LIFETIME INVESTIGATIONS ON SCREENPRINTED SILICON SOLAR CELLS

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ABSTRACT: The PCVD (Photo Current/Voltage Decay)-method supplies a possibiliy to determine the effective backside recombination velocity S_B and the emitter saturation current I_{0E} if the bulk diffusion length L_n of the solar cell is known. An evaluation method is described which allows under inclusion of a spectral response measurement the determination of all three parameters L_n, S_B and I_{0E}. The applicability of the method to characterize screenprinted silicon solar cells is demonstrated. The emitter saturation current of different $POCl_3$-diffused and screenprinted emitters is measured and compared with calculated values using the programm PC1D. The bulk-passivation due to a fired silicon nitride is shown. Even on mechanically V-textured screenprinted solar cells the emitter saturation current is mesured. Finally, with CV-measurements the influence of the deposition parameters on the interface properties of LF-PECVD silicon nitride layers is measured.

Keywords: Characterisation: 1 - Silicon Nitride: 2 - Lifetime: 3

The passivation of the front and the back surface of conventionally processed screenprinted silicon solar cells is investigated. The process sequence is shown in Fig. 1.

defect etching
↓
$POCl_3$-diffusion
↓
dicing of the parasitic junction
↓
PECVD silicon nitride deposition
↓
back and front contact screenprinting
↓
co-firing

***Fig. 1**: The process sequence of screenprinted solar cells. The front metallization is fired through the silicon nitride in the final co-firing step.*

After the defect etching and the $POCl_3$-diffusion a silicon nitride antireflection coating (ARC) is deposited in a commercial direct plasma LF-PECVD reactor (f = 50 kHz). A full area aluminium back contact and the front metallization pattern are screenprinted. In a final co-firing step the back surface field (BSF) is formed and the front contact is fired through the nitride. The hydrogen containing silicon nitride acts as a passivating layer. In the high temperature co-firing step hydrogen migrates to the silicon surface and along grain boundaries into the multicrystalline material. A passivation of the surface and the bulk in the case of multicrystalline material is the consequence [1].

THE PCVD (PHOTO CURRENT/VOLTAGE DECAY)-METHOD

The PCVD (PhotoCurrent/Voltage Decay) method is a lifetime measurement on finished solar cells. The cells are illuminated with a short light pulse and the exponential decay of the short circuit current and the open circuit voltage are measured [2,3]. Fig. 2 shows the experimental setup. A GaAs laser diode with a wavelength of 905 nm and a risetime of 100 ns illuminates the solar cell. The constant bias light defines the injection level of the measurement.

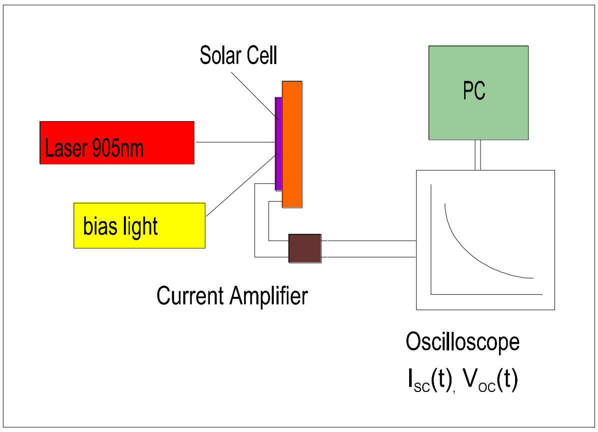

***Fig. 2:** The experimetal setup of the PCVD-measurement.*

The exponential decay rate of the current τ_J is a function of the diffusion length L_n and the effective surface recombination velocity (SRV) at the backside S_B. The inclusion of the effective diffusion length L_{eff} [4] which is determined from a linear fit of the inverse internal quantum efficiency (IQE) versus the inverse absorption coefficient from the measurement of the spectral response allows a simple separation of L_n and S_B.
The τ_J as well as the L_{eff} are functions of L_n and S_B. These two functions can be solved for $S_B(L_n)$. Fig. 3 shows the graphical representation of the $S_B(L_n)$-functions from the τ_J (PCVD) and from the L_{eff} (SR). The τ_J and the L_{eff} were measured on a screenprinted solar cell made of CZ-material. The point of intersection supplies L_n and S_B which is the only solution of both functions. In the following this kind of figure is called parameter-plot $S_B(L_n)$.

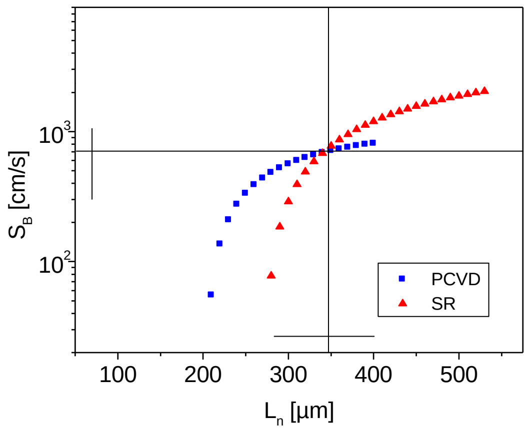

Fig. 3: *The parameter-plots $S_B(L_n)$ from the τ_J (PCVD) and the L_{eff} (SR). The point of intersection supplies L_n and S_B. The bars parallel to the graph axis give the uncertainty of the measurement.*

For the construction of the parameter plots in addition to the measured values τ_J and L_{eff} only the thickness of the cell base and the diffusion constant of the material have to be known. The diffusion constant is calculated from the specific resistance using the numerical model of the program PC1D [5].

The emitter saturation current I_{0E} can be calculated with the known L_n and the exponential decay rate of the voltage τ_V. τ_V is influenced by the capacitive time constant of the pn-junction and the shunt resistance of the solar cell. Commonly the measured decay rate of the voltage τ_U is not equal to τ_V. Fig. 4 shows τ_U in dependence of the bias light cell-voltage. The RC-time constant of the pn-junction (dotted line) and the τ_U of a cell with a shunt resistance (solid line) are shown. The measured τ_U is determined from the largest time-constant. In the low bias-voltage regime the RC-time constant determines τ_U. Near the minimum of the τ_U-curve τ_U is smaller than τ_V due to the shunt resistance. If τ_U is measured in the region of the plateau at a high bias light level the influence of both, the capacitance and the shunt, are negligible. The τ_U equals τ_V.

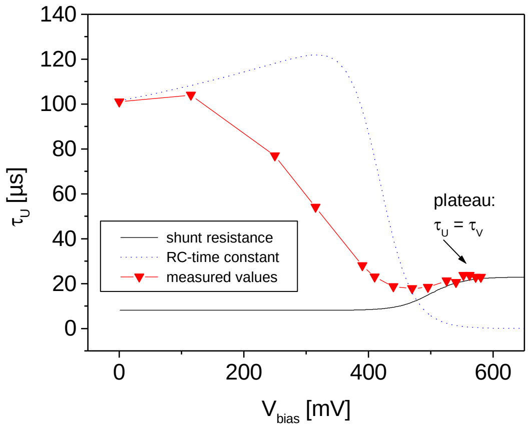

Fig. 4: *τ_U in dependence on the cell-voltage due to the bias light. Further the influence of the capacitive time constant of the pn-junction and the shunt resistance of the cell are shown (explanation in the text).*

PCVD-CHARACTERIZATION OF SCREENPRINTED SOLAR CELLS

A: Bulk-passivation due to a PECVD silicon nitride

To investigate the bulk passivation properties due to a fired PECVD silicon nitride ARC screenprinted solar cells with and without ARC were produced. Baysix CZ and Baysix multi-Si material was used. The cells with the ARC were fired at a slightly higher temperature than the cells without ARC for technical reasons. Else the cells were processed identically. The cells were characterized with the PCVD-method described above. Fig. 5 shows the parameter-plot $S_B(L_n)$ for the CZ-cells with and without SiN-ARC. The points of intersection supply L_n and S_B of the cells. The uncertainty of the extracted values is shown as bars near the graph axis. It was expected that the diffusion length of the monocrystalline material is not influenced by the passivating layer.

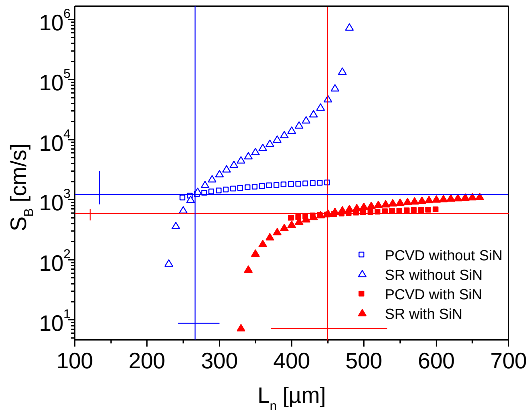

Fig. 5: *Parameter plots $S_B(L_n)$ for two solar cells with and without a fired silicon nitride (SiN) ARC. The cells are made of CZ-material. A large increase of the diffusion length is clearly visible.*

A large difference in the diffusion length of both cells is visible. S_B of both cells differ hardly and can be explained with a slightly better BSF-formation on the cell with the higher firing temperature.

Fig. 6 shows the result of the determination of the diffusion length of the multicrystalline cells. The cells made of Baysix multi-Si show a strong increase of L_n.

Cell	L_n [µm]
CZ	240 - 300
CZ + SiN-ARC	370 - 530
multi-Si	170 - 190
multi-Si + SiN-ARC	310 - 420

Fig. 6: *Bulk diffusion length L_n of screenprinted solar cells made of Baysix CZ- and multi-Si material with and without a fired PECVD SiN ARC.*

A strong increase of the diffusion length in multicrystalline silicon due to a PECVD silicon nitride layer was observed by [1]. Finding a comparable improvement of L_n in the relatively large grained multi-Si and above all in the monocrystalline CZ-material is surprising. Maybe some defects are induced during the emitter formation which lower the diffusion length of the silicon. These defects are passivated through hydrogen which is migrating from the nitride into the bulk during the firing process.

B: Saturation current of different emitters

Solar cells with five different emitters and the process sequence which is shown in Fig. 1 were produced. The diffusion temperature and the drive-in time is varied to obtain emitters with a different junction depth and phosphorus concentration at the surface. A highly doped region at the surface is important to avoid contact problems with the front metallization. The emitter sheet resistivity was measured after the diffusion. The junction depth and surface phosphorus concentration were estimated to model the emitters with the computer program PC1D [5]. Fig. 7 shows the sheet resistance R_S, the estimated junction depth d_{pn} and the calculated phosphorus concentration at the surface N_{Ph} for an erfc-shaped emitter profile. The emitter saturation current I_{0E} is calculated with an SRV at the frontside $S_F = 10^5$ cm/s. The I_{0E} depends on the phosphorus concentration at the surface.

Emitter	R_s[Ω/sq]	d_{pn} [µm]	N_{Ph} [cm^{-3}]	I_{0E}[pA/cm^2]
1	30	0.5	$2.8*10^{20}$	0.42
2	36	0.5	$2.3*10^{20}$	0.40
3	23	0.75	$2.4*10^{20}$	0.39
4	38	0.75	$1.3*10^{20}$	0.36
5	30	1.0	$1.2*10^{20}$	0.34

Fig. 7: *Sheet resistivity R_s, junction depth d_{pn}, phosphorus concentration at the surface N_{Ph} and the calculated saturation current I_{0E} of 5 different $POCl_3$-diffused emitters.*

The investigated cells were made of CZ-silicon and received a PECVD SiN ARC. The result of the PCVD-measurement is shown in Fig. 8 together with the efficiencies of the cells. The cells were processed together with the cells from Fig. 5. For that reason the diffusion length are identical. The S_B-values are typical for a full-area screenprinted deep BSF [6].

Emitter	L_n [µm]	S_B [cm/s]	I_{0E} [pA/cm^2]	η [%]
1	370 - 530	700	1.03	13.8
2	‘ ’	500	0.36	13.7
3	‘ ’	550	0.44	13.7
4	‘ ’	680	0.30	14.1
5	‘ ’	830	0.27	14.6

Fig. 8: *Measured L_n, S_B and I_{0E} of the cells with the 5 different emitters. The efficiencies of the cells are given in the last column.*

The emitter saturation current depends on the emitter formation. Emitter 1 shows a much higher I_{0E} than the other four emitters. To compare the measured with the calculated values Fig. 9 shows the measured I_{0E} with error bars additional to the calculated values with $S_F = 10^5$ cm/s of Fig. 7 and $S_F = 10^4$ cm/s. Except emitter 1 all measured values are in the region between the theoretical curves for $S_F = 10^4$ cm/s and $S_F = 10^5$ cm/s.

This good agreement shows that the frontside SRV of the LF-PECVD silicon nitride ARC is between 10^4 and 10^5 cm/s, optimal emitter formation supposed, or even better.

Emitter 5 with the lowest phosphorus concentration at the surface supplies the lowest emitter saturation current and the highest efficiency.

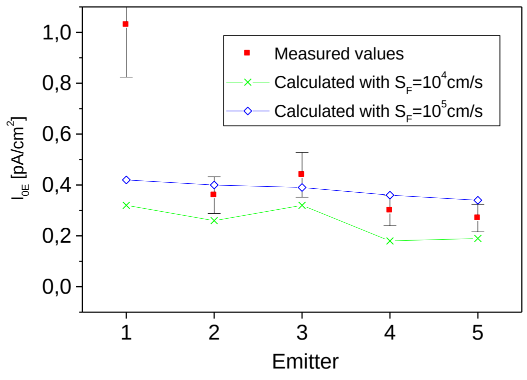

Fig. 9: *The measured saturation currents of the five emitters compared with calculated values. The calculations were done for $S_F = 10^4$ and 10^5 cm/s with the program PC1D.*

C: Screenprinted emitters

In the screenprinting process the emitter formation can be done by screenprinting and firing of a phosphorus containing paste. The screenprinting of an emitter can be done faster than the conventional $POCl_3$-diffusion.

It is important to compare the emitter saturation current of the screenprinted emitter with the I_{0E} of a $POCl_3$-diffused emitter.

Fig. 10 shows the result of a PCVD-chracterization of a solar cell with a screenprinted emitter in comparison to an identically processed cell with a conventional $POCl_3$-diffused emitter. Both cells are made of CZ-material without BSF and ARC. The sheet resistivity of both emitters is around 30 Ω/sq. The efficiencies of both cells are comparable.

Emitter	L_n [µm]	S_B [cm/s]	I_{0E} [pA/cm^2]	η [%]
$POCl_3$	170-210	$1\text{-}3{\cdot}10^4$	< 0.34	9.1
screenpr.	160-190	10^4-10^5	0.23-0.66	9.0

Fig. 10: *Comparison of screenprinted cells with $POCl_3$-diffused and screenprinted emitter. The cells have no ARC and no BSF.*

The diffusion length and the S_B-values of both cells are comparable. The measured S_B is a typical value for a Ag/Al back contact, which does not form an efficient BSF. The uncertainty in the determination of I_{0E} is large, because the base thickness of the cells is not exactly known. For that reason only the tendency is visible that the screenprinted emitter shows a larger I_{0E} than the diffused emitter. But the saturation current of the screenprinted emitter is still small enough to produce efficient solar cells.

D: Characterization of V-textured solar cells

The mechanical V-texturization of the surface of a solar cell is an effective possibility to reduce the front reflectance of the cell and to exhibit a more efficient generation profile [7].

The characterization problem of mechanical textured solar cells with the PCVD-method is the deep texturing in the range of 50 - 60 µm. The device does not remain one-dimensional. The thickness of the base is not a constant.

For that reason first an identical processed cell with a flat surface is measured. The parameter-plot $S_B(L_n)$ of this cell supplies L_n and S_B. Assuming that the V-texturization influences only the emitter saturation current an effective

thickness of the textured cell can be found for which the same L_n and S_B as measured for the flat cell are valid. With this effective thickness the emitter saturation current of the V-textured cell can be determined.
Fig. 11 shows the result of the investigation. The cells are made of multicrystalline Baysix multi-Si material. The cells have a BSF and a PECVD SiN ARC. They are an identical processed pair with a flat/V-textured surface. The I_{0E} of these cells can directly be compared. The surface is increased due to the texturing by a factor of 1.6. For an optimally processed emitter the I_{0E} of the textured cell exceeds the I_{0E} of the flat reference by about this factor.
The cells show an increase of the I_{0E} by a factor of 3 due to the texturization.

Surface	L_n [µm]	S_B [cm/s]	I_{0E} [pA/cm^2]	η [%]
untextured	340 ± 50	680 ± 300	1.0 ± 0.2	12.9
V-textured	‘’	‘’	3.0 ± 0.2	13.1

Fig. 11: *Result of the PCVD-characterization of mechanically V-textured screenprinted solar cells.*

CV-CHARACTERIZATION

The passivating properties of PECVD silicon nitride layers are characterized by measuring the interface trap density D_{it} and the fixed charge Q_{SS}. High frequency CV (Capacitance/Voltage) measurements are carried out to determine D_{it} and Q_{SS} of MIS (Metal-Insulator-Semiconductor) samples. Fig. 12 shows the D_{it} of a MIS sample which was fired together with solar cells in a co-firing step. The silicon nitride was deposited at a temperature of 305° with a plasma power of 780 W/m^2. The D_{it} equals $1{,}2{\cdot}10^{12}$ cm^{-2}eV^{-1} at midgap and the fixed charge Q_{SS} is $3{,}2{\cdot}10^{12}$ cm^{-2}.

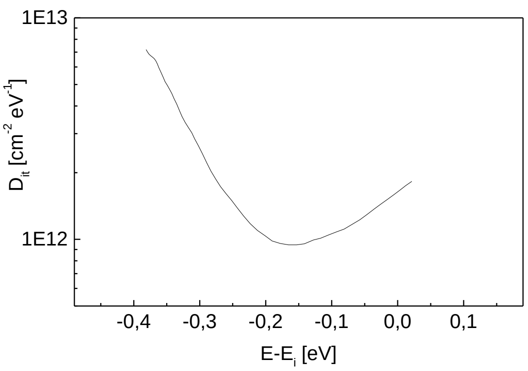

Fig. 12: *The interface trap density D_{it} of a PECVD silicon nitride MIS-sample in dependence of the energy in the bandgap. The SiN was deposited at 305°C 780 W/m^2 and fired in an infrared furnace. The midgap $D_{it} = 1{,}2{\cdot}10^{12}$ cm^{-2}eV^{-1} and the fixed charge $Q_{SS} = 3{,}2{\cdot}10^{12}$cm^{-2}.*

Fig. 13 shows the dependence of D_{it} and Q_{SS} on the PECVD deposition parameters. The deposition temperature is 260°. The plasma power and the gas pressure were varied. The D_{it} depends clearly on the deposition plasma power.

power[W/m^2]	pressure [Pa]	Q_{ss} [cm^{-2}]	D_{it} [cm^{-2}eV^{-1}]
195	40	$3{\cdot}10^{12}$	$1{\cdot}10^{11}$
195	27	$4{\cdot}10^{12}$	$1{\cdot}10^{11}$
780	40	$3{\cdot}10^{12}$	$3{\cdot}10^{11}$
780	27	$3{\cdot}10^{12}$	$4{\cdot}10^{11}$

Fig. 13: *The interface trap density D_{it} and the fixed charge Q_{ss} of PECVD silicon nitrides in dependence of the deposition parameters pressure and plasma power. The deposition temperature is 260° C. The samples are annealed in Ar/H.*

The emitter saturation current of screenprinted solar cells with a fired PECVD silicon nitride ARC do not show any dependency on the deposition parameters of the nitride. It is supposed that the passivation is dominated due to the large positive fixed charge. The fixed charge is independent of the deposition conditions.

CONCLUSION

The PCVD-method allows the determination of the diffusion length, the backside recombination velocity and the emitter saturation current. In addition to the decay rates and the internal quantum efficiency only the base thickness of the solar cell and the diffusion constant of the material have to be known.
The PCVD-method was applied to characterize screenprinted solar cells. A large increase of the diffusion length due to a fired PECVD silicon nitride was observed even on monocrystalline CZ material. The saturation currents of different emitters were measured and compared with calculated values. A frontside recombination velocity due to the passivation of the PECVD silicon nitride of 10^4 - 10^5 cm/s was extracted. With the definition of an effective thickness mechanically V-textured solar cells could be characterized.
The passivation properties of differently deposited PECVD silicon nitride layers were investigated by CV-measurements.

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