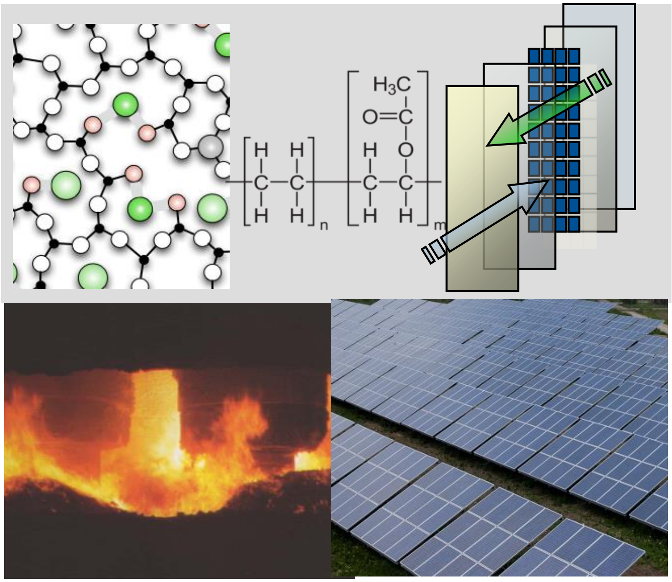
PID – Figured out?



PV-DAYS Halle

21. – 22. 10. 2014

by

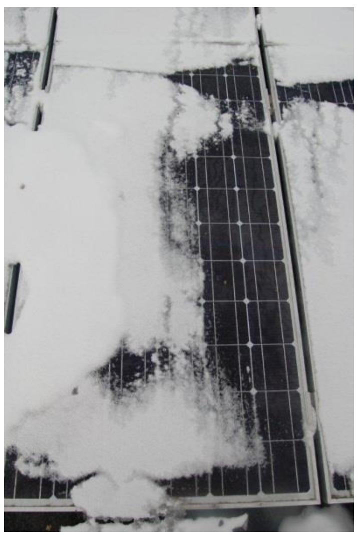
Ingo A. Schwirtlich

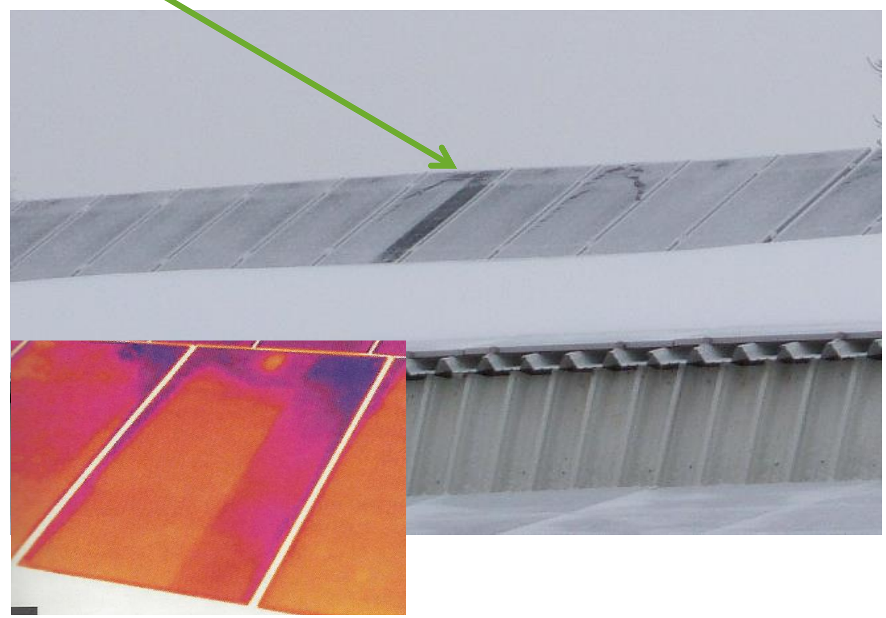
www.cem-concept.de

PID- Potential Induced Degradation

Temperature rise on snow covered modules due to PID in cell strings visualized by melting snow.

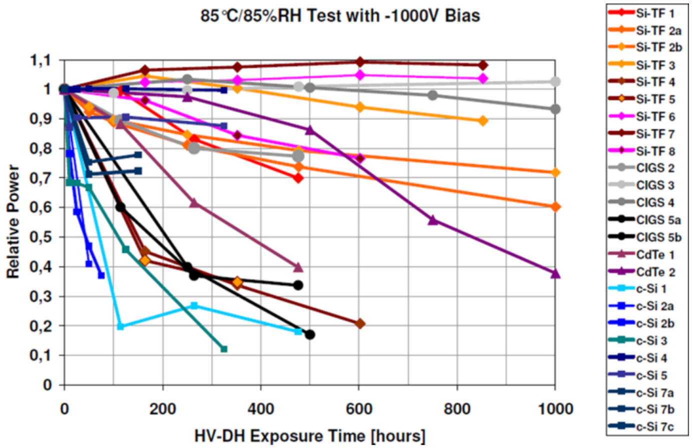
The heat effect of activated protection diode.





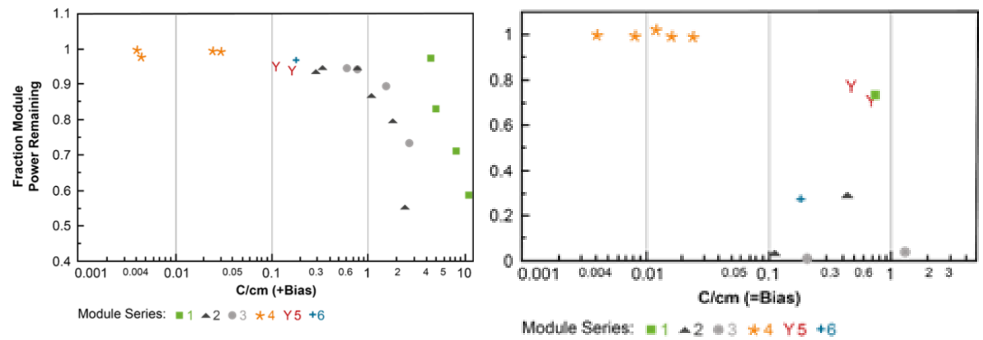
Open questions:

- **Why is there “PID” in different module technologies?**



P. Lechner, D. Geyer, H.-D. Mohring , ZSW, 28. Symposium Photovoltaische Solarenergie, Bad Staffelstein, 06.- 08.03.2013

- **Why does PID come up at changed polarity of the bias voltage (in x-Si-modules)?**

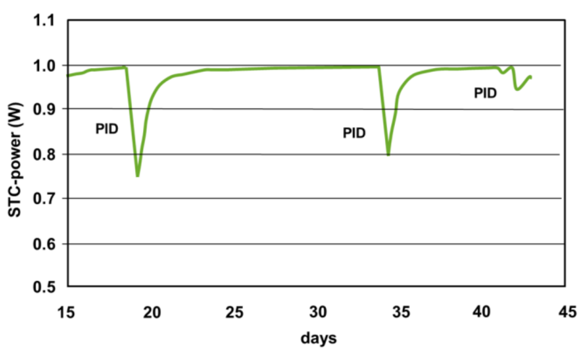


+ 600 V

- 600 V

P. Hacke, M. Kempe, K. Terwilliger, S. Glick, N. Call, S. Johnston, S. Kurtz, I. Bennett, M. Kloos, Characterization of Multicrystalline Silicon Modules with System Bias Voltage Applied in Damp Heat, 25th, European Photovoltaic Solar Energy Conference and Exhibition / 5th World Conference on Photovoltaic Energy Conversion, 6 – 10-September 2010, Valencia, Spain, pp. 3760

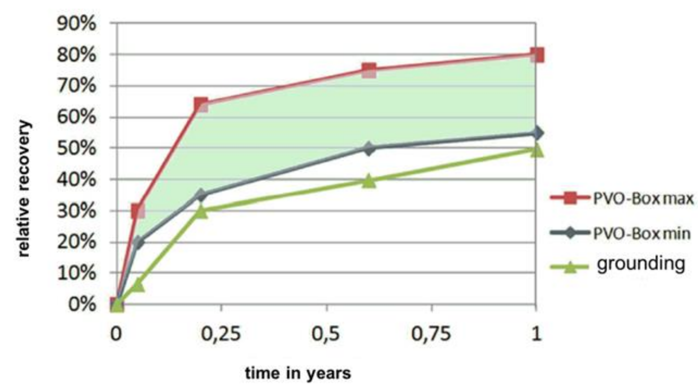
- **What about the recovery mechanism?**



Recovery in the lab: PID caused by 1000 V, 2 h, repeated annealing at 25 ° C, 95 % RH.

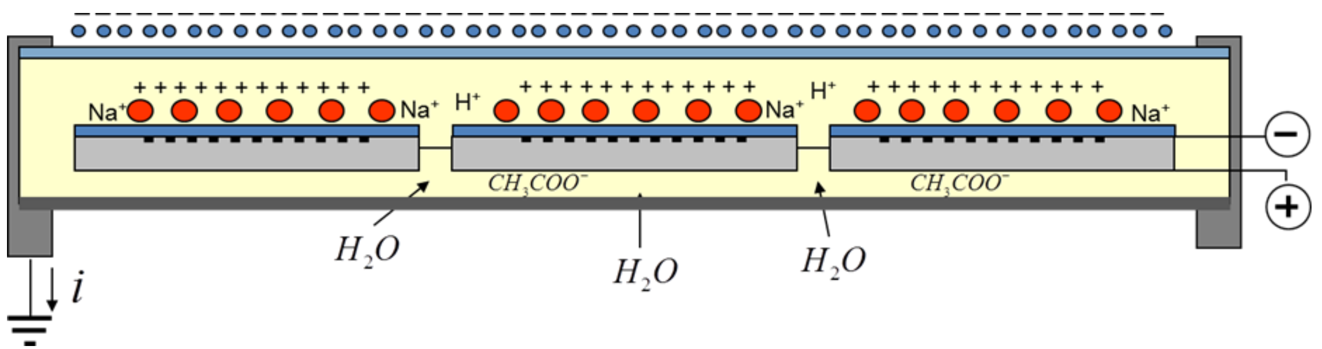
P. Lechner, D. Geyer, H.-D. Mohring , ZSW, 28. Symposium Photovoltaische Solarenergie, Bad Staffelstein, 06.- 08.03.2013

- **Why does it not recover 100 % in any case?**



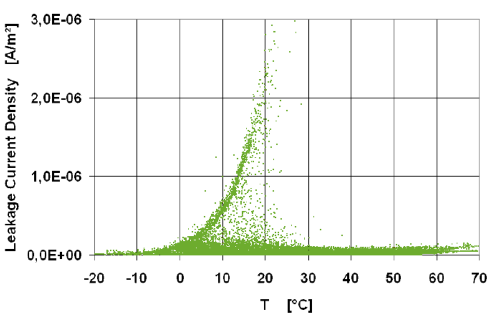
G. Mathiak, M. Schweiger, W. Herrmann, M. Stalder, J. Laschinski, 28. Symposium Photovoltaische Solarenergie, Bad Staffelstein, 06. - 08.03.2013

Degradation models

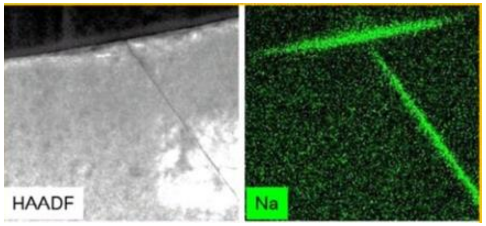


Agreements at p-type solar cells:

1. Positively charged ions (Na^+) migrate to the AR coating of the cells.
2. The compensation charges are conducted to ground via the front glass and frame.
3. The conductivity of the front glass esp. of its surface (moisture) determines the charge transfer.
4. The AR-layer has a big impact on PID.



P. Lechner, D. Geyer, H.-D. Mohring , ZSW, 28. Symposium Photovoltaische Solarenergie, Bad Staffelstein, 06.-08.03.2013

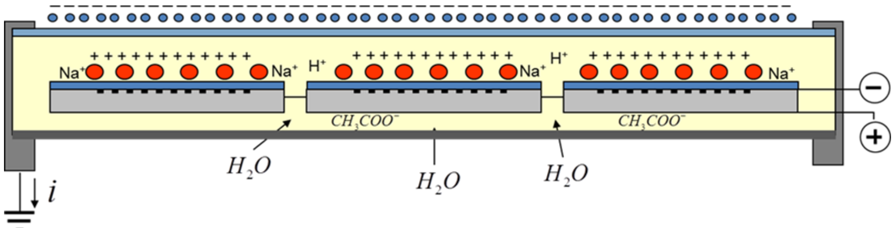


V. Naumann et al., Physica Status Solidi RRL, online DOI 10.1002/pssr.201307090

PID models:

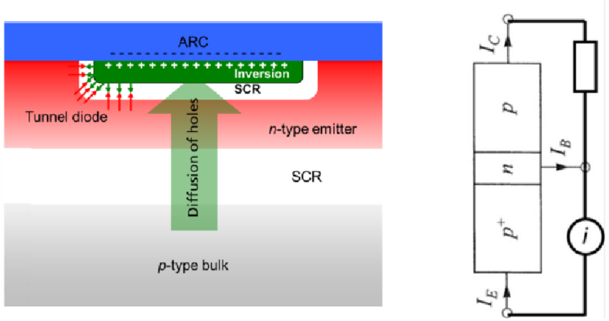
In discussion:

- Polarization model



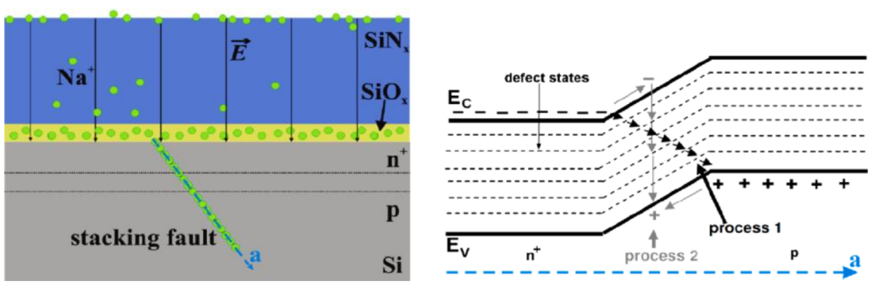
I.A. Schwirtlich, Spezifische Zuverlässigkeitsthemen in der Modultechnik, Workshop: Qualität und Zuverlässigkeit in der Photovoltaik, Solarvalley Erfurt, 16.März 2011

- Inversion field model



Jonas Schön, Pierre Saint-Cast, Cristian Reichel, Martin Hermle, Numerical Simulation of PID Effect, xµ-Projekttreffen, SolarValley, PID Workshop 10.09.2013 at Hanwa Q-Cells, Bitterfeld

- Shunt model

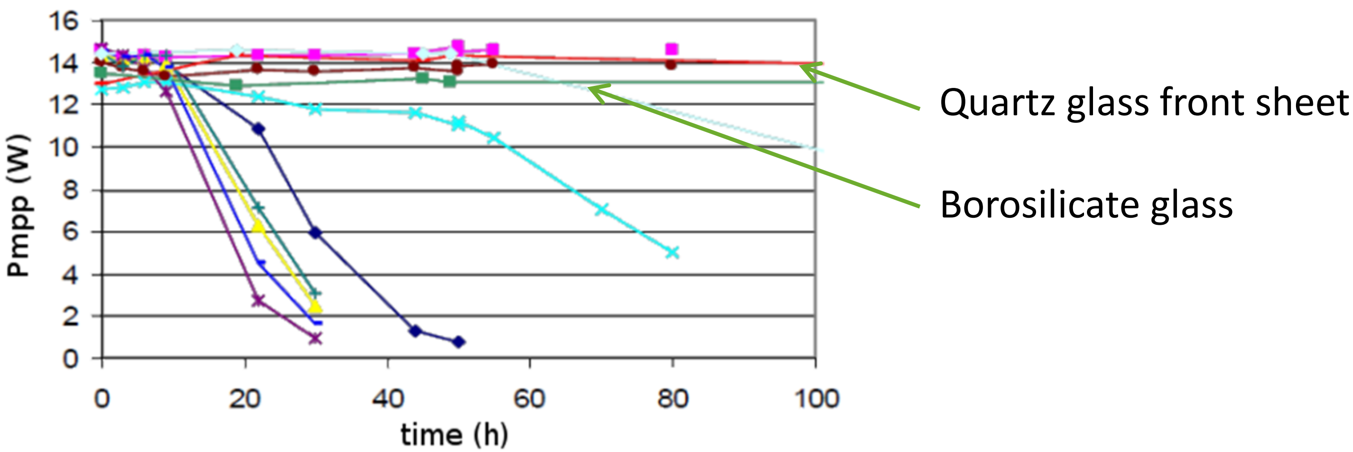


V. Naumann, D. Lausch, M. Turek, S. Großer, J. Bagdahn, C. Hagendorf, A. Graff, A. Hähnel, J. Bauer, O. Breitenstein, The Shunting Mechanism of Potential-Induced Degradation in Crystalline Silicon, 28th EU PVSEC 2013, Paris, 4DO.3.2

Glass compositions

glass	SiO_2	Al_2O_3	Na_2O	K_2O	MgO	CaO	B_2O_3	PbO	TiO_2	F
quartz-glass	100	-	-	-	-	-	-	-	-	-
soda-lime glass	72	2	14	-	-	10	-	-	-	-
float-glass	72	1,5	13,5	-	3,5	8,5	-	-	-	-
lead-crystal-glass	58	-	4	9	-	-	2	24	-	-
borosilicate-glass	80	3	4	0,5	-	-	12,5	-	-	-
E-glass	54	0,14	-	-	4,5	17,5	10	-	-	-
enamel	40	1,5	9	6	1	-	10	4	15	13

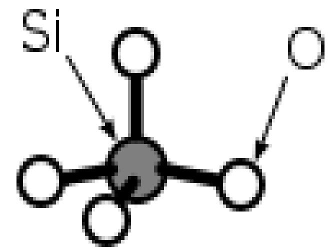
(data in $\%_{wt}$) Wikipedia



I.A. Schwirtlich, Spezifische Zuverlässigkeitsthemen in der Modultechnik,
Workshop: Qualität und Zuverlässigkeit in der Photovoltaik, Solarvalley Erfurt, 16.März 2011

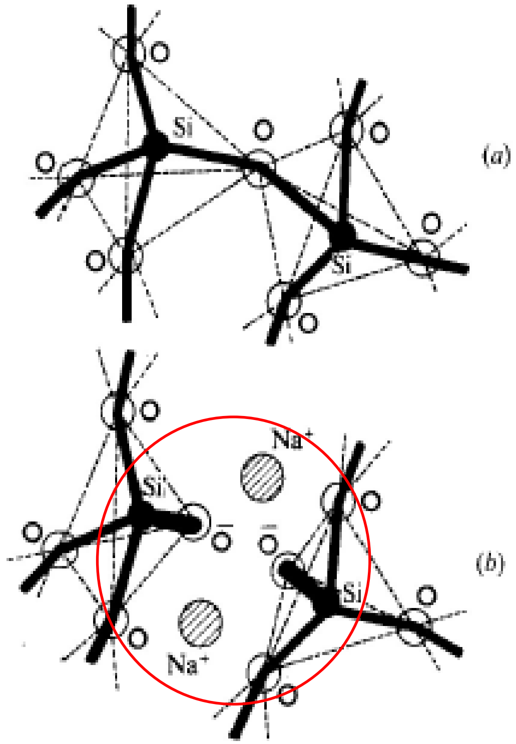
Basics of glass-structure

Na^+ as SiO_2 network modifier:



In pure SiO_2-glass all O^{2-} — ions are bound to two Si^{4+} - ions (bridging oxygen „BO“, fig. a)).

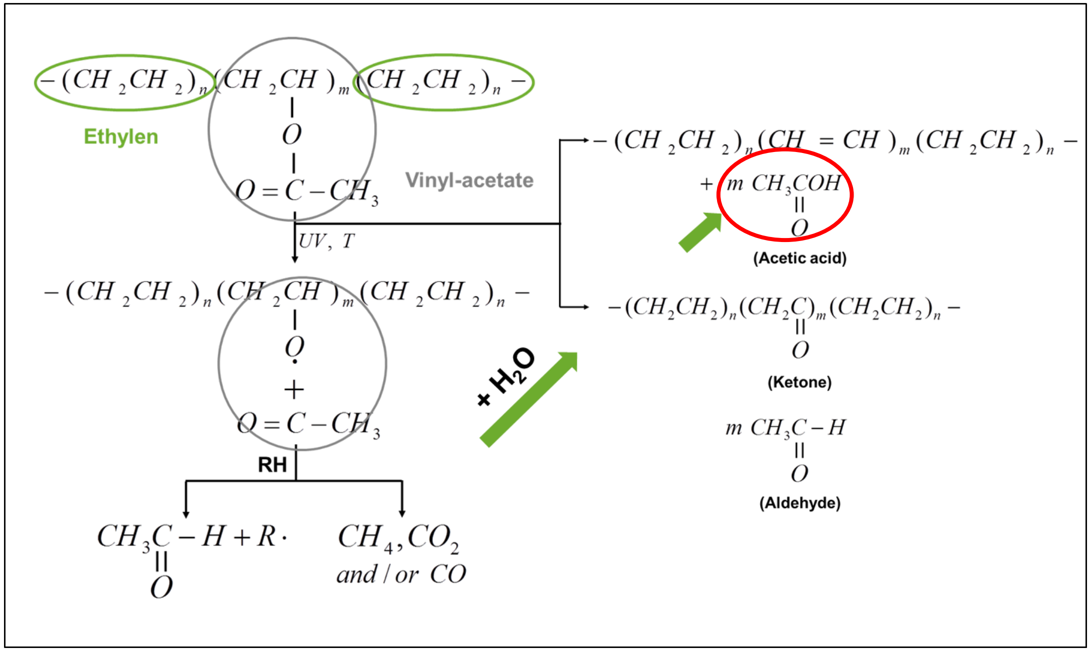
$$\equiv Si-O-Si\equiv + Na-O-Na \rightarrow \equiv Si-O-Na \quad Na-O-Si\equiv$$



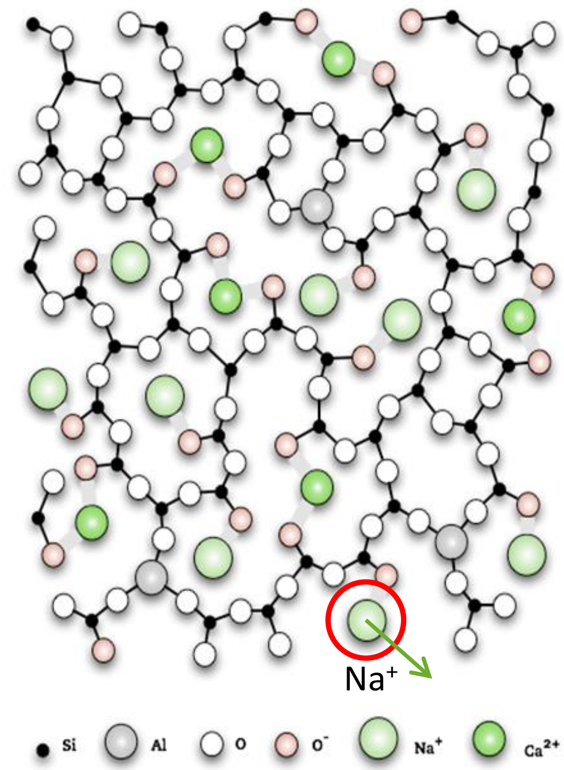
The incorporation of NaO breaks the Si-O-Si – „bridge“ . Neighboring Si^{4+} - ions are formed with single bound O^{2-} - ions (non-bridging oxygen „NBO“, fig. b)).

SCHOTT AG

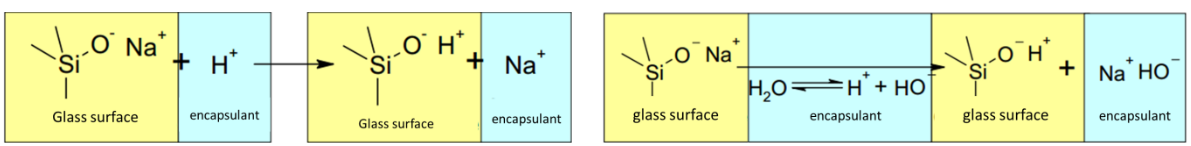
Formation of acetic acid inside EVA



M.D. Kempe et al., Solar Energy Materials & Solar Cells 91(2007) 315 - 329



Wikipedia

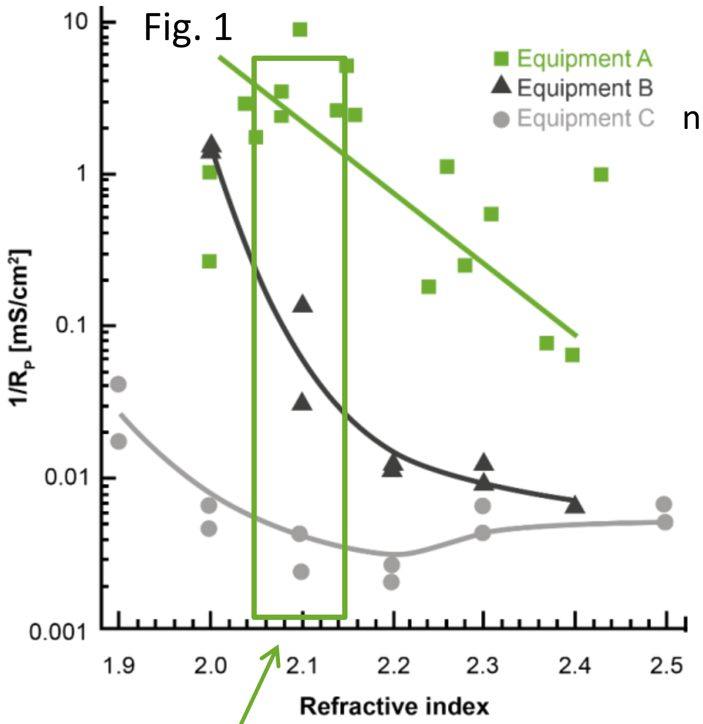


Acetic acid is able to dissolve Na^+ from the glass that is able to drift by an electric field of an external bias voltage.

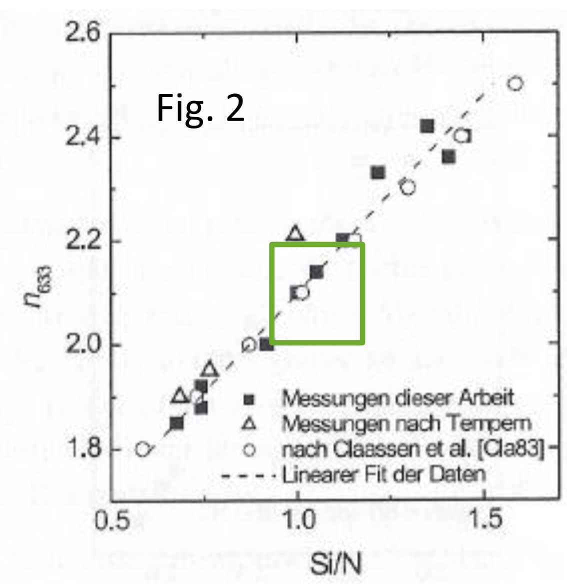
AR-coating

SiN_x-AR-coatings with the same refractive index produced by different PECVD equipment show different sensitivity against PID.

Figure 1 shows the inverse shunt resistance of solar cells with AR-coatings prepared in different equipment after accomplishment of a standardized PID test.
Figure 2 shows the correlation between **n** and the ratio of [Si]/[N].



Refractive index window for solar cells.



[Si]/[N] = 3/4: stoichiometric Si_3N_4, low conductance, lower **n**

[Si]/[N] > 1,1: higher conductance, higher **n**

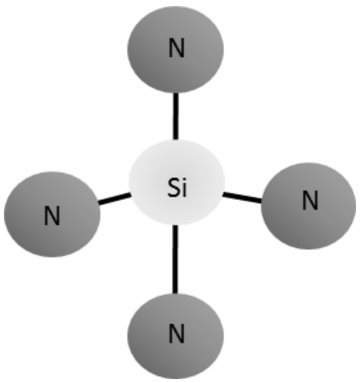
H. Nagel, A. Metz and K. Wangemann, CRYSTALLINE SI SOLAR CELLS AND MODULES FEATURING EXCELLENT STABILITY AGAINST POTENTIAL-INDUCED DEGRADATION, 26th European Photovoltaic Solar Energy Conference and Exhibition 2011, Hamburg, Paper 4CO, 5.6

Beate Lenkeit, Elektronische und strukturelle Eigenschaften von Plasma Silizium-Nitrid zur Oberflächenpassivierung von siebgedruckten, bifazialen Silizium-Solarzellen, Dissertation 2002 im Fachbereich Physik an der Universität Hannover

AR-coating

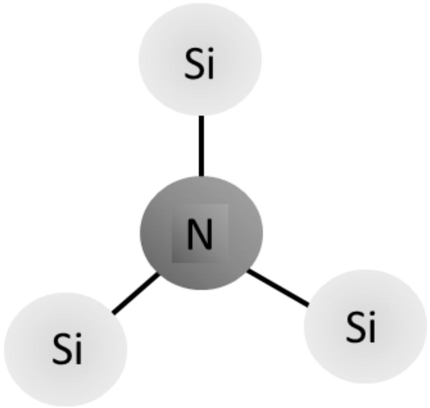
The optical, chemical, mechanical and electrical properties of SiN_x-layers depend from the deposition process parameters.

In amorphous SiN_x – layers the tetravalent Si- as well as the trivalent N-binding-structure exists.



tetravalent Si-structure

By the presence of hydrogen inside the SiN_x-layer, the N-content is able to be enhanced to values beyond the stoichiometric ratio by formation of =NH und $-NH_2$ – groups. It is supposed that all hydrogen is bound as Si-H or N-H.

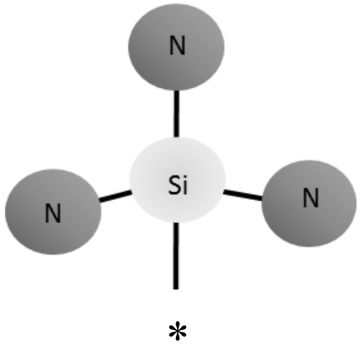


trivalent N-structure

Beate Lenkeit, Elektronische und strukturelle Eigenschaften von Plasma Silizium-Nitrid zur Oberflächenpassivierung von siebgedruckten, bifazialen Silizium-Solarzellen, Dissertation 2002 im Fachbereich Physik an der Universität Hannover

AR-coating

In the case of Si-atom correlated with 3 N-atoms instead of 4, a free bond remains, the K-center (∗Si-N_3). The K-center is responsible for the formation of localized charges. As the K-center is positioned in the middle of the band gap is supposed to show an amphoteric behavior, i.e. it can have 3 different states of charge:



K-center

K^+ ()	filled with one hole, electrically positive, diamagnetic, stable
K^0 (↑)	empty, electrically neutral, paramagnetic, meta stable
K^- (↑↓)	filled with an electron, electrically negative, diamagnetic, stable

Arrows indicate the electron-spin.

K-centers with a concentration of 10^{16} – 10^{18} cm^{-3} are able to pick up minority carriers from the emitter.
The corresponding charged centers are able to form a dielectric double layer between AR-layer and Na^+ ions migrated onto its surface → polarization.

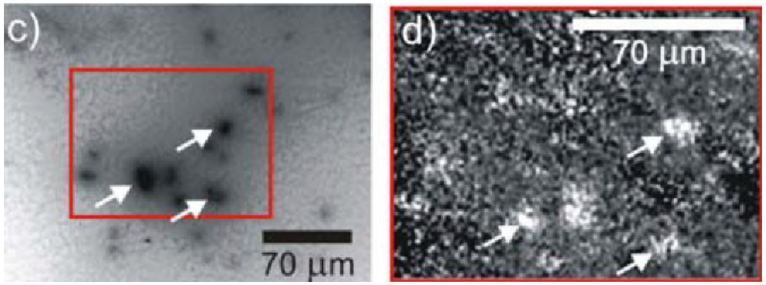
Beate Lenkeit, Elektronische und strukturelle Eigenschaften von Plasma Silizium-Nitrid zur Oberflächenpassivierung von siebgedruckten, bifazialen Silizium-Solarzellen, Dissertation 2002 im Fachbereich Physik an der Universität Hannover

Contemplation

Locally different Si/N ratio of the AR-coating :

Si/N < 1.1

- K-centers
- Low conductivity
- High voltage drop V_{SiN}.
- Formation of charged K-centers
- Na^+ ions driven inside the AR-layer to interface.
- Shunt formation via crystal defects (stacking faults)

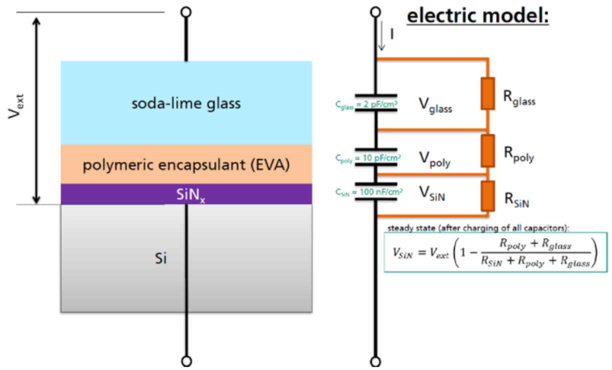


J. Bauer, V. Naumann, S. Großer, C. Hagendorf, M. Schütze, and O. Breitenstein Phys. Status Solidi RRL 6, No. 8, 331–333 (2012) / DOI 10.1002/pssr.201206276

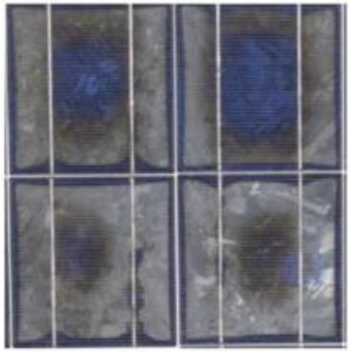
- A SiO_2-barrier layer blocks the diffusion of Na^+ and minority charges.
- Recovery by changing the voltage polarity (reloading of the K-centers).
- Higher temperature and higher humidity improves the mobility of Na^+ ions.

Si/N ≥1.1

- No K-centers
- High conductivity
- Low voltage drop V_{SiN}.
- No PID



Volker Naumann, Dominik Lausch, Christian Hagendorf, Stephan Großer, Jan Bauer, Otwin Breitenstein, J. Bagdahn, EUPVSEC Paris, 2013



Removal of Si-Nitride layer after 1000h at -600V, 85°C, and 85% RH due to formation of sodium silicate because of Na-migration under influence of humidity inside the laminate.

P. Hacke, M. Kempe, K. Terwilliger, S. Glick, N. Call, S. Johnston, S. Kurtz, I. Bennett, M. Kloos, 25th, European Photovoltaic Solar Energy Conference and Exhibition / 5th World Conference on Photovoltaic Energy Conversion, 6 – 10-September 2010, Valencia, Spain, pp. 3760

3-stage PID-model

1st stage:

- Permeation of ions (Na^+) to the front side of the cells:
  if Si/N < 1.1
  → dielectric double layer with charged K-centers
  → polarization field in forward direction (diode behavior).

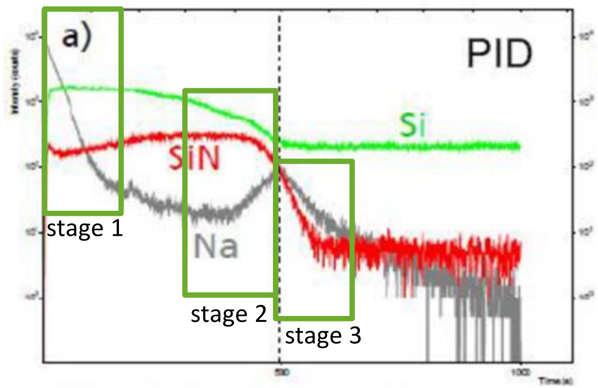
2nd stage:

- Diffusion of the ions (Na^+) into the AR-layer:
  → reloading the charged K-centers
  → accumulating at the interface between AR-coating and emitter
  → inversion field (transistor behavior).

3rd stage:

- Local diffusion of ions from the interface into the emitter via crystal defects (stacking faults)
  → trapping- behavior
  → shunt behavior

This model seems to be consistent with the analysis in the figure →



V. Naumann, Ch. Hagendorf, S. Großer, J. Bagdahn, MICROSTRUCTURAL ROOT CAUSE ANALYSIS OF POTENTIAL INDUCED DEGRADATION IN C-SI SOLAR CELLS, Silicon PV 2012,

PID – figured out?

Not really – but a concept!

Measures against PID

Cell level:

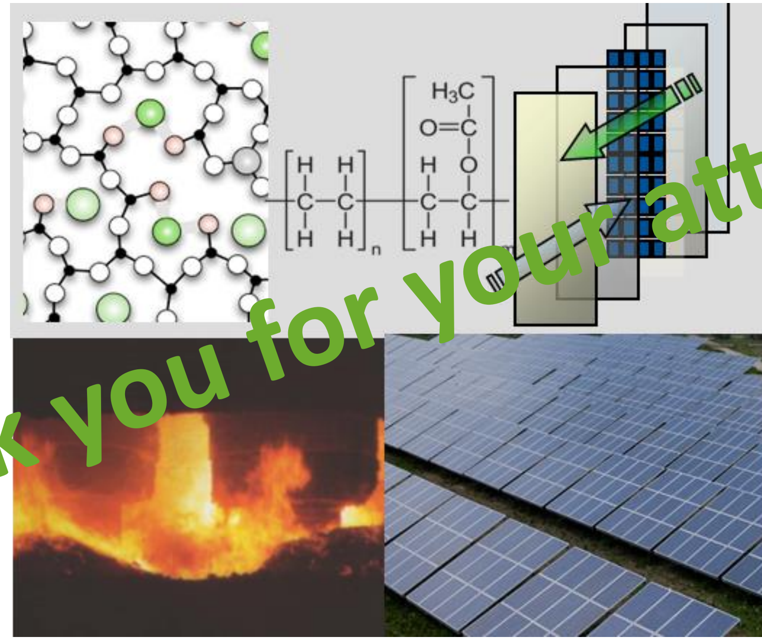
- AR coating with higher Si content Si/N $\geq$ 1.1.
- Barrier layers between AR-coating and emitter with Si/N > 1 and application of an electric field to introduce additional charges into the interlayer (charging of K-centers to create an opposing internal electric field)
- Conductive layer on the front side of the AR coating.
- Modified dead layer on top of the emitter for higher conductivity
- Barrier oxide between AR-coating and emitter, rep. SQI (surface quality improvement).

Module level:

- Low sodium front glass.
- Diffusion barriers on internal side of the front glass.
- Thicker EVA encapsulant on front side.
- Encapsulants with low moisture vapor transmission rate (MVTR).
- Back sheet with low MVTR
- Double glass design.
- EVA Substitute encapsulants (ionomere, polyolefine).

System level:

- Grounding of minus pole using transformer containing inverters
- Opposite bias voltage at night (PVO-box)



This study was accomplished by CEM Concept GmbH as task M 670 of subproject xµ-Module, Phase 2, "Potential Induced Degradation" of the Fraunhofer Institute THM in Freiberg, supported by SolarValley Central Germany and funded by the Ministry of Research and Technology (BMBF) under contract number 03SF0400B.

Bundesministerium für Bildung und Forschung

SOLARVALLEY Mitteldeutschland

Fraunhofer THM

CEM Concept consulting engineering media