Photovoltaic modules - current status, further trends and reliability issue

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Fraunhofer CSP

Agenda

- Fraunhofer Center Silicon Photovoltaics CSP
- Module technologies and market development
- Reliability
  - Potential induced degradation
  - Mechanical failure: Cell fracture, fatigue Cu ribbons
- Technology Trends
- Summary

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Fraunhofer Center for Silicon Photovoltaics

- Founded 2007 as joint research center for applied PV research between Fraunhofer Institute for Solar Energy Systems (ISE) and Institute for Mechanics of Materials (IWM)
- 65 employees + appr. 40 students and guests
- Directors: Prof. Jörg Bagdahn / Dr. Peter Dold
- Investment volume: 60 Mio. € (EU, State of Saxony-Anhalt, Fraunhofer)
- Project volume 2011: ~4.5 Mio. € (contract research, public grants, basic funding)

Crystallization
Dr. Roland Kunert

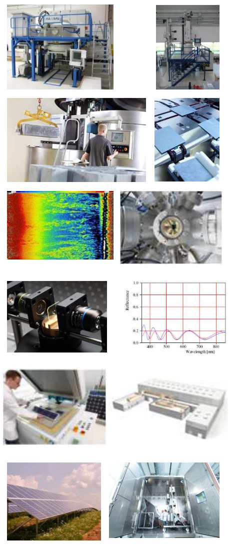
Silicon Wafers
Dr. Hartmut Schwabe

Diagnostic Solar Cells
Dr. Christian Hagendorf

Optical Materials
Prof. Stefan Schweizer

Module Technology
Dr. Jens Schneider

Module Reliability
Dr. Matthias Ebert



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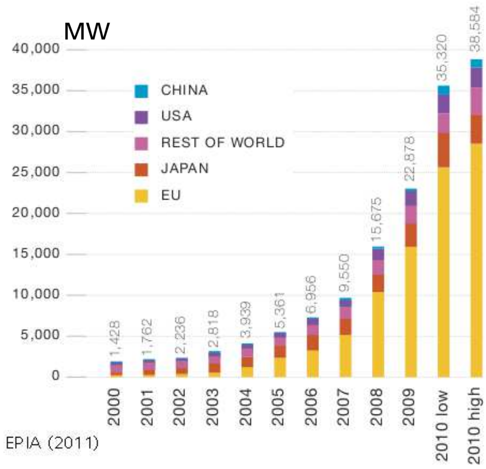
Photovoltaic Market
Market development between 2000-2010

- Exponential growth of the market
- Europe is dominating market (Germany ~ Σ 24 GW until 2011)
- Worldwide share of electric energy production is still small < 1 % (in Germany 2011: 3,2%, 2012e: >4 %)
- Huge further potential



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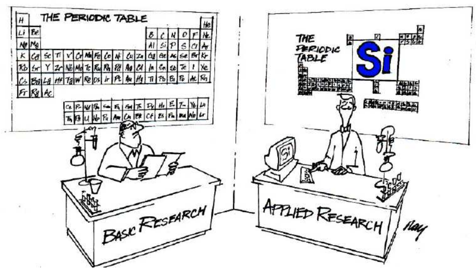
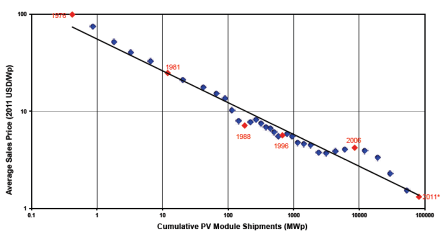
Technologies
Solar Module Technologies

- Crystalline silicon solar (mc-Si, sc-Si, ribbon Si) cells are dominating the market (~ 89 % in 2011)
- Thin film is currently loosing market shares (2009: 20 %, 2011: 11 %)



- Price are decreasing following a learning curve
  - 20% reduction by doubling of cumulated production
  - a module of today with a value of 200 € was worth 20.000 € in 1976



 Photon, IRTPV
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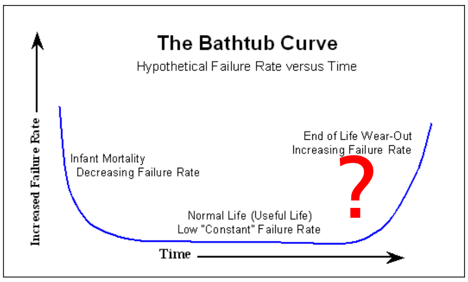
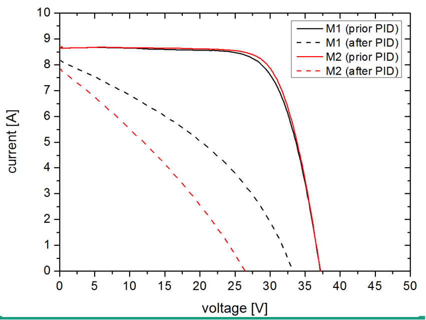
Reliability
Motivation

- More than 80 % of all modules worldwide were installed within in the last 5 years → companies give warranties between 20 – 30 years
- Failure rate will increase while modules reach end of the life time ("bathtub curve")
- Cost reduction pressure leads to introduction of new (low cost) materials → reliability ?
- New failure mechanisms occur in the field which were not known from laboratory studies ("physics of failure")
- Use of modules in "new" more aggressive environments





http://www.weibull.com

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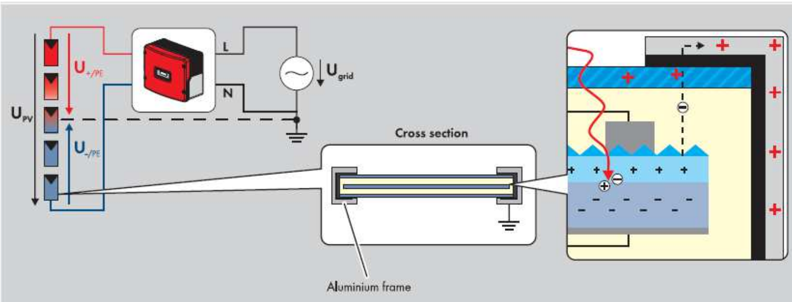
Reliability c-Si modules
PID – an unexpected failure mechanism

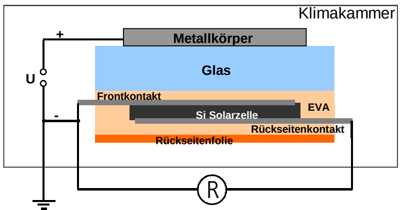
- Since 2 years strong degradation (30-50 %) of p-type module are observed in field
- It was shown that the degradation effect is related to negative potential of cells (≥ - 400 V, transformerless inverters)) → effect was called "Potential induced degradation" (PID) → [Berghold 2010]
- Effect was found in p-type cells, string ribbon cells and (n-type IBC cells)



http://files.sma.de/dl/7418/PID-TI-UEN113410.pdf

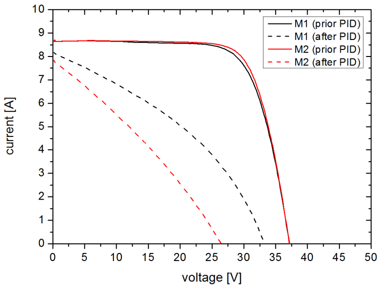
Reliability c-Si modules
PID – Test of modules

- Two approaches are currently under discussion
  - Homogeneous electric field at glass front side using a Al foil, 1000 V bias, 50 °C, 50% rel. H, 48 h [Schütze]
  - Electric field at frame, 1000 V bias, 60 °C, 85 % rel. H, 72 h [Hacke]
- Since it was shown that PID susceptibility is related to leackage current is useful to measure the leakage current or shunt resistant
- Test can be performed on full size module level or on mini module level

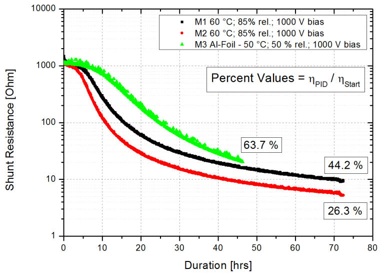


Reliability c-Si modules
PID test results

- I-V curve of a commercial (brand) c-Si solar module bought a month ago after PID test (1000 V bias, 60 °C, 85% rel. H, 72 h)



- Shunt resistant of the module during testing
  - Different test conditions seems to result in similar degradation
  - Variation between modules has to be considered

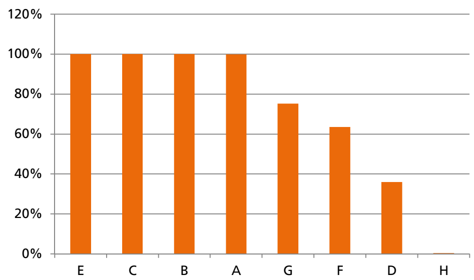


Reliability c-Si modules
Potential induced Degradation PID

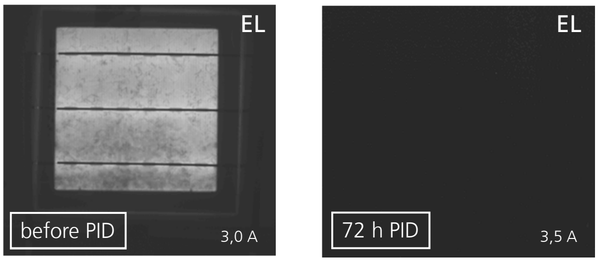
- Fraunhofer CSP has conducted High-Voltage-Stress-Test
  - HV = -1000V full contact Al foil, RH = 50%, T = 50°C, duration 48h
  - Failure criteria: more than 5% power loss
- Different commercial modules are under investigation (see table)

Hersteller	Typ
Q_Cells	Q.Pro
Sanyo	HIT-N235SE10
Kyocera	KD235GH-2PB
S-Energy	SM-215 PA8
LG	LG225 P1C-G1
Schott	Perform Poly 235
REC	240PE
Yingli	Panda YL265C-30b
Trina	TSM-255 PC05 A Honey
Canadian Solar	CS6P 240P
Bosch	C Si M60 240M
Suntech Power	STP 250 S-S-20/Wp
Sharp	
Luxor	ECO LINE 60 LX-250M/156-60+

- Analysis (see figure) shows the remaining power at MPP
- Only half of the modules withstand the PID test so far
- Final test are under way until end of May

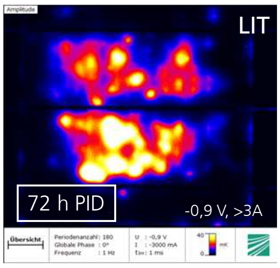


Understanding of the degradation effect



Electroluminescence (EL) at +0,8 V

→ PID affected cells exhibit large extremely shunted regions



Lock-In Thermography (LIT)

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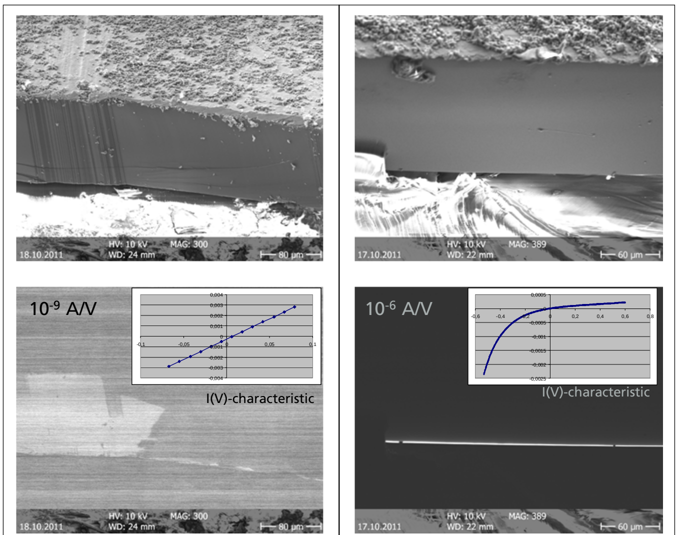
SEM/EBIC at fractured solar cell cross sections

- Cross section analysis in shunted areas

SEM

Very weak EBIC-signal and linear I-V characteristic at PID affected position.

EBIC



Degraded (PID) | Reference without PID

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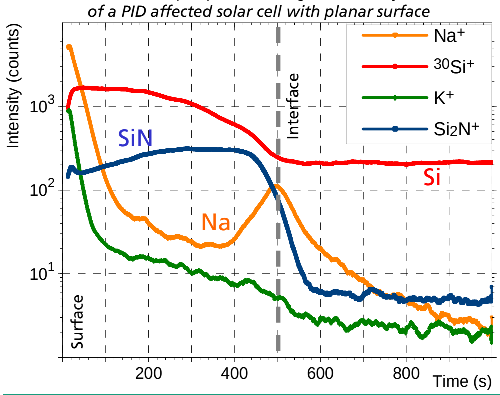
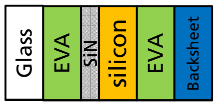
ToF-SIMS at PID samples

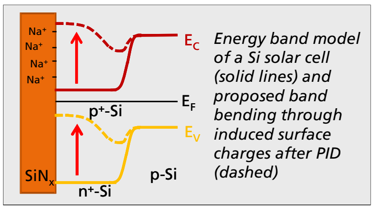
- Qualitative determination of Na distribution within the SiN anti-reflective layer at PID affected cell areas
- Extensive preparation necessary (delamination, removal of EVA from cells)
- Planar (non-textured) cell surface required for a reasonable depth resolution

ToF-SIMS depth profile though the SiN layer of a PID affected solar cell with planar surface



→ Elevated Na signal in SiN and Na peak at the interface between SiN and Si





Energy band model of a Si solar cell (solid lines) and proposed band bending through induced surface charges after PID (dashed)

V. Naumann et.al , Energy procedia, 2012

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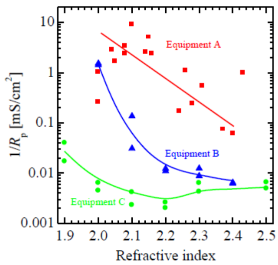
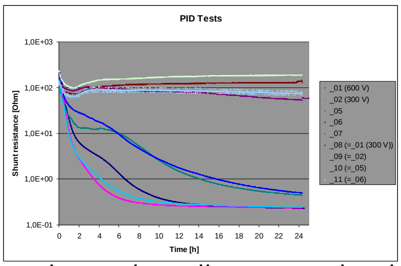
PID
How to avoid the effect?

- Solutions
  - System level
  - Cell level
  - Encapsulate

Current IEC test standards do not consider the effect → urgent update of the standards is required!





- Solution:
  - Fully integrated companies can solve on the cell or encapsulate level
  - Module manufacturers have to solve the problem on the encapsulate level

Nagel, PVSEC 2011

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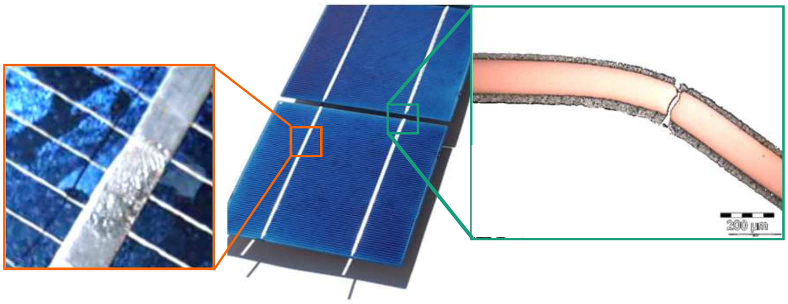
Copper Ribbons as Solar Cell Interconnectors
Motivation – Scenario-of-Failure

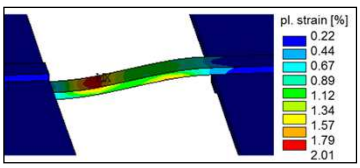


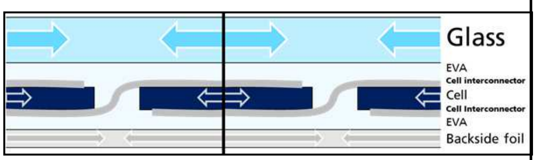
- Soldering process: mechanical and thermal coupling of ribbon and solar cell
  → different thermal contraction leads to mechanical stresses
  → loading of brittle solar cells → Danger: ***Cell breakage***

- Changes in thermal / mechanical load cause cell displacement within module
  → cyclic loading of the cell interconnectors between neighboring cells
  → Danger: ***Fatigue of the cell interconnectors***

Failure of copper ribbons

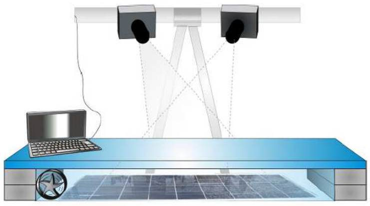
- Laboratory investigations have shown that fatigue of Cu ribbons is caused by temperature cycles
- Hypothesis: TC causes cell movement due to different CTEs and lead to a cyclic loading of the Cu ribbons which can fatigue the Cu ribbons
- Experimental investigations:
  - Measurement of cell movement during TC
  - Measurement of S-N (fatigue) curves of Cu ribbons



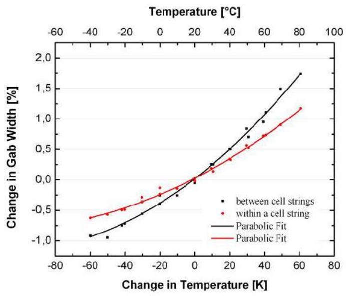


Measurement of cell movement

- A test setup was developed which allow to measure the movement of cell during temperature cycling



- Displacement of cells can be measured in a string and between strings can be measured
  - Displacement is non-linear (encapsulate)
  - E.g. during a cycle between -60 °C and +60° a displacement of 1.5 % occurs



Meier et. Al, SPIE 2011, PVSEC 2010

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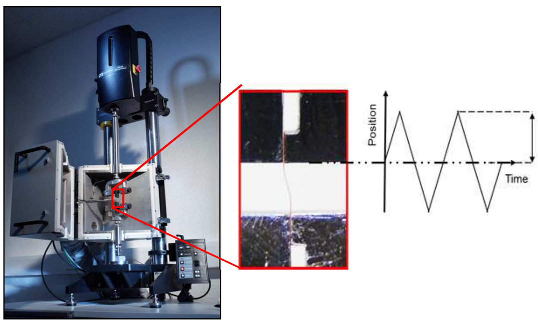
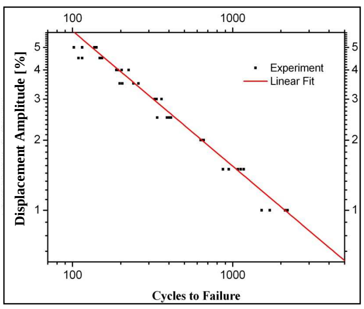
Copper Ribbons as Solar Cell Interconnectors
Fatigue of Ribbons

- Copper ribbons were tested under cyclic conditions (constant temperature, variation of amplitude)
- Fatigue experiments give fatigue model for the simulation
- Calculated position of highest local strain (from FEA) correlates with observed microstructural crack growth





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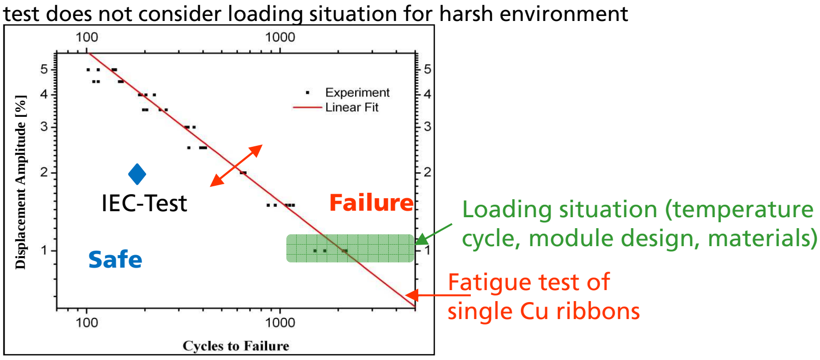
Combination of fatigue results and loading in module
Fatigue of Ribbons

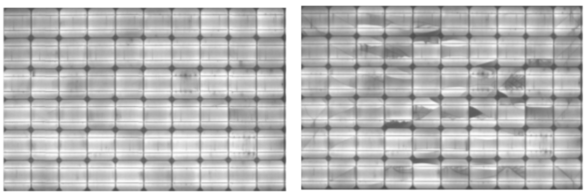
- Number of cycles can be predict from known fatigue-curve of the ribbon (have to measured for specific material) and the displacement amplitude of the cells in the module (have to measured for a specific module)
- Analysis can be performed which also consider various frequencies of amplitude displacement
- IEC test does not consider loading situation for harsh environment



Motivation
Observed crack initiation in solar cells in modules

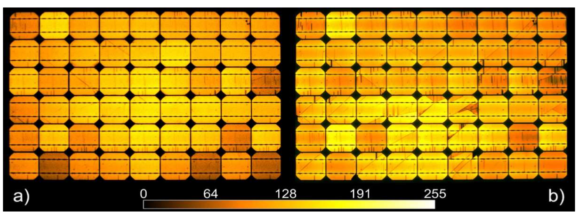
Cracks in solar modules after mechanical loading

EL images:
a) as delivered status
b) after loading a 2400 kPa (wind load)



Cracks in a commercial solar modules after temperature cycling

EL images:
a) as delivered status
b) after 20 temperature cycles from -40°C to 85°C



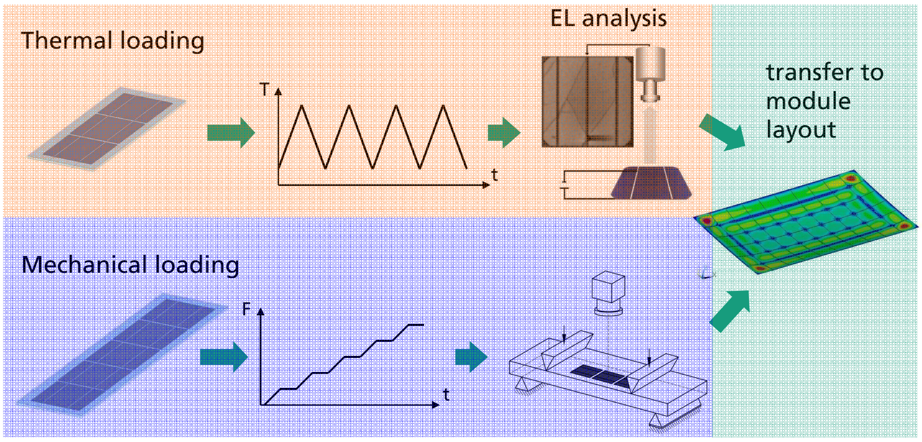
- Cracks, cause be wind, snow and thermal load, lead to power loss of modules and also subsequent effect like "snail trails"

Potthoff, ISFH; PV-Modul-Workshop, TÜV, 2008
Sander, Fraunhofer CSP, SPIE Optics and Photonics, 2010

Crack growth in embedded solar cells

Concept of investigation

- separate investigation of different stress influences



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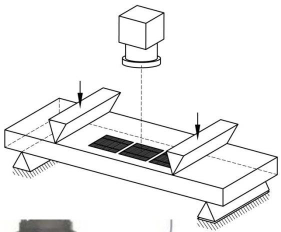
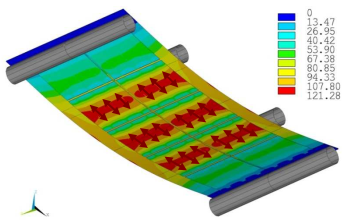
Crack growth in embedded solar cells

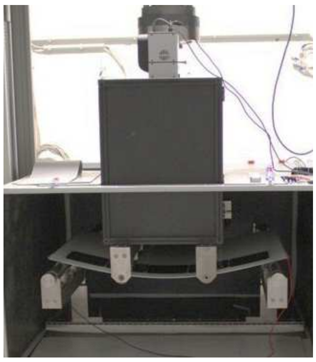
Test setup: Mechanical loading



- 4-point-bending to achieve constant stress value and to inspect cells during testing
- force is increased stepwise
- EL analysis at each load step



Finite element analysis: 1st principal stress in solar cells during 4 point bending



Test setup: EL analysis during mechanical load test

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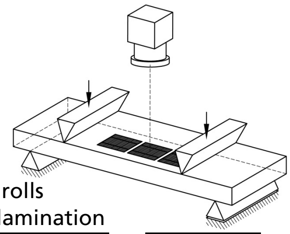
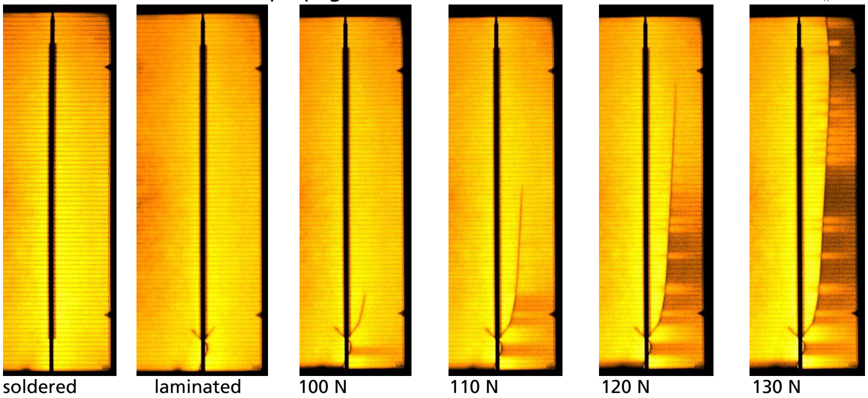
Crack growth in embedded solar cells
Results: Mechanical loading



Detail of specimen including monocrystalline solar cells, load rolls parallel to busbars → crack propagation at initial crack after lamination



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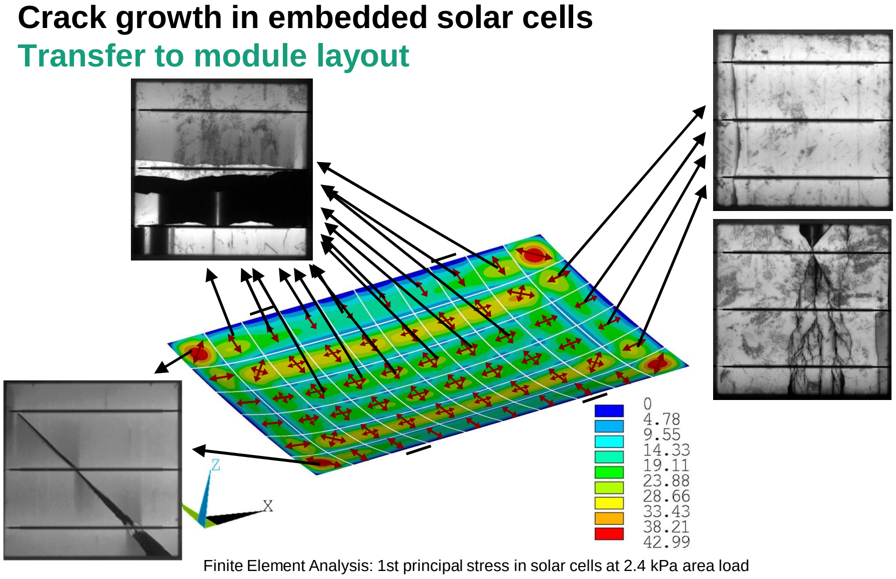
Crack growth in embedded solar cells
Transfer to module layout



Finite Element Analysis: 1st principal stress in solar cells at 2.4 kPa area load

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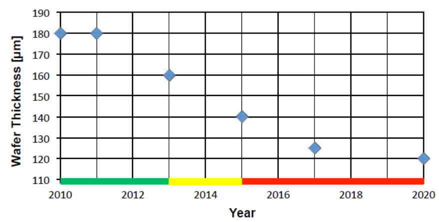
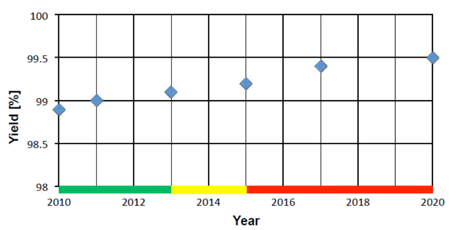
Reliability of further modules

Less silicon: Thinner cells

- Silicon still has the highest cost share in cell production → requirement of use of thinner wafers
- On the other hand:
  - Mechanical failure rate during cell fabrication has to decrease from 2% to 1 % in 2020
  - Lead free solders are required → higher thermo-mechanical stress due to higher soldering temperature
  - Thinner glass should be used (from 3.2 → 2.8 mm in 2020)
  - Yield in module fabrication should increase





http://www.itrpv.net/doc/roadmap_itrpv_2012_full_web.pdf

Reliability of further c-Si modules

Trends

- Reduction of cost (amount) of consumables:
  - Less silicon →thinner Wafers/Cells
  - Less silver → transfer to copper metallization (IRT 2015)
  - Module assembly materials (encapsulate, glass, ..)
  - Frameless concepts
  - Thinner glass
- Local production
  - It might be a opportunity for the future
  - Modules for local requirements
- Environmental and recycling issues
  - Lead free solder materials
  - Thermoplastic encapsulate ?

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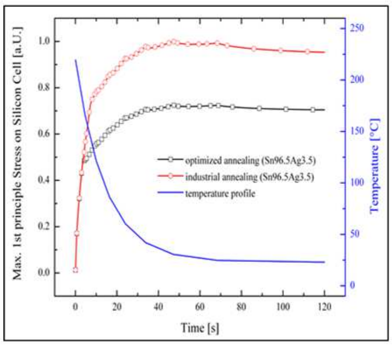
Reduction of stress in solar cells

Optimization of Cu ribbons

- Development of annealing test
- Optimization of annealing profile
- Microstructural analysis indicates further optimization potential
- Mechanical characterization gives material model for simulation
- Simulation quantifies reduced stresses generated during soldering process
- Experimental results verify simulation



Above: Simulation of mechanical stresses in the silicon cell generated during cooling from soldering temperature (lead-free solder)

Left: different microstructure morphologies generated by different annealing profiles

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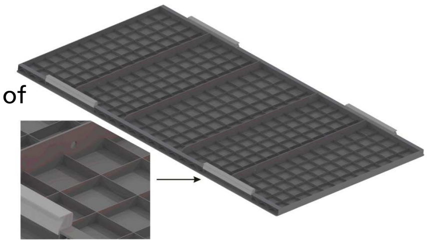
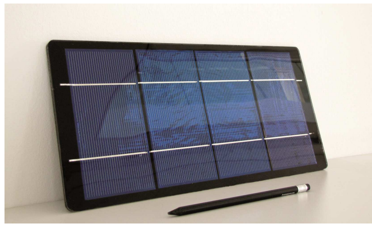
Low cost and light weight module with an polymer frame



- Module assembly has a share of ~ 30% of the overall cost
- Standard modules have a weight up to 20 kg

- A new frame structure is under development
  - Fiber reinforced plate
  - PMMA front side
  - PUR encapsulation
- Weight reduction: 12 kg
- Full size modules will be available in fall



Summary

- Crystalline Silicon Technology is the dominating PV technology, it is assumed that it will have a share of > 80% in the next years
- Strong market penetration during the last years, new technology developments together with the long-term warranties of modules cause reliability issues
  - PID- Potential induced degradation
  - Mechanical failure of cells and metallic interconnections
- Future technology developments are focused on
  - Increase of efficiency
  - Cost reduction
  - New Materials (ROHS, availability)
  - Local module production (?)
  - Specific modules (??)

Acknowledgment

- Co-workers at Fraunhofer CSP
  - Dr. Christian Hagendorf, Volker Naumann
  - Dr. Matthias Ebert, Dr. Stefan Schulze, Sascha Dietrich, Rico Meier, Jens Fröbel, Marti Sander
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