INVESTIGATION OF VARIOUS SURFACE PASSIVATION LAYERS USING OXIDE/NITRIDE STACKS OF SILICON SOLAR CELLS

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ABSTRACT

In this work, three different surface passivation technologies are used: classical thermal oxidation (CTO), rapid thermal oxidation (RTO) and silicon nitride using PECVD. Eight combined passivation schemes including SiO_2/SiN_x stacks are investigated on 1 Ω cm FZ silicon without and with emitter (100 Ω/□ and 40 Ω/□). SiO_2/SiN_x stack passivation results in excellent lifetime of 1361 µs without emitter and shows as a good passivation quality as CTO (300-400 µs) for 100 Ω/□ emitter. The RTO/SiN_x stack layers are used to passivate front and rear surfaces of the solar cells. The planar RTO/SiN_x cell has a very high V_{oc} of 675.6 mV. However, the J_{sc} and FF of the RTO/SiN_x cells are lower than those of CTO cells. The main reasons of J_{sc} and FF losses are also discussed.

1. INTRODUCTION

For high-efficiency solar cells, low surface recombination and high effective lifetimes are both significantly important. Normally, the classical thermal oxidation (CTO) at high temperatures is used for laboratory high efficiency solar cells as passivation of the rear and front surface while for the industry solar cells, TiO_2 and either no passivation or Al back surface fields are used on the front and rear surface, respectively.

Rapid thermal oxidation (RTO) and SiN_x are the alternative passivation layers can be grown/deposited using fast and cost-effective methods. RTO is grown very fast (< 5min.) and an efficiency 19.1 % [1] can be reached for solar cells passivated by 12 nm thick RTO. SiN_x by plasma enhanced chemical vapor deposition (PECVD) is deposited at low temperatures (≥400 °C) and has additional advantages, e. g., the adjustable refractive index and the higher passivation quality.

The aim of this work is to study systematically and comprehensively the different passivation technologies for solar cells without and with emitter. Furthermore, the oxide/silicon nitride stacks layers are investigated. Finally, the optimal layers are used in fabrics of the solar cells.

2. EXPERMENTS

2.1. Passivation for without and with emitter

1 Ω cm p-type FZ silicon materials of 250 µm thickness were used in this work in order to investigate passivation quality of the various layers.

After RCA cleaning wafers without and with emitter diffusion were coated with various passivation layers. Emitters were diffused on both sides in a classical furnace since the sheet resistance of the emitter should not be changed after the passivation processing for an accurate measurement. The study was performed on emitters with 100 Ω/□ and 40 Ω/□ to be applicable to high efficiency and industrial solar cells.

CTO at temperatures of 1050 °C for 38 min results in an oxide thickness of approximately 105 nm, which is used in high efficiency solar cells as an emitter passivation and antireflection coating (ARC). RTO was grown at temperatures of 1050 °C for 2 min resulting in an oxide thickness of about 12 nm. SiN_x by PECVD was performed in two different process parameters and is therefore referred to as SiN1 and SiN2. The thickness of both SiN_x layers is about 60 nm and the refractive index was measured 2.8 for SiN1 and 2.2 for SiN2.

The effective carrier lifetime was measured by means of the microwave-detected photoconductance decay (MWPCD) technique under 0.5-sun illumination after forming gas annealing (FGA) at 425 °C for 25 min.

2.2. Solar cell structure and process sequence

0.5 Ω cm p-type FZ silicon materials with a thickness of 250 µm were used for solar cells. The cell size was 2×2 cm^2, seven cells were processed on one 4 inch diameter wafer. Both planar and textured solar cells with inverted pyramids were passivated with RTO/SiN_x stacks.

After standard RCA cleaning, a masking oxide was grown on the wafer with a thickness of 200 nm (Fig. 1). Using photolithography technology, the front surface of some cells was textured with inverted pyramids. The emitter was formed in a classical furnace resulting in the sheet resistance of about 120 Ω/□. The front and rear surface of cells were passivated by RTO simultaneously at temperatures of 1050 °C for 120 s resulting in a thickness of 10-12 nm. Two different SiN_x layers, SiN2 and SiN1 were deposited on front and rear surface, respectively. After etching of the rear and front contact grids by means of PECVD the rear and front were metallized with Al 2 µm and Ti/Pd/Ag, respectively. Finally, solar cells were annealed at temperatures 310 °C for 25 min for the metal contacts. MgF was deposited to a thickness of about 110 nm.

3. RESULTS AND DISCUSSION

3.1. Passivation quality without and with emitter

Silicon surface passivation by SiO_2(1), SiN_x(2), SiO_2/SiN1(3), and SiO_2/SiN2(4) stacks was investigated on wafers without and with emitter as shown in Fig. 2.

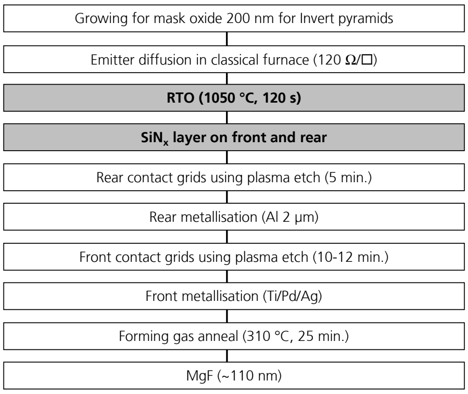

Figure 1: Processing sequence for simplified PERC cells passivated with RTO/SiN_x stacks.

Oxides (1): Passivation of both SiO_2 layers on the 100 Ω/□ is 2-3 times better than on the without emitter. It is well known that SiO_2 layer passivates better on n-Si than on p-Si. This behavior is due to the high σ_n/σ_p ratio of 100 [2].

SiN_x (2): SiN1 is an excellent passivation layer resulting in an effective lifetime 897 µs while SiN2 is an relatively good layer resulting 315 µs on the without emitter. However, on the emitter with 100 Ω/□ and 40 Ω/□ both SiN_x layers showed a decreased τ_{eff}. The improved τ_{eff} of SiN_x layers on pure p-Si is contributed by the field effect passivation. A high positive charge density, Q_f at the interface results in a inversion layer and repels holes from the surface. Therefore, Shockley-Read-Hall recombination at the silicon surface is strongly reduced.

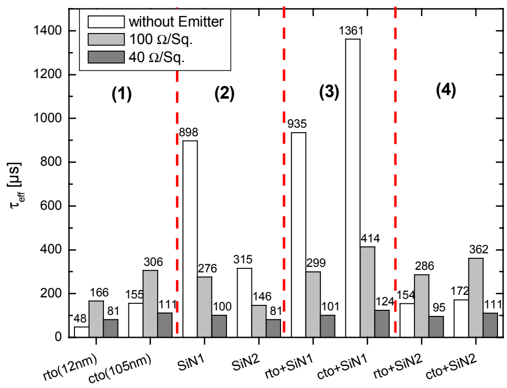

Figure 2: Comparison of the effective carrier lifetime achieved with eight different surface passivation schemes on 1 Ω cm FZ-Si without and with emitter.

Oxide/SiN1: τ_{eff} values for the RTO/SiN1 and CTO/SiN1 stack layers are observed 935 µs and 1361 µs on pure p-Si, respectively, whereas τ_{eff} reduces by a factor of 3-4 on the emitter. We assume that the improvement of τ_{eff} for the oxide/SiN1 stack on pure p-Si is attributed a combined to effect of advantages of both oxide and nitride layer, i. e., the low D_{it} at Si-SiO_2 interface and the high Q_f resulting the field effect in SiN_x layer.

Oxide/SiN2: The behavior of the oxide/SiN2 stack is inverted to that of oxide/SiN1 stack. τ_{eff} on the pure p-Si is inferior to the single SiN2 layer whereas the passivation on 100 Ω/□ emitter is superior to the single SiN2 layer. This difference can be due to the different deposition parameters resulting in different passivation qualities.

3.2. Solar cells

The best results for each type of solar cells are summarized in table I. The samples, Refl and Ref2 passivated with an oxide of thickness 105 nm were used as a reference for the RTO/stacks passivated solar cells.

Table I. Solar cell results with respect to different front structures and different parameters.

parameter	No2_3	No8_2	Ref1	Ref2
Ω cm	0.5	0.5	0.5	0.5
structure	planar	invert	planar	invert
Front	RTO/SiN2 /MgF	RTO/SiN2 /MgF	CTO	CTO
rear	RTO/SiN1	RTO/SiN1	CTO	CTO
Grids etch	plasma	plasma	Chemi.	Chemi.
V_{oc} [mV]	675.6	662.4	678.5	675.7
J_{sc} [mA/cm^2]	35.1	36.8	32.3	37.9
FF [%]	78.1	77.2	80.7	80.6
η [%]	18.5	18.2	17.7	20.1

The planar RTO/SiN_x cell has a high V_{oc} of 675.6 mV and a J_{sc} of 35.1 mA/cm^2. In comparison to the CTO cell (Refl) V_{oc} and J_{sc} are only 2.9 mV (0.4 %) lower and 2.8 mA/cm^2 (8.6 %) higher, respectively. On the other hand, V_{oc} and J_{sc} of the inverted pyramids RTO/SiN_x cells are both reduced by 13.3 mV (2 %) and 1.1 mA/cm^2 (3 %) in comparison to the inverted pyramids CTO cells, respectively. The planar and textured RTO/SiN_x cells have lower FF than reference cells.

The reasons for the observed losses for the RTO/SiN_x cells could be explained as follows:

A. Higher reflection losses
B. higher recombination in the bulk and the surfaces
C. Light absorption in the layer
D. Inferior dark parameters

A. Higher reflection losses

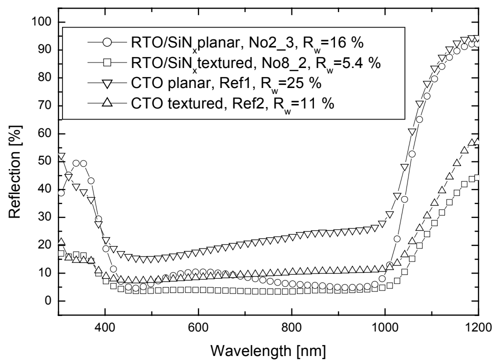

Figure 3: Reflection of four different types of solar cells.

First, an optical reflection measured on four different types of solar cells was carried out. As shown in Fig. 3 the weighted reflection, R_w of both RTO/SiN_x/MgF cells are lower than reference cells. Especially, the R_w of 5.4 % can be obtained by textured cells passivated with RTO/SiN_x/MgF. Note that the reflection was measured including the metallization, fingers. Therefore, the loss in J_{sc} of RTO/SiN_x textured cells can not be attributed by an optical reflection.

B. Higher recombination in the bulk and at surfaces

Fig. 4 shows the internal quantum efficiency (IQE) of four different types of solar cells. Both RTO/SiN_x stack cells and both CTO cells have a similar IQE over 1000 nm. A hump of both planar cells (No2_3 and Ref1) in long wavelengths over 1000 nm can be caused by drastically increased reflection in Fig. 3. In comparison to CTO cells, both RTO/SiN_x stacks cells have a reduced IQE in short wavelengths (>500 nm) and in long wavelengths (<800 nm) while both have a identical IQE in the intermediate wavelengths. It is concluded that RTO/SiN_x stacks cells have a weak passivation at the front and rear surface.

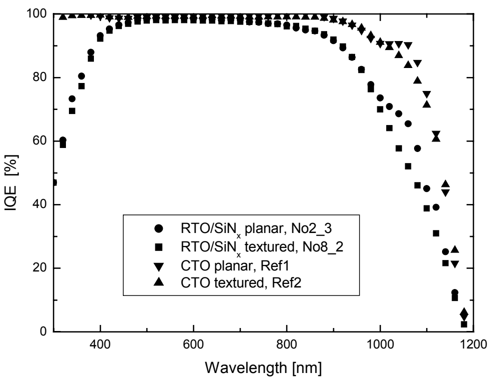

Figure 4: Internal quantum efficiency (IQE) of four different types of solar cells.

In order to investigate the reason for these losses, the effective diffusion length, L_{eff} was determined from the measured IQE using the method from [3].

Table II shows the calculated L_{eff} and S_{eff} from IQE for four different types of solar cells. Both RTO/SiN_x cells (No2_3 and No8_2) have lower L_{eff} values (300-400 μs) while the CTO reference cells have high L_{eff} values over 1000 μs. The S_{rear} of RTO/SiN_x cells is 3-4.5 times lower than of the CTO reference cells.

Table II. Calculated parameters from IQE.

parameter	No2_3	No8_2	Ref1	Ref2
L_{eff} [μm]	370	270	1120	1250
S_{rear} [cm/s]	750	1000	250	222
$S_{rear,max}$ [cm/s]	2300	13400	277	320

The V_{oc} of RTO/SiN_x cells is high. Therefore, the bulk lifetime and the SRV at an injection level corresponding to 1-sun illumination (over 10^{15} cm^{-3}) have to be good [4]. It is possible that the bulk lifetime and the surface passivation quality at the low level injections (about 10^{13} cm^{-3}) corresponding to short-circuit conditions be lower.

In order to investigate the dependence of lifetime on the injection level, the quasi-steady photoconductance method (QSSPC) was used on the lifetime test samples (see Fig. 2 in section 3.1). As shown in Fig. 5 the τ_{eff} of the RTO/SiN_x cell, is higher than CTO reference cells not only at the high injection, but also at the low injection. Thus, the reason of a low J_{sc} and high SRV of RTO/SiN_x cells cannot be explained by this assumption.

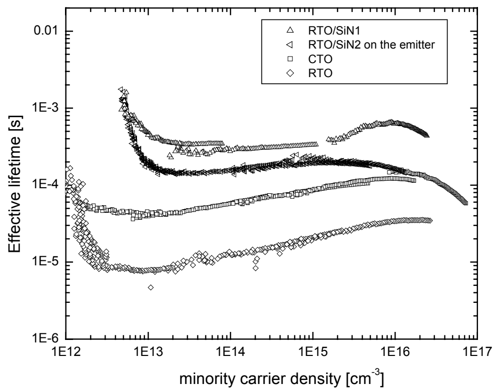

Figure 5: Effective lifetime for 1 Ω cm p-type FZ-Si passivated with different layers on both surfaces measured with QSSPC. RTO/SiN2 stack layer passivates on the 100 Ω/□ emitter.

Another reason could be that passivation qualities of RTO/SiN_x stack layers would be different between on the surface without metal contacts (test wafer) and with metal contacts (solar cells). The band structure under the SiN_x layer is bended caused by a high Q_f and this results in an inversion layer at the silicon surface. Electrons are accumulated at the surface and form a shallow n^+ inversion layer which acts as a floating junction passivation layer [5]. However, a parasitic shunt between the floating and the real metal contacts caused a decrease of V_{oc}, J_{sc} and fill factor [6].

On the other hand, the parasitic shunt is not critical in SiO_2 passivated cells, since SiO_2 layers contains the low Q_f resulting in no or only weak inversion layer. Dauwe et al. [7] have investigated the influence of the SiN_x and SiO_2 layer on solar cells as a rear surface passivation. SiN_x passivated cells had a lower J_{sc} and FF than SiO_2 passivated cells while SiN_x/SiO_2 cells which are passivated with SiO_2 lines of about 200 μm width around the metal contacts and with SiN_x layer on remaining areas had the same J_{sc} and FF as SiO_2 passivated cells.

C. Light absorption in the layer

The SiN2 layer which was used the passivation on front surface of solar cells can absorb light in the layer resulting in current losses. To account for J_{sc} losses due to the absorption in the layer, the wavelength dependent refractive index is needed for the analysis. The wavelength dependent refractive index N of a medium can be represented by a real part and an imaginary part (N=n-ik). The absorption coefficient α is relative to the imaginary, i.e., the extinction coefficient k ($\alpha=4\pi k/\lambda$).

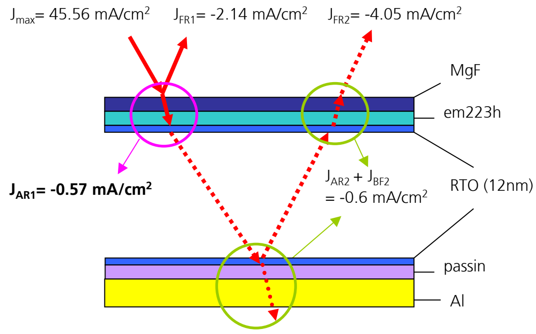

Figure 6: Improved simulation of optical performance using the enhanced model with a wavelength dependent.

The improved model of an optical performance by Schumacher [3] was used in order to calculate the absorption on the RTO/SiN2 stack layers. Fig. 6 shows the different current losses due to absorption in the front and rear layer and the reflection of the different layers. Those different J losses are explained on the following:

- J_{max} = 45.56 mA/cm^2: Maximum current if all incident light generates photon current.
- Loss J_{FR1} = 2.14 mA/cm^2: Loss due to the reflection of the front surface. It is calculated by setting the rear reflection infinite ($R_b = \infty$) and the medium is absorption zero, i. e., R = 1-T.
- Loss J_{AR1} =-0.57 mA/cm^2: Loss due to the absorption in the front layer. It is calculated by setting the rear reflection infinite ($R_b = \infty$), i. e., R = 1-(T+A).
- Loss J_{FR2} = 2.14 mA/cm^2: Loss due to the external reflection in the front surface of the reflected light on the rear surface. It is calculated by setting the rear reflection finite ($R_b \neq \infty$) and the medium absorption zero, i. e., R = 1-T.
- Loss J_{AR2} + J_{BF2}=-0.6 mA/cm^2: Loss due to the front and rear absorption of the reflected light on the rear surface. It is calculated by setting the rear reflection finite ($R_b \neq \infty$) and the medium absorption zero, i. e., R = 1-(T+A).

D. Inferior dark parameters

Table III shows the measured dark parameters of four different types of cells. Unfortunately, No2_3 could not fitted with two-diode model because of a 'hump' in the dark I-V curve caused by high n_2 (about 5) while other cells are ideal (n_1=1, n_2=near of 2).

Table III. Measured dark parameters of four different types of solar cells.

Parameter	No2_3	No8_2	Ref1	Ref2
J_{01} [10^{-13} A/cm^2]		1.88	86	1.09
J_{o2} [10^{-9} A/cm^2]		79.7	2.71	6.77
R_s [Ω cm^2]		0.99	0.64	0.5
R_p [Ω cm^2]		2×10^8	>1e10	3×10^6
n_1		1	1	1
n_2		2.29	1.89	2

In comparison to CTO reference cells, the J_{02} and R_s of RTO/SiN$_x$ cells are higher. We assume that during the plasma etching, which was used due to open the front and rear metal grids, not only SiN$_x$, but also the emitter is etched since the plasma-etch process is not optimized [8]. Therefore, the surface concentration of the plasma-etched emitter is lower than that etched with chemistry. Furthermore, the non-optimal plasma etching can damage the cell surface. It induces electrically active defects which causes a high J_{02} and R_s.

4. CONCLUSION

The various surface passivation layer were investigated in this study: CTO, RTO, two different SiN$_x$ layers, and combined SiO$_2$/SiN$_x$ stack layers. On the emitter, both oxide layers and SiO$_2$/SiN2 stack layers passivate relatively good while the SiN$_x$ and SiO$_2$/SiN1 stack layer passivate better on the without emitter. Especially, the τ_{eff} for the SiO$_2$/SiN1 stack layer results in over 1000 µs on the 1 Ω cm FZ materials.

The efficiency potential of RTO/SiN$_x$ stack layers passivated cells with planar surface and textured surface with inverted pyramids has been investigated. The excellent V_{oc} of 675.6 mV and high J_{sc} of 35.1 mA/cm^2 is obtained for the planar cell with RTO/SiN$_x$ stack. However, all RTO/SiN$_x$ cells have lower J_{sc} and FF than the CTO reference cells. Three main reasons of the losses of J_{sc} and FF could be considered: (1) Contribution by the parasitic shunt current between the strong inverted layer at the rear surface due to high Q_f and metal rear contacts. In the dark-condition related to J_{sc} the parasitic shunt current has a significant impact on S_{eff} and reduces J_{sc} and FF. (2) The loss J_{sc} of 0.57 mA/cm^2 due to an absorption in the SiN2 layer was calculated. (3) High J_{02} and R_s caused by etched and damaged emitter due to the non-optimal etch process by PECVD.

ACKNOWLEDGEMENTS

The authors would like to thank Professor W. Wettling for fruitful discussions, T. Leimenstoll and E. Schäffer for the fabrication of solar cells and for measurement of solar cells. J. Y. Lee is supported by a funding program for female scientists of the Fraunhofer Society.

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