70 °C to 105 °C subsequently (~20 min) and 1 h at 100 °C. In this experiment all annealing steps of the photolithography process are applied directly one after another.

To establish rear side contacting, the samples are coated with 2 µm Al on the rear side by EBPVD. During this process (~30 min) the samples are heated up to 220 °C. Then LFC is applied (pitch 0.5 mm and different pump current/frequency sets). An annealing step (40 min, 350 °C) with Al on the rear side follows.

3 RESULTS

3.1 Optimisation of LFC parameters

All stated lifetime values τ_{eff} in this experiment are arithmetic mean values from TR-PL images [3]. τ_{eff} = 1,340 µs is the mean value of seven 1 Ωcm FZ wafers after Al_2O_3 passivation. This corresponds to $S_{eff,Al2O3}$ = 6.0 cm/s. This value was used to calculate $S_{eff,LFC}$ of LFC contacted back sides of the wafers from $\tau_{eff,LFC}$.

Our LFC standard parameters are: pump current 34 A, frequency 1,000 Hz, pitch 0.5 mm. Higher frequency (up to 20,000 Hz) means reduction of pulse energy, smaller LFCs and less damage of the passivation layer. More than 20,000 Hz means that the LFC points become inhomogeneous. That is why LFC parameter sets with frequency 20,000 Hz were used primarily in this examination. The pump current was varied between 27 A and 34 A. Below 27 A, LFC points become also more inhomogeneous. A comparison of results between standard parameter set and the weakest parameter set (27°A, 20,000 Hz) is shown in Tab. I. A pitch of 0.5 mm was used in all parameter sets.

Table I: Comparison of LFC results between standard parameter set and the weakest parameter set.

Parameter set:	**34 A, 1 kHz**	**27 A, 20 kHz**
$\tau_{eff,LFC}$ [µs]	168	545
$S_{eff,LFC}$ [cm/s]	142	33.6
R_{LFC} [Ω]	33.5	93.1
$\varnothing_{LFC}$ [µm]	130	45

Fig. 1 shows all results for frequency 20,000 Hz and pump currents from 34 A down to 27 A.

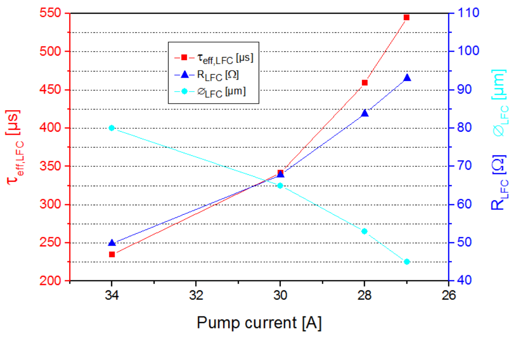

Figure 1: $\tau_{eff,LFC}$, R_{LFC} and $\varnothing_{LFC}$ depending on pump current. Frequency is 20,000 Hz and pitch is 0.5 mm for all measurement points.

3.2 Annealing experiment on RST material

This experiment was carried out to investigate the effect of annealing at 400 °C on τ_{bulk} of RST wafers. Results of this experiment are shown in Fig. 2 and Fig. 3

(QSSPC lifetimes). FZ wafers have been used to determine S_{eff}. With these values, τ_{bulk} was calculated from τ_{eff} for RST wafers. Fig. 2 shows the results of group 1 (passivated and annealed with Al_2O_3). The green curves belong to RST batch 1, the red curves belong to RST batch 2. Triangles show τ_{eff}, squares show τ_{bulk}. Each point in the graph is a mean value calculated from four samples. The graph shows that τ_{bulk} increases for both batches up to an annealing time of 60 min, although only by approx. 0.5 µs. Surface passivation (blue curve) improves up to an annealing time of 120 min.

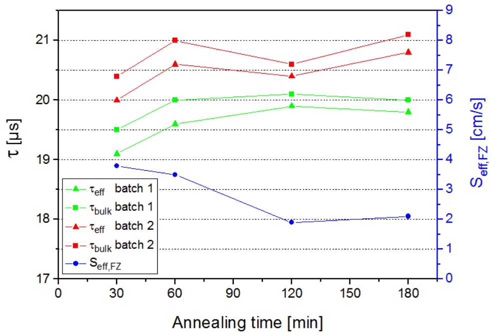

Figure 2: QSSPC lifetime results of group 1. τ_{bulk} was calculated from τ_{eff} with S_{eff} from FZ wafers.

Fig. 3 shows the results of group 2. Each point of the green and blue curves is a mean value calculated from four samples. The red curve depicts only one sample. After deposition of SiN_x:H, the samples were annealed for 3 h in total and were measured several times, but nothing really interesting happened. So, the first point in the graph includes SiN_x:H deposition and 3 h annealing. Then the samples were fired and annealed again. τ_{bulk} of batch 1 improves slightly by approx. 1.5 µs during the first 60 min of annealing. The only sample of batch 2 was annealed only for 30 min. The last step (etching off the SiN_x:H, passivation and annealing with Al_2O_3) shows that $S_{eff,FZ}$ and τ_{eff} of batch 1 reach the same level as in group 1 (Fig. 2) with the same surface passivation layer. τ_{bulk} of batch 1 improves by approx. 1 µs and τ_{bulk} of the sample from batch 2 rises strongly from 24.1 µs to 36.8 µs in this last step.

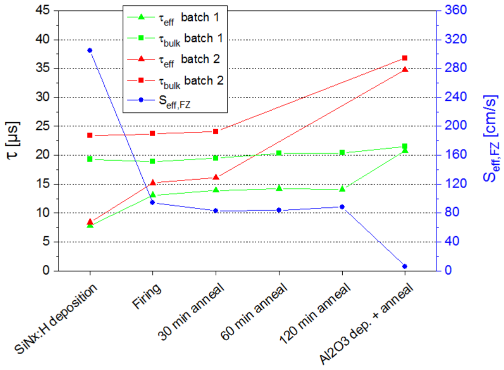

Figure 3: QSSPC lifetime results of group 2. τ_{bulk} was calculated from τ_{eff} with S_{eff} from FZ wafers.

3.3 Multi-passivation, low temperature annealing, Al metallization and LFC on RST material

Multi-passivation induces lifetime improvement of 2 – 5 µs for most RST wafers. But after three passivation steps there is no further improvement visible. Primarily good regions improve by multi-passivation. τ_{eff} of the sample from batch 2 in Fig. 3 could be improved further by multi-passivation up to 39.6 µs (QSSPC measurement). This means a new record for RST material.

In Fig. 4 the effects of multi-passivation, low temperature annealing, Al deposition and annealing on lifetime are depicted by the example of three samples. All three samples are from batch 1 (see 2.2 and 3.2). SF_1 is from group 1 (Fig. 2). SF_2 and SF_3 are from group 2 (Fig. 3). These samples were processed further in this experiment. SF_1 and SF_3 got all process steps (steps 1-3 in Fig. 4). SF_2 got no multi-passivation (step 1 in Fig. 4). Arithmetic and harmonic mean effective lifetime values of TR-PLI measurements are shown in Fig. 4. If primarily good regions improve, the arithmetic mean value increases stronger than the harmonic mean value. If primarily poor regions improve, the harmonic mean value increases stronger than the arithmetic mean value. The three process steps (abscissa in Fig 4) are depicted in Table II (see also 2.3 and 2.4).

Table II: Starting situation and three process steps in Fig. 4

Step	Description
0	Starting situation: One Al_2O_3 passivation, at least 1 h annealing at 400 °C
1	Multi-passivation
2	Low temperature annealing (70 °C – 170 °C)
3	Al deposition and 20 min annealing at 350 °C

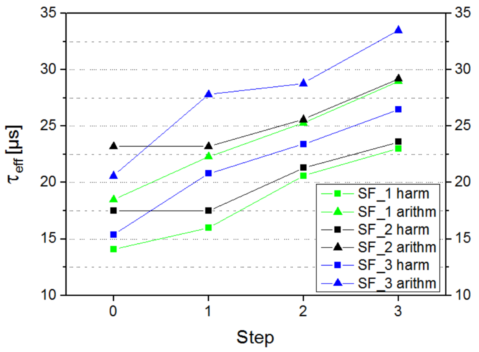

Figure 4: TR-PLI lifetimes after starting situation (step 0) and three process steps (see Table 2).

Fig. 4 shows that the total improvement of the three samples is in the same range (9 – 12 µs in total for all steps). This result corresponds to all other samples which were processed in this way, regardless of the fact that the other samples were not part of the annealing experiment (sections 2.2, 3.2) before and were only annealed for 1 h with Al_2O_3 passivation before this experiment. Furthermore, the increase of lifetime of sample SF_2, which got no multi-passivation (3 times etching off the old Al_2O_3 passivation, new Al_2O_3 deposition (ALD) and 1 h annealing at 400 °C in N_2 atmosphere), behaves similar to SF_1 and SF_3 after step 1.

By comparing the development of arithmetic and harmonic mean values, we can state that the harmonic mean values increase stronger than the arithmetic mean values for all samples during low temperature annealing. For all other process steps the arithmetic mean values increase stronger than the harmonic mean values. This means that low temperature annealing primarily increases the lifetimes of poor quality regions. The other process steps increase primarily the lifetimes of good regions.

Fig. 5 shows TR-PLI images before and after low temperature annealing (left and right map with histogram) of sample SF_3. The left image and histogram reveals that the poorest regions have lifetimes between 3 µs and 7 µs before low temperature annealing. The right image and histogram shows that there is no point with lifetime less than 11 µs after low temperature annealing.

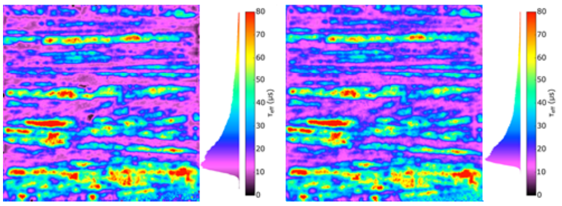

Figure 5: TR-PLI images of sample SF_3. Left: before low temperature annealing. Right: after low temperature annealing. Minimum lifetime increases from 3 µs (left) to 11 µs (right).

Fig. 6 shows TR-PLI images before and after LFC and 40 min annealing at 350 °C. The four marked regions were contacted with different LFC parameter sets. Tab. 3 lists the parameter sets and harmonic mean values of τ_{eff} before and after LFC. Pitch 0.5 mm was used in all regions.

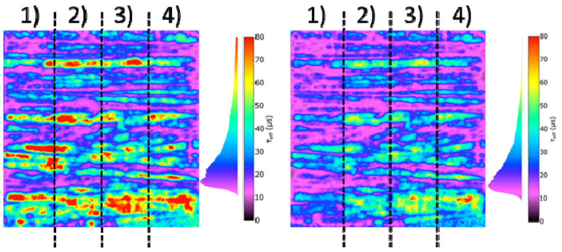

Figure 6: TR-PLI images of sample SF_3. Left: before LFC. Right: after LFC. Four marked regions contacted with different LFC parameter sets (Tab. 3).

Table III: Parameter sets and harmonic mean values of τ_{eff} before and after LFC. Pitch 0.5 mm was used in all regions.

Region	LFC parameter set	$\tau_{eff,harm}$ [µs] before LFC	$\tau_{eff,harm}$ [µs] after LFC
1	34 A, 1 kHz	25.5	18.5
2	30 A, 20 kHz	26.5	22.3
3	28 A, 20 kHz	28.0	24.3
4	27 A, 20 kHz	25.9	22.9

Fig. 6 and Tab. III reveal that also for RST material higher τ_{eff} values are possible with the new LFC parameter sets, which were tested first on FZ wafers (sec. 2.1, 3.1).

4 DISCUSSION

The optimization of LFC parameter sets (sec. 2.1, 3.1) revealed that $\tau_{eff,LFC}$ up to 545 µs and $\varnothing_{LFC}$ down to 45 µm are possible with a frequency of 20,000 Hz and pump currents down to 27 A. Further investigation is necessary to determine the lower limit more precisely. R_{LFC} = 93 Ω and a pitch of 0.5 mm result in a contribution to series resistance of 0.24 Ωcm², compared to 0.09 Ωcm² with standard parameters. This means a decrease of fill factor by ~ 0.7 %. But the higher τ_{eff} should easily overcompensate this disadvantage.

The annealing experiment of RST shows that one time passivation with either Al_2O_3 or SiN_x:H passivation layer and annealing for several hours at 400 °C has only little effect on bulk lifetime. But Fig. 3 reveals that the combination of SiN_x:H passivation, annealing, etching off the passivation layer and afterwards Al_2O_3 passivation and annealing seems to be an effective way to increase bulk lifetime for some kinds of RST material. This effect has to be investigated further.

Multi-passivation with Al_2O_3 is a possibility to increase bulk lifetime of RST material. But improvement is limited to ~ 5 µs and 3 additional passivation steps. Nevertheless, the new record of τ_{eff} = 39.6 µs was reached in this experiment.

The results of low temperature annealing (70 - 170 °C) are promising, because it enables to improve primarily poor regions of RST wafers. Fig. 5 shows that the lifetime of the poorest region of sample SF_3 could be increased from ~ 3 µs to over 11 µs. This effect has to be investigated further and the optimal annealing temperature and time have to be found.

The deposition of Al and subsequent annealing at 350 °C (with Al) leads to further lifetime improvement. This is another promising result which has to be investigated further.

Fig. 6 depicts that the new LFC parameter sets are also beneficial for RST material. Because of the elongated grain structure with closely packed grain boundaries, even smaller or asymmetrical pitches could be beneficial for RST material.

5 CONCLUSION

The results with new LFC parameter sets are very promising and should enable significantly higher V_{oc} in future solar cell experiments.

Different passivation and annealing processes were examined to improve τ_{bulk} of RST material. If applied one after another, a total improvement of more than 10 µs for τ_{eff} compared to a standard passivation treatment was demonstrated in this study. This is a good starting point for further investigation. Particular attention should be paid to the effect of low temperature annealing, because it is a process which primarily improves the bulk lifetime of poor regions.

Finally the new record τ_{eff} = 39.6 µs was set in this study.

6 ACKNOWLEDGEMENTS

Part of this work was funded by the German BMWi (0325581). The content is the responsibility of the authors.

7 REFERENCES

[1] C. Belouet et al., Journal of Crystal Growth 82 (1987) 110.
[2] J. Junge et al., Proceedings 25th European Photovoltaic Solar Energy Conference (2010) 1722.
[3] D. Kiliani et al., Solar Energy Materials and Solar Cells 106 (2012) 55.
[4] F. De Moro et al., Phys. Status Solidi C9(10-11) (2012) 2092.