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Improvement of V_{OC} for thin RST solar cells by enhanced back side passivation

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Abstract

The Ribbon on Sacrificial Template (RST) casting process enables the production of silicon ribbon wafers below 100 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. Furthermore, thin solar cells have lower requirement on the charge carrier lifetime because smaller diffusion lengths are sufficient to separate the carriers. For this contribution, an established lab-type PERC solar cell process was applied on <100 µm thick RST wafers. This cell process was developed further by using an ICP PECVD tool to deposit SiN_x:H as capping layer on the Al_2O_3 passivation layer at the back side of the solar cell. This reduces damaging of the Al_2O_3 passivation layer by ion bombardment using a PECVD tool with direct plasma. With this improvement it was possible to increase V_{OC} to up to 611 mV, which is a new record for 1.5 Ωcm RST material. Furthermore, an efficiency of 16.1 % was achieved which means also a new record for RST material. To compare RST solar cells equitably with standard references, 1 Ωcm FZ wafers and 1-1.5 Ωcm standard multicrystalline wafers with initial thickness of 200-250 µm were etched back to 100 µm and were also processed into solar cells. The effect of wafer thickness and the difference in material quality between RST and standard mc material was analyzed by means of IV data, wavelength depending IQE measurements and LBIC maps.

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Keywords: RST; thin silicon, back side passivation, ICP PECVD

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1. Introduction

The photovoltaic industry has the aim of being cost-competitive to other energy sources as soon as possible. An important issue to lower module production costs is the production cost of the wafer, which still represents ~40 % of the module cost [1]. One way to reduce wafer production costs is to save energy-intensive silicon material. This can be implemented with the RST (Ribbon on Sacrificial Template) process [2], which is a kerf-loss free direct wafer casting method. Furthermore, it enables the production of silicon ribbon wafers with thicknesses down to 50 µm. In this study RST p-type wafers, produced by the company Solarforce SA (France) [3], with initial thickness of 80 - 100 µm and typical minority carrier lifetime of 20 – 30 µs [4] were used for a lab-type PERC solar cell process which was developed to evaluate the efficiency limits of defect-rich, low cost multicrystalline silicon material [5].

Thin solar cells have lower requirements on charge carrier lifetime. But the thinner the cell, back side passivation is all the more important. Because of this requirement, our cell process was developed further by using a Singulus ICP PECVD (inductively coupled plasma plasma-enhanced chemical vapour deposition) tool [6], instead of a direct plasma PECVD tool, to deposit SiN_x:H (30 nm) as capping layer on the atomic layer deposited Al_2O_3 passivation layer at the back side of the solar cell, to reduce damaging of the Al_2O_3 passivation layer by ion bombardment. To find out the optimal parameters for the Al_2O_3/SiN_x:H stack, a preliminary investigation with 2 Ωcm FZ lifetime samples was executed prior to cell processing (see section 2.1 and 3.1).

The cell process (see section 2.2) was performed with 1 - 2 Ωcm RST wafers, 1 - 1.5 Ωcm mc wafers and 1 Ωcm FZ wafers. To evaluate the effect of wafer thickness, some of the mc and FZ standard reference wafers with initial thickness of 200 - 250 µm were etched back to ~100 µm and were also processed into solar cells. IV results of the best cells of each wafer type are presented in section 3.2.1. The effect of wafer thickness and the comparison of material quality between RST and standard mc material were investigated by means of wavelength depending IQE (internal quantum efficiency) measurements and LBIC (light beam induced current) IQE maps and are depicted in section 3.2.2.

2. Experiment

2.1. Back side passivation

Before starting the cell process, a preliminary investigation of the passivation quality of the new Al_2O_3/SiN_X:H stack was made: FZ wafers (5x5 cm^2) with 2 Ωcm resistivity were cleaned with a standard RCA cleaning before Al_2O_3 deposition. Afterwards the wafers of group 1, 2, 5 and 6 (see Table I) were annealed (30 min, 400°C), wafers of group 3,4 were not annealed. Then, all wafers were coated with SiN_x:H and subsequently annealed (20 min, 350°C). Transient photoconductance decay lifetime measurements (PCD) followed. The Al_2O_3/SiN_x:H stack was deposited on both sides of the samples. The results of the lifetime measurements are shown in Table I. Some parameters were varied to find out the optimal process. Concerning SiN_x:H deposition, the gas flow was varied. “high-flow-SiN_x:H” is more dense than “low-flow-SiN_x:H”.

2.2. Cell process

The cell process was performed with RST wafers (80 - 100 µm initial thickness), mc wafers (~200 µm initial thickness) and FZ wafers (~250 µm initial thickness). To evaluate the effect of wafer thickness, some of the mc and FZ standard reference wafers were etched back to ~100 µm in wet-chemical solution (alkaline KOH for FZ and acidic chemical polishing for mc). The front side of each wafer was textured with a plasma etching tool, and by $POCl_3$ diffusion an emitter with sheet resistivity of about 100 Ω/sq was applied. The wafers were coated with a SiN_x:H anti-reflection coating on the front side. The front contact was established by photolithography structuring and evaporation of Ti/Pd/Ag by physical vapor deposition (PVD) followed by Ag electroplating. The back side was passivated with an Al_2O_3/SiN_x:H stack and aluminium was evaporated on top of it. Back contact was realized by laser fired contacts (LFC) and lab-type solar cells have a dimension of 2x2 cm^2.

To reduce damaging of the Al_2O_3 passivation layer by ion bombardment during deposition of the SiN_x:H capping layer on the backside, an ICP-PECVD tool from Singulus was used instead of a direct plasma PECVD tool.

3. Results

3.1. Back side passivation

Table 1. PCD lifetime results on FZ wafers, passivated on both sides with $Al_2O_3/SiN_x:H$ stack.

Group	*Al_2O_3 coating thickness (nm)*	*Al_2O_3 deposition temperature (°C)*	*Annealing after Al_2O_3 deposition*	*$SiN_x:H$* deposition gas flow	*Lifetime @ MCD 1E15cm^{-3} (ms)*
1	7.5	170	yes	low flow	3.07
2	7.5	170	yes	high flow	3.60
3	7.5	170	no	low flow	2.78
4	7.5	170	no	high flow	2.30
5	7.5	300	yes	low flow	1.46
6	15.0	170	yes	low flow	4.32

Each group comprises two lifetime samples. Hence, the stated lifetime values are arithmetic mean values in each case of two samples. In former cell processes an Al_2O_3 coating thickness of 7.5 nm and Al_2O_3 deposition temperature of 300 °C were applied for back side passivation and the samples were not annealed prior of $SiN_x:H$ deposition. In the latest experiment the parameters of group 2 were applied because of the improved lifetime result. The parameters of group 6 were not chosen, because it is not clear if a thicker Al_2O_3 coating could degrade the backside contacting via LFCs. Further investigation is necessary to determine this influence.

3.2. Cell results

3.2.1. IV results

Table 2. IV-parameters of the best solar cells from RST wafers, mc and FZ references with single layer anti-reflection coating (SARC).

Wafer type	*Coating*	*Thickness (µm)*	*Resistivity (Ωcm)*	j_{SC} (mA/cm^2)	*V_{OC} (mV)*	*FF (%)*	*η (%)*
RST	SARC	70	1.5	32.4	609	76.9	15.2
mc thin	SARC	95	1 – 1.5	34.5	632	78.8	17.2
mc thick	SARC	170	1 – 1.5	34.8	631	78.6	17.3
FZ thin	SARC	95	1	35.3	641	80.4	18.2
FZ thick	SARC	220	1	36.3	643	80.1	18.7

IV results of the best cells with single layer anti-reflection coating (SARC) on plasma textured surface are presented in Table 2. The IV measurements are performed under standard test conditions (AM 1.5G, 25 °C). Regarding only the thin solar cells there is a gap of 2 $\%_{abs}$ between the best RST solar cell and the best mc solar cell and a gap of 3 $\%_{abs}$ between RST and FZ. The comparison between thick cells and thin cells show, that the thick solar cell made of FZ material gains 1 mA/cm^2 in comparison to the thin one, while the thick mc solar cell supplies only 0.3 mA/cm^2 more current density than the thin one. For both types of material thin cells exhibit slightly higher fill factors (FF) than thick cells while open circuit voltages (V_{OC}) are comparable. The efficiency of the thick FZ cell is ultimately 0.5 $\%_{abs}$ higher than the efficiency of the thin FZ cell. The thick standard mc cell gains only 0.1 $\%_{abs}$ compared to the thin standard mc cell. Both mc cells are from neighbouring wafers, so that the material quality should be similar.

To reach the best possible results in efficiency, the best RST and FZ cells were coated additionally with MgF_2 on top of the cell to get a double layer anti-reflection coating (DARC), which reduces reflexion and enables to couple more light into the solar cell. IV results of the best cells with DARC are shown in Table 3. A V_{OC} of 611 mV is promising for RST solar cells with a resistivity of ~1.5 Ωcm and means an improvement compared to former experiments [7]. The efficiency of 16.1 % is a record for solar cells made of RST material. The efficiency of 19.8 % for the thick FZ cell is a good value, taking account of the applied solar cell process, which was optimized for defect-rich, low cost multicrystalline silicon material [5].

Table 3. IV-parameters of the best RST and FZ solar cells with double layer anti-reflection coating (DARC).

Wafer type	*Coating*	*Thickness (µm)*	*Resistivity (Ωcm)*	j_{SC} (mA/cm^2)	V_{OC} *(mV)*	*FF (%)*	η *(%)*
RST	DARC	70	1.5	34.1	611	77.0	16.1
FZ thick	DARC	220	1	38.2	644	80.2	19.8

3.2.2. IQE measurements

To evaluate the effect of wafer thickness versus material quality, wavelength depending IQE curves (Fig. 1) from the best RST, thin mc, thin FZ and thick FZ cells were analyzed. The effect of material quality is visible in the entire wavelength range. This is shown in the fact, that IQE of the RST cell is always lower than for the thin mc cell, and IQE of the thin mc cell is always lower than for both FZ cells for each wavelength. The effect of wafer thickness is visible at wavelengths >890 nm (absorption length: >29 µm), where the IQE curves of the two FZ solar cells separate. Comparing the thin mc cell with the two FZ cells it seems that the effect of wafer thickness is dominant from a wavelength of ~1030 nm (absorption length ~330 µm), where the IQE of the thin FZ solar cell is closer to the IQE of the thin mc solar cell than to the thick FZ solar cell. For wavelengths <1030 nm the difference in bulk quality dominates. Comparing the RST cell with the two FZ cells the limit is 1060 nm, but it should be noted, that the RST cell is even thinner than the thin cells made from FZ and mc material. IQE at wavelength <500 nm cannot be reported because absorption in SiN$_x$:H anti-reflection layer on the front side is unknown.

To compare the material quality of RST wafers with mc standard wafers, some LBIC-IQE maps of the second best RST cell and the best thin mc cell were recorded (Fig. 2). A wavelength of 980 nm was used for excitation. The

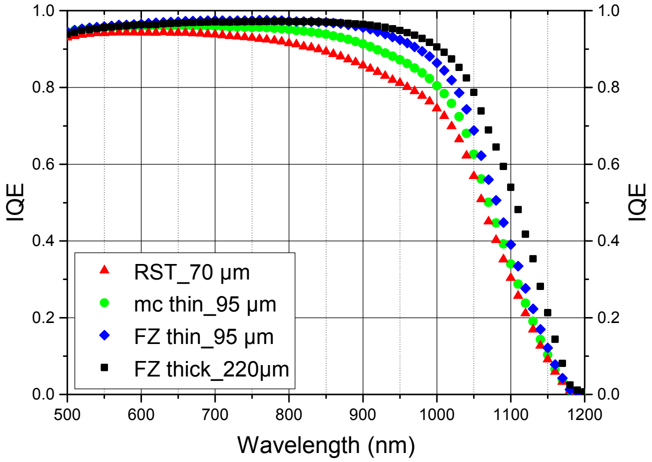

Fig. 1. Wavelength depending IQE curves of the best solar cells made from RST, thin mc, thin FZ and thick FZ wafers.

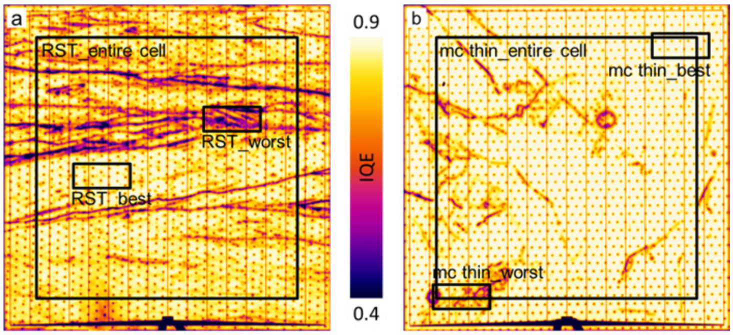

Fig. 2. LBIC-IQE images (excitation with 980 nm light beam): a) RST cell; b) thin mc cell. The black framed rectangles display the areas, from where the IQE curves in Fig. 3 were recorded. The “entire cell”-rectangles measure 16x16 mm^2 and comprise almost the whole cells. The small rectangles indicate the best and worst areas of the cells and measure 3.5x1.5 mm^2.

images show that the RST cell exhibits on the one hand much more defect-rich areas with IQE < 0.7 (red and purple zones in the image) than the mc cell and also the best zones of both cells differ in quality. The most frequently measured IQE value (mode) of the RST cell is 0.85 (yellow in the image), the mode of the mc cell is 0.89 (almost white in the image).

IQE curves were recorded from the areas which are indicated by black framed rectangles. The “entire cell”-rectangles measure 16x16 mm^3 and comprise almost the whole cell area. The small rectangles indicate the best and worst areas of the cells and measure 3.5x1.5 mm^3. These IQE curves are presented in Fig. 3. The thin mc cell is only slightly thicker than the RST cell. This means, that the IQE curves point out essentially differences in material quality. It is conspicuous that the IQE curve of the entire RST cell exhibits only slightly higher IQE values than the IQE curve of the worst area of the thin mc cell. And the IQE curve of the best area of the RST cell has even slightly lower IQE values than the IQE curve of the entire mc cell. Regarding only the worst areas of both cells, there is a big difference up to ~20 %$_{abs}$ between the IQE values. Effective diffusion lengths are also listed in Fig. 3. They are obtained from the fit of IQE values between 800 nm and 1000 nm according to the Basore model [8].

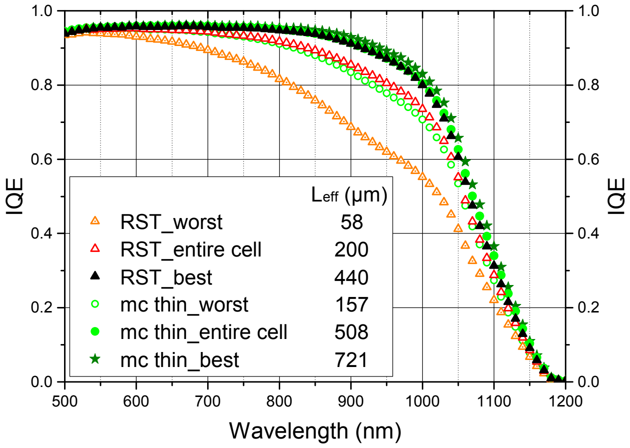

Fig. 3. Wavelength depending IQE curves of the second best RST cell and the best thin mc cell. The curves are obtained on specific areas of the cell. These areas are indicated by black framed rectangles in Fig. 2.

Combining the results of LBIC-IQE measurements (Fig. 2) and wavelength depending IQE measurements of specific areas on the RST and thin mc cell, we conclude that the RST cell is less efficient both in the best and in the worst areas than the thin mc cell and the percentage of defect-rich areas is additionally much larger in the RST cell.

This explains the gap of j_{SC}, V_{OC} and FF between RST and standard mc cells and leads to the gap of 2 %$_{abs}$ in efficiency between the best RST cell and the best thin mc cell.

4. Discussion

The IQE measurements in section 3.2.2 show that there is a considerable difference in material quality between RST wafers and standard materials. If we want to produce nonetheless solar cells with high efficiency and with V_{OC} values significantly above 600 mV, we have to produce thin solar cells with good back side passivation. A clear effect of back side passivation is visible if the diffusion length of minority charge carriers in the base L_n is higher than the thickness of the base [9]. If in addition the surface recombination velocity S is lower than the recombination velocity of minority charge carriers in the silicon crystal S_∞, the base saturation current density decreases and a higher V_{OC} can be reached (see e.g. [9]).

The cell result of the best thick FZ cell (Tab. 2 and 3) shows that our cell process is not optimal for FZ material, because V_{OC} values of over 660 mV have been published by many groups using lab-type PERC processes. Part of the limitation can be explained by the comparably low LFC pitch, which was optimized to the small grain size of the RST material to avoid the situation that holes (majority charge carriers in the base) have to cross too many grain boundaries before collected at the rear contacts. And the LFCs impair the back side passivation. The emitter plays an important role on the other hand and is not optimized yet. But if we focus the attention on back side passivation and compare V_{OC} values of the best thick and thin FZ cells (Tab. 2), it can be seen that the loss in V_{OC} is small if we go to thinner cells. If we compare the V_{OC} values of the best thick and thin mc cells we found no loss in V_{OC}. There is even a slight increase detectable. These results are confirmed by the V_{OC} results of the other FZ and mc cells, which are not presented in this contribution. This means that S on the back side is at least in the range of the recombination velocity in the silicon crystal S_∞ of the mc cells. S_∞ is inversely proportional to L_n [9]:

$$S_\infty = \frac{D_n}{L_n} \qquad (1)$$

D_n is the diffusion coefficient of the minority charge carriers in the base. If L_n values of RST and thin mc cells are in the range of the L_{eff} values listed in Fig. 3, we have:

$$\frac{S}{S_{\infty,RST}} < 1 \qquad (2)$$

This means that with the applied back side passivation S is lower than the recombination velocity of the minority charge carriers in the silicon crystal of the RST material $S_{\infty,RST}$. If this ratio is <1, the base saturation current density decreases, compared to a solar cell which is assumed to be infinitely thick [9]. Further improvement of back side passivation can result in even lower base saturation current density and thus higher V_{OC} values.

In former experiments with comparable RST material, V_{OC} of the produced solar cells was limited to ~604 mV. In this experiment the back side passivation was improved by using an ICP PECVD tool [6] to deposit SiN_X:H as capping layer on the Al_2O_3 passivation layer at the back side of the solar cell to reduce damaging of the Al_2O_3 passivation layer by ion bombardment. The preliminary investigation with lifetime samples (see section 3.1) shows higher effective lifetimes on FZ material with the new process. And with the improved cell process a V_{OC} of 611 mV was reached with RST material. This significant improvement is understandable with the explanation above. A further result of this analysis is that solar cells from RST material improve in V_{OC} if they become thinner. Precondition for this is also equation (2).

Regarding back side passivation, further improvement is possible by optimization of Al_2O_3 coating thickness (Tab. 1, lifetime result of group 6). This investigation has to be combined with optimizing the LFCs, because a thicker passivation layer could change backside contacting via LFCs.

The current losses due to reduction of solar cell thickness, which are found for FZ and mc cells (see section 3.2.1) are caused by limited Si absorption. This is visible in the IQE curve (Fig. 1) at wavelengths > 890 nm (absorption length: >29 µm). Absorption length l_α 29 µm means, that the intensity of an incident light beam $I(l)$ decreases to ~4 % at 95 µm penetration depth l (cell thickness of thin FZ cells).

$$I(l) = I_0 exp(-l/l_\alpha) \tag{3}$$

At longer wavelengths the absorption length increases strongly and the effect of wafer thickness is clearly visible in the IQE curves (Fig. 1).

5. Conclusion

It was shown that there is still a significant difference in material quality between RST and standard mc material. But the small thickness (70 µm in this experiment) of RST wafers could be utilized to improve V_{OC} by enhancement of back side passivation. A V_{OC} of 611 mV for 1.5 Ωcm RST solar cells is promising, because a limit of ~604 mV was found in former cell results with comparable material [7]. The achieved efficiency of 16.1 % means also a new record for solar cells made of RST material. The efficiency of FZ solar cells becomes significantly worse if the cells become thinner due to limited absorption. The main reason is the loss in IQE starting from a wavelength of 890 nm due to limited Si absorption, while there is only a small loss in V_{OC}. mc cells have only small losses in current density and no loss in V_{OC} if they become thinner (with the applied back side passivation). This can be explained by the lower bulk material quality as compared to FZ material. Thin RST cells are able to improve significantly in V_{OC} if back side passivation is getting better and have probably only small losses in current density if they become thinner (down to 50 µm).

Variation of Al_2O_3 coating thickness can result in further improvement of back side passivation, but has to be combined with optimizing of the LFCs.

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