ACCURATE INDOOR DATA FOR ENERGY RATING

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Fraunhofer Institute for Solar Energy Systems ISE

PVPMC Workshop

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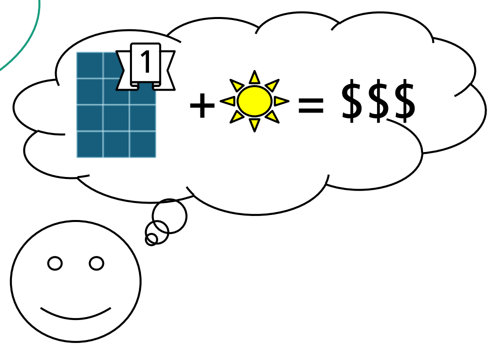
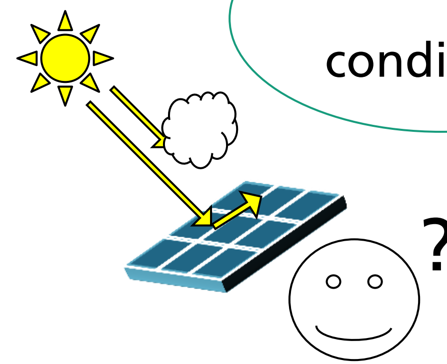
PV MODULE RATINGS

STC

Nominal power





Realistic

conditions

- Standardized testing for energy rating (e.g. IEC 61853)
  - Angle-of-incidence (AOI) effects
  - Spectral response
  - Absolute module temperature
  - Irradiance and temperature coefficients

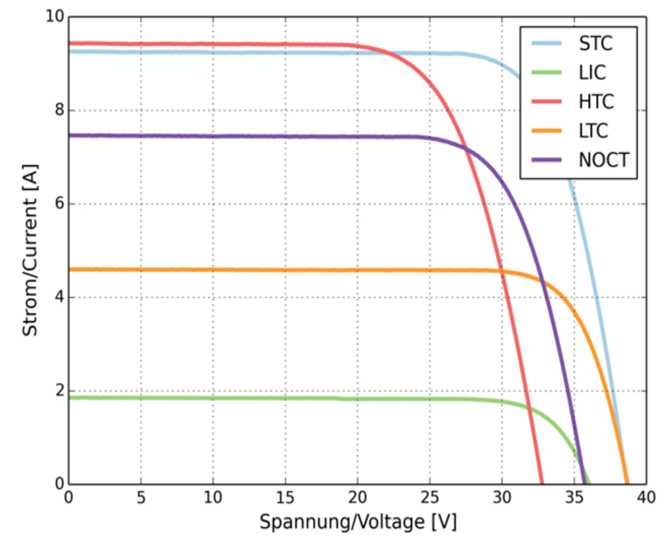
OUTLINE

- PV Modules
  - Irradiance and temperature coefficients
  - Angle-of-incidence (AOI) measurement

- PV Cells (Lower the uncertainty)
  - Temperature coefficients
  - Angle-of-incidence (AOI) measurement - A Study on front texturization

Characterization of PV Modules
Power Rating measurements in accordance to IEC 61853

- Power Rating Matrix:
  - mandatory (dark green)
  - at CalLab PV Modules (light green)
  - on request (grey)



Temperature in °Ct Irradiance in W/m²↓	15	25	NOCT	50	75
1100					
1000 (incl. TC)		STC			HTC
900					
800			NOCT		
700					
600					
500	LTC				
400					
300					
200		LIC			
100					

- CalLab PV Modules:
  IV(*T*) 15-75°C in 1K steps

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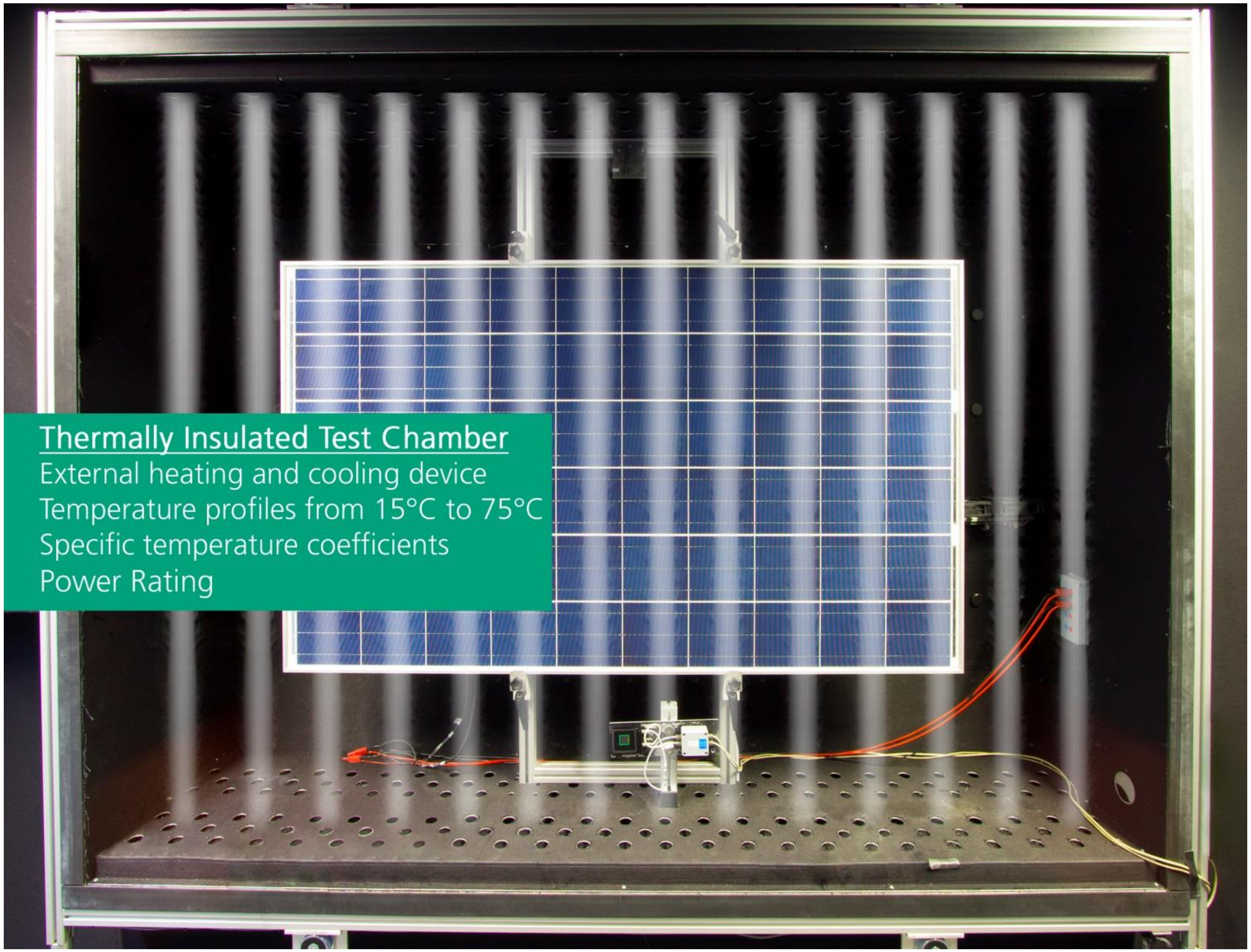
Characterization of PV Modules

Power Rating measurements in accordance to IEC 61853



Thermally Insulated Test Chamber

External heating and cooling device

Temperature profiles from 15°C to 75°C

Specific temperature coefficients

Power Rating

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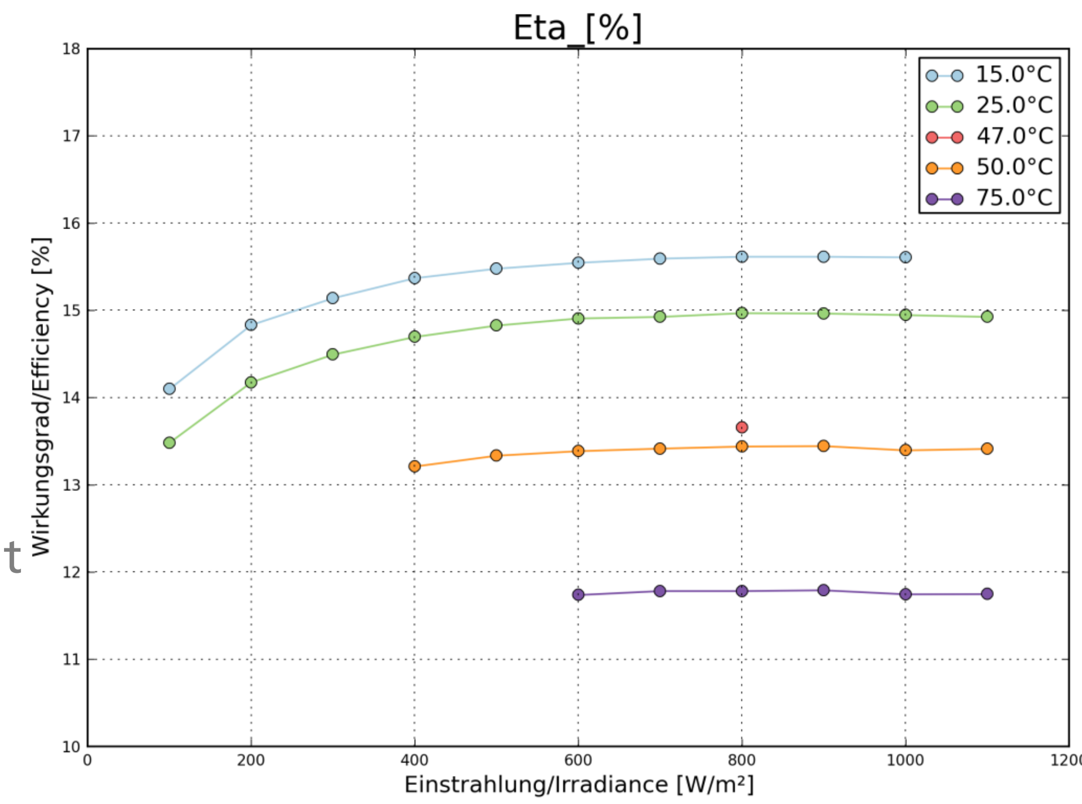
Characterization of PV Modules
Power Rating measurements in accordance to IEC 61853

Power Rating is characterization of modules by …

…determination of the irradiance dependency

…evaluation of the temperature coefficients

…determination of incident angle dependency



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Characterization of PV Modules

Power Rating measurements in accordance to IEC 61853

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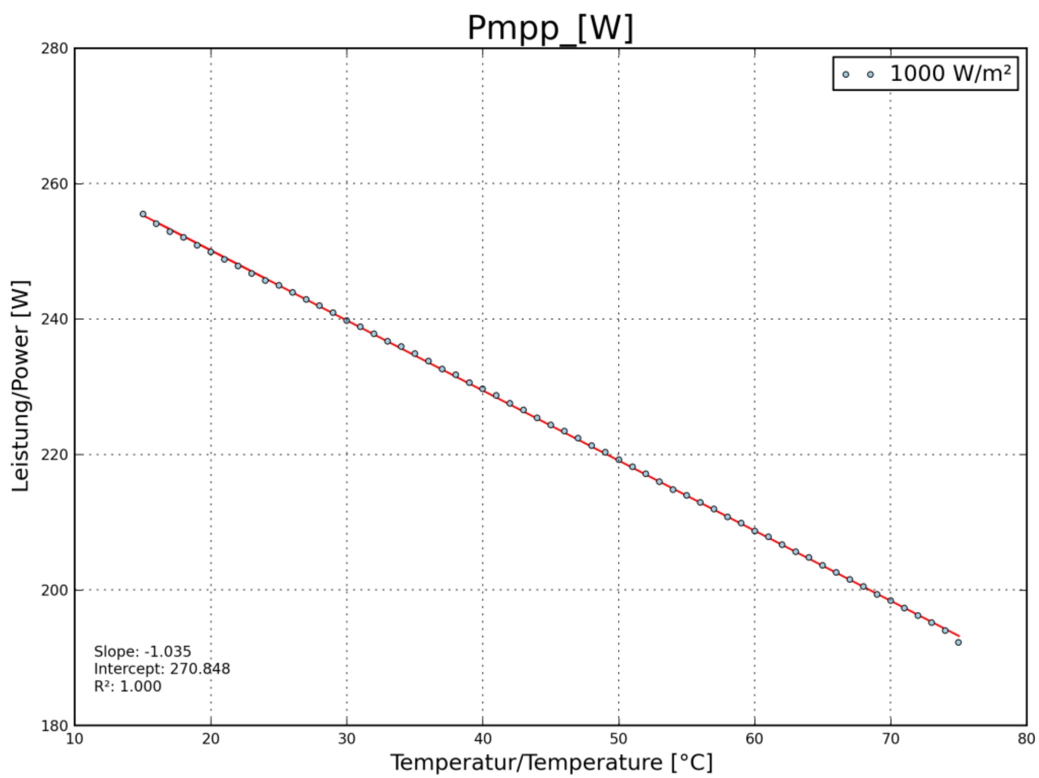

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Characterization of PV Modules
Power Rating measurements in accordance to IEC 61853

Power Rating is characterization of modules by …

…determination of the irradiance dependency

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…determination of incident angle dependency

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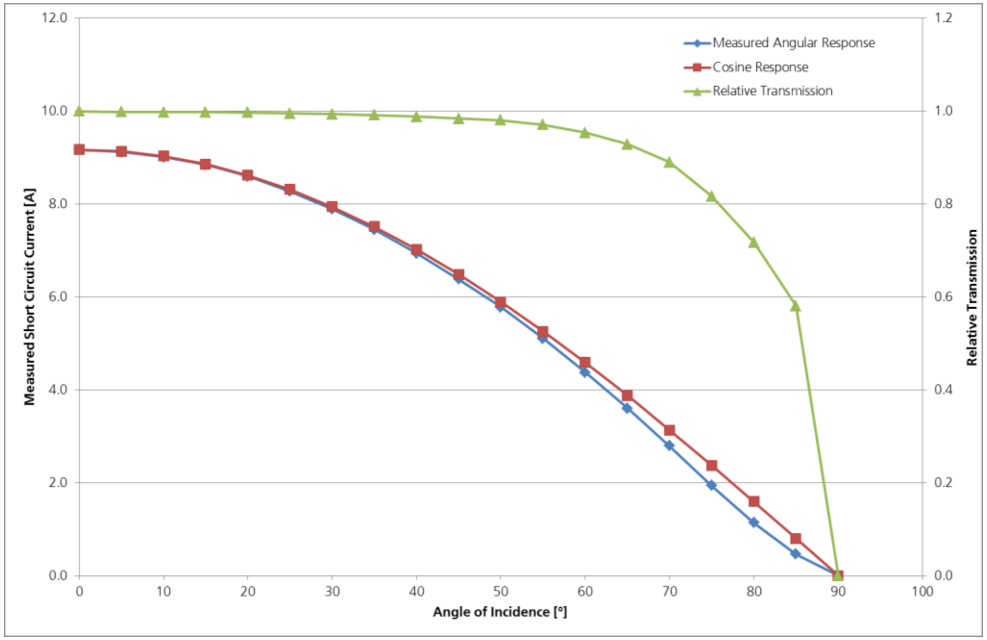
Characterization of PV Modules
Angular Response Measurement

- Part of standard IEC 61853-2
- Test set up to rotate module in fixed steps (~7° increments)
- Measurement on one single cell, either with electrical connection or by shading this cell
- Measured short circuit current is normalized to relative transmittance $\tau(AOI)$, which is the „incidence angle modifier (IAM)" used e. g. in PVSyst



Measured and normalized angular response of a typical PV module

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Characterization of PV Modules
Angular Response Measurement

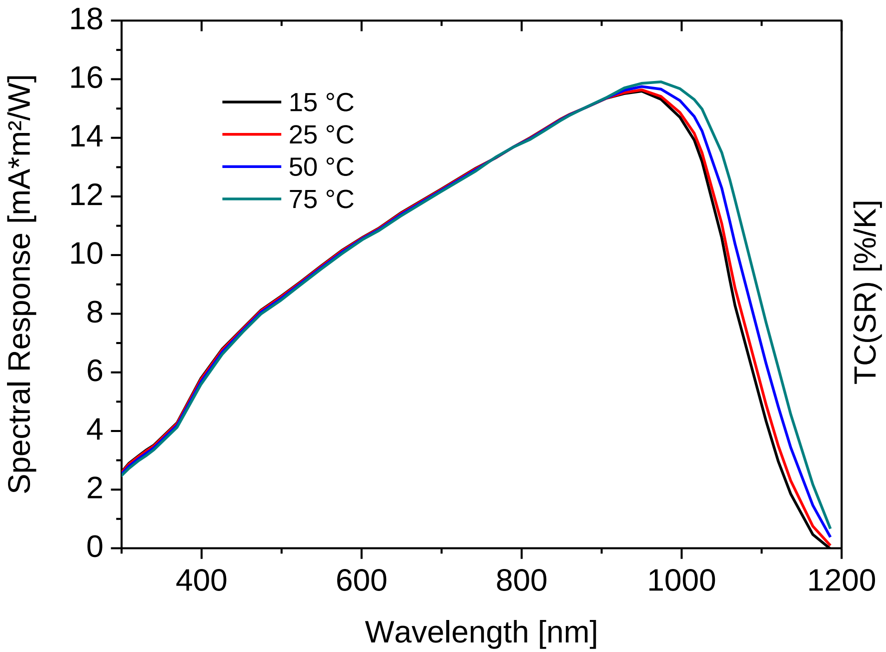
View from inside of the simulator on the tilted module

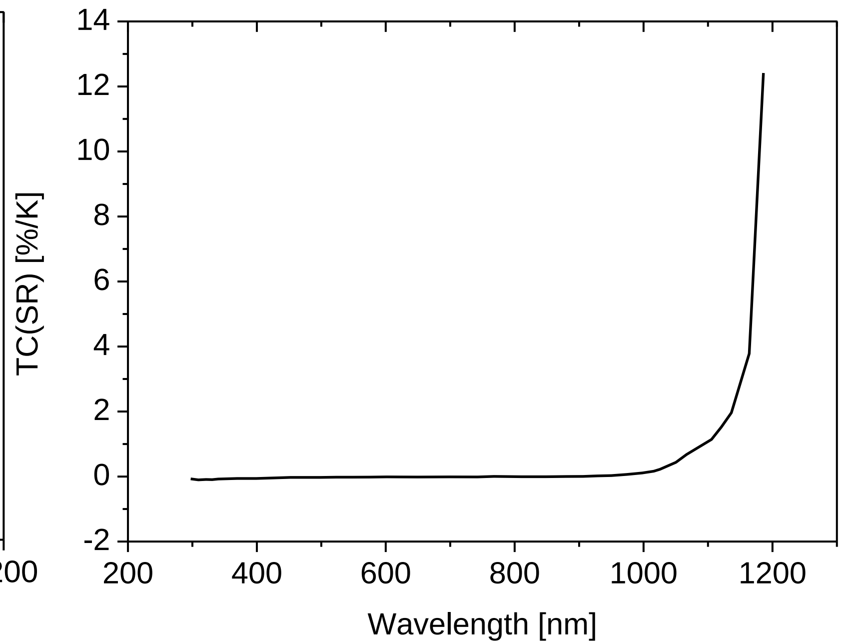
OUTLINE

- PV Modules
  - Irradiance and temperature coefficients
  - Angle-of-incidence (AOI) measurement

- PV Cells (Lower the uncertainty)
  - Temperature coefficients
  - Angle-of-incidence (AOI) measurement -
    A Study on front texturization

Temperature Coefficient Determination on Cells
T-Dependent Spectral Response





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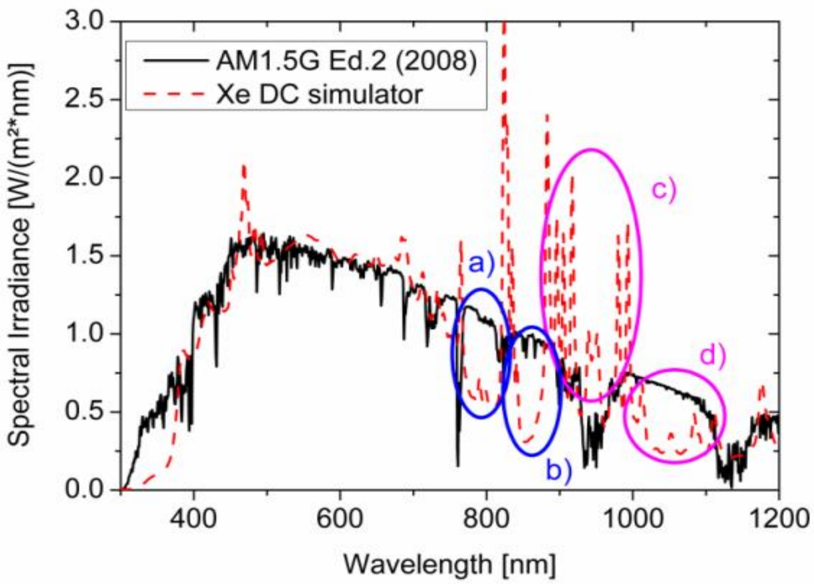
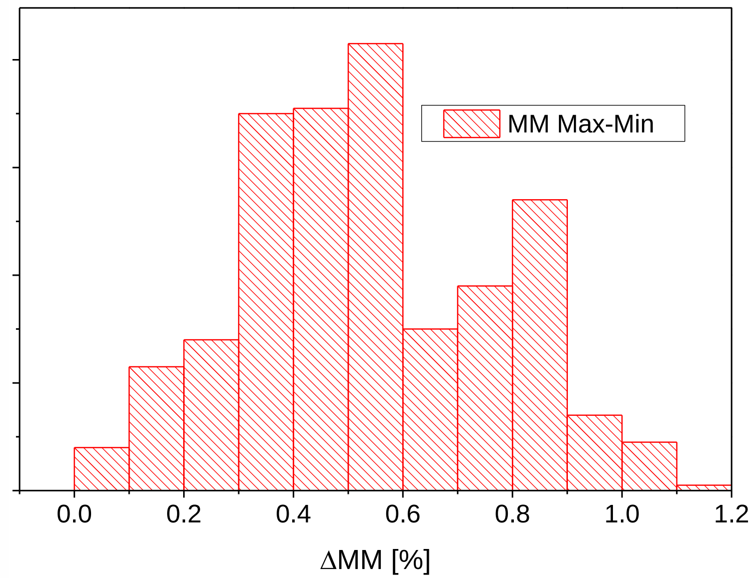
Temperature Coefficient Determination on Cells
T-Dependent Spectral Mismatch

- Class A Simulator Spectrum
- MM Change (T 15°C->75°C)





**Osterwald* et al., Temperature-Dependent Spectral Mismatch Corrections, IEEE JOURNAL OF PHOTOVOLTAICS

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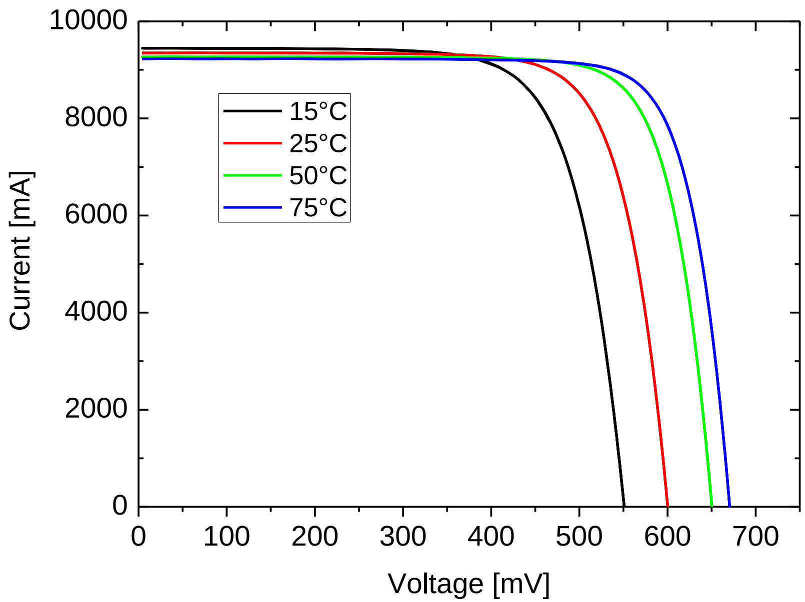
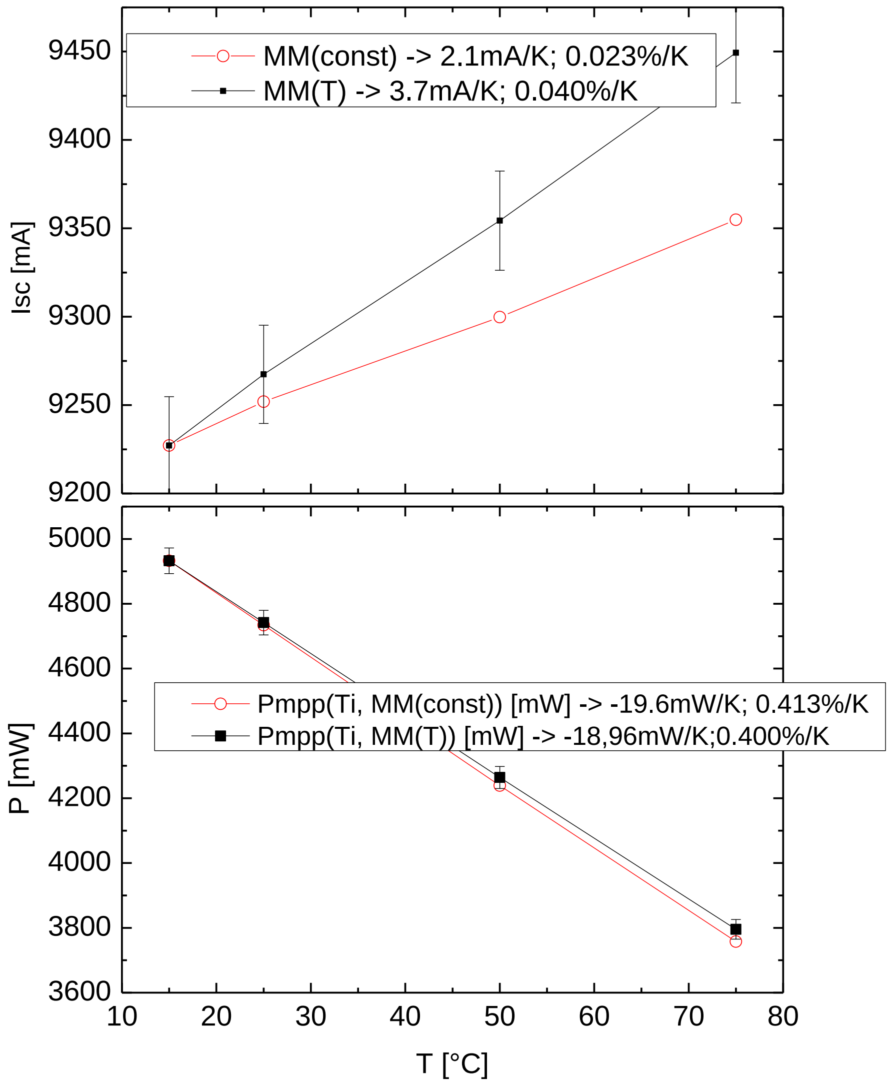
Temperature Coefficient Determination on Cells

MM(T) vs MM(const)

- Assumtion: 1% MM Change
  (T 15°C->75°C)





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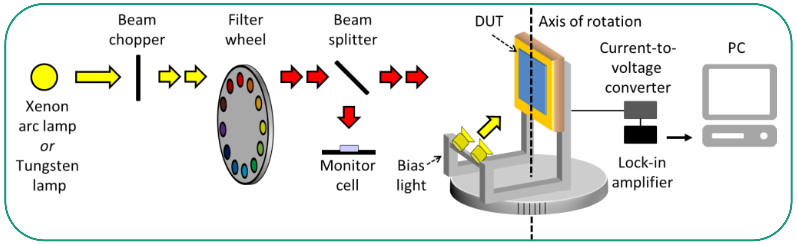
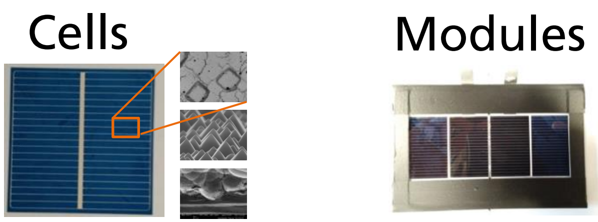
Texturization Study

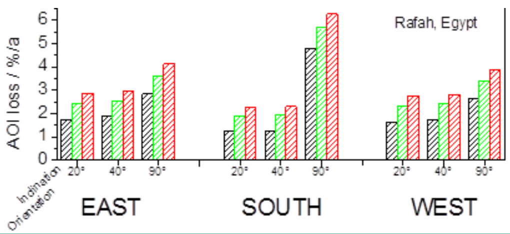
- Angular spectral response
  - Measurement setup
  - Uncertainty analysis



- Test samples (cells & modules)
  - Different front surface textures



- Energy rating



*Geisemeyer et al., Angle Dependence of Solar Cells and Modules: The Role of Cell Texturization, DOI: 10.1109/JPHOTOV.2016.2614120

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Measurement of AOI Effects
Integral vs. Spectrally Resolved

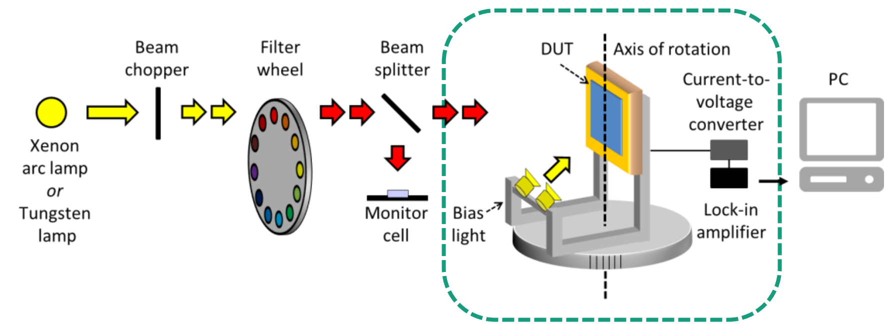
- Why spectrally resolved?
  - Understand differences
  - Validate simulation models
  - Low measurement uncertainty

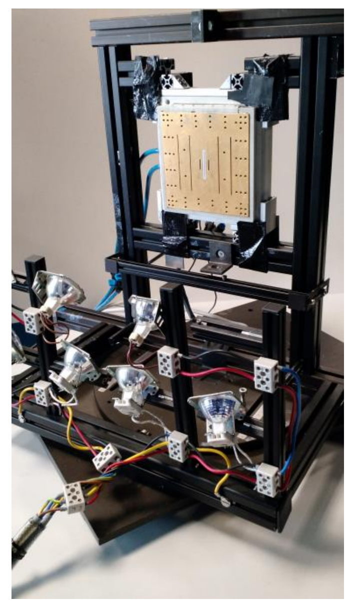
**Geisemeyer* et al., Angle Dependence of Solar Cells and Modules: The Role of Cell Texturization, DOI: 10.1109/JPHOTOV.2016.2614120

Angular Spectral Response (SR)
Measurement Setup

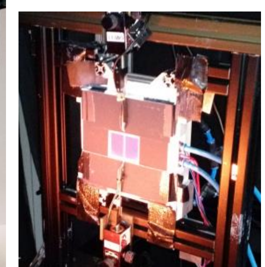
- Filter monochromator
  - Two light sources
  - Lock-in procedure
  - Fully illuminated sample

- Rotary measurement unit
  - T-control
  - Rotating bias light
    - Separates injection-dep.
  - One axis of rotation

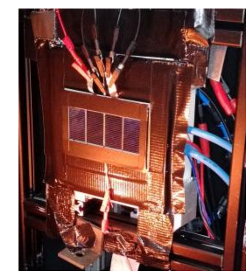




Cells



Modules



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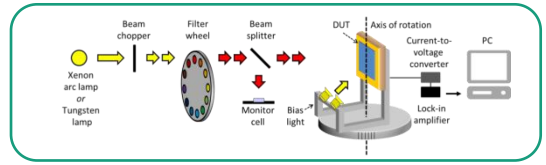
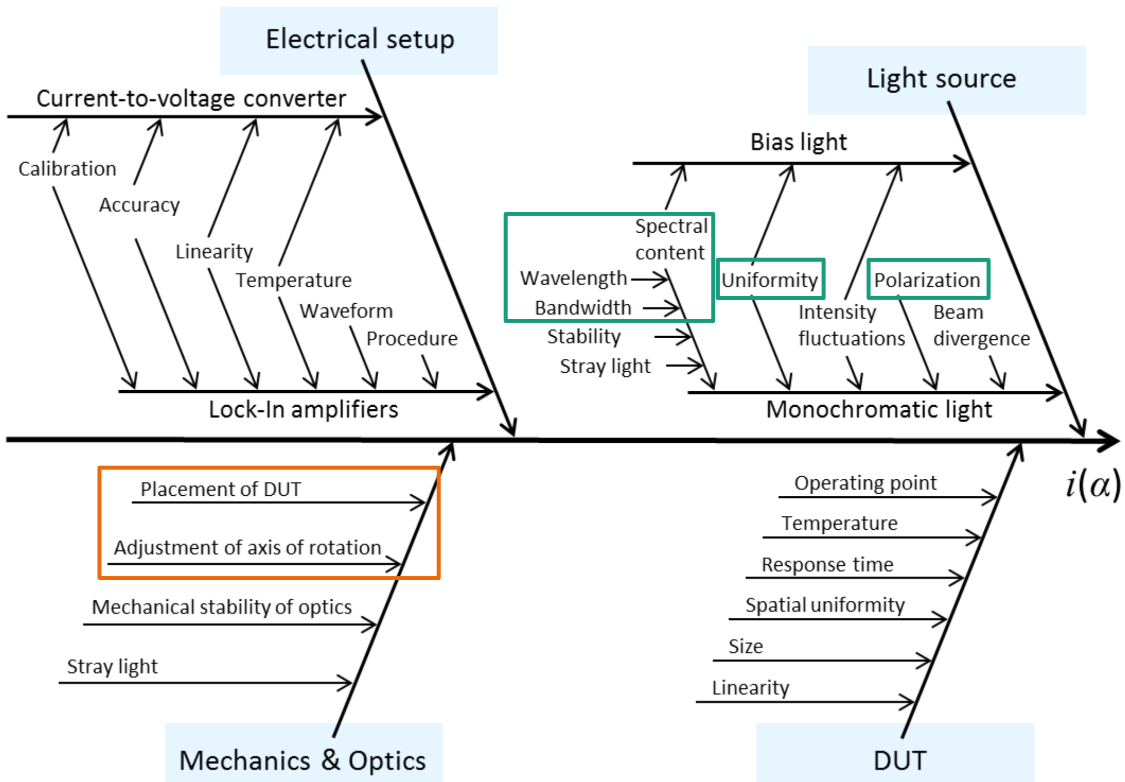
Angular Spectral Response (SR)
Uncertainty Analysis



- Based on measured data
  - Spectral content
  - Polarization
  - Uniformity
  - Angular response of different cells and modules



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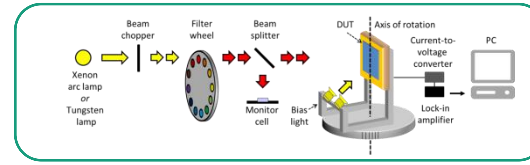
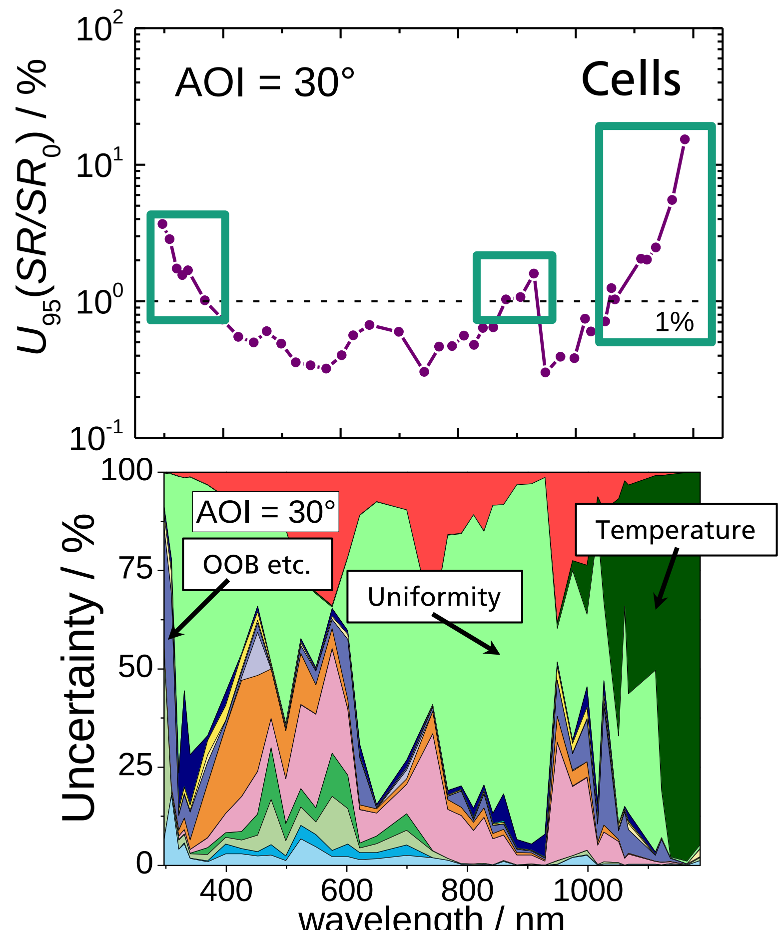
Change in Angular SR
Uncertainty Analysis



- AOI = 30°: 95% confidence level typically below 1%
  - UV: Out-of-band radiation, bandwidth, etc…
  - Visible/NIR: Position of sample and associated uniformity correction
  - NIR: Temperature



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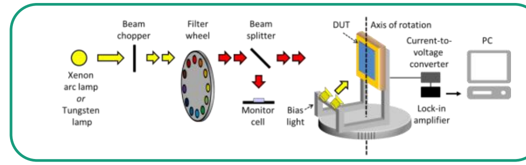
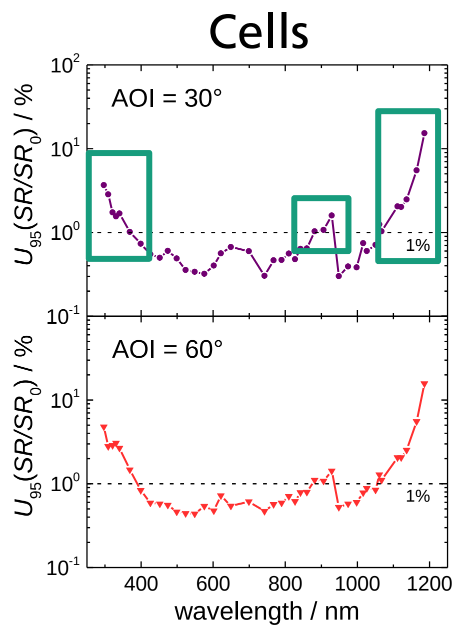
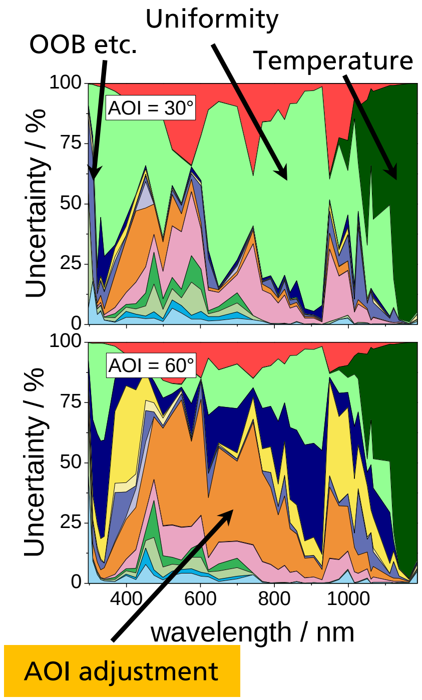
Change in Angular SR
Uncertainty Analysis



- AOI = 30°: 95% confidence level typically below 1%
  - UV: Out-of-band radiation, bandwidth, etc…
  - Visible/NIR: Position of sample and associated uniformity correction
  - NIR: Temperature
- AOI = 60°: Increasing influence of adjustment of rotating frame (AOI adjustm.)





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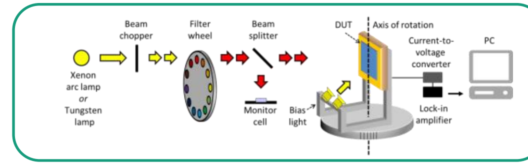
Uncertainty Analysis



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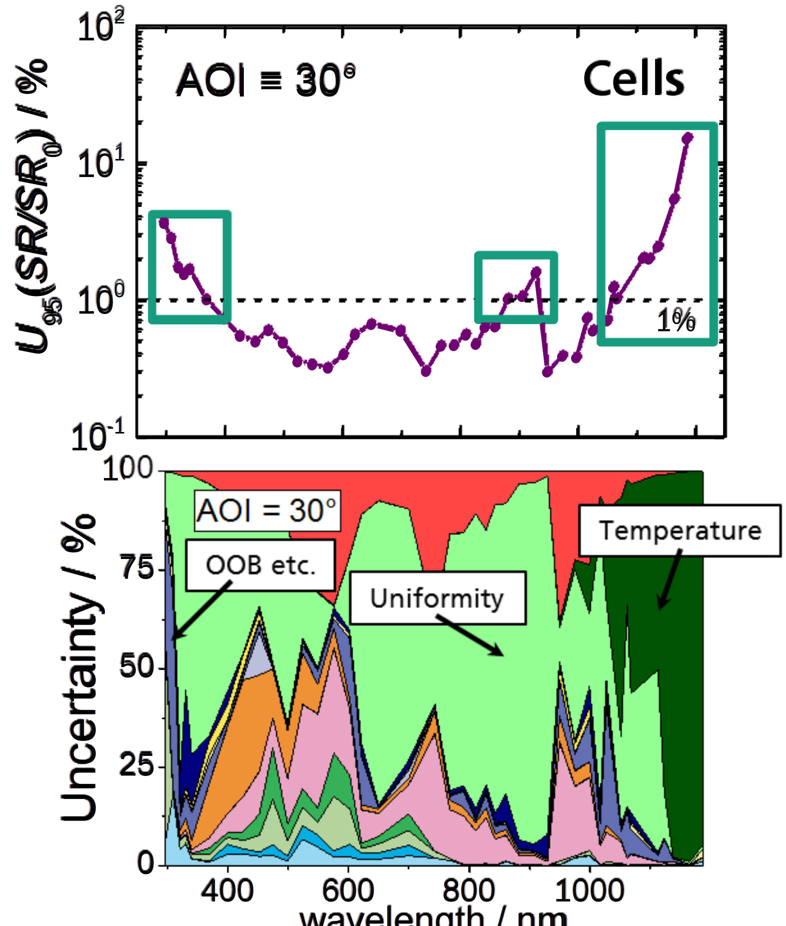
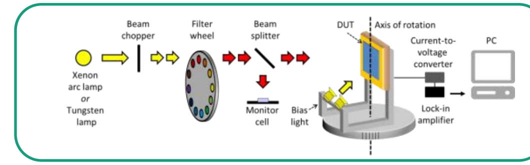


Change in Angular SR
Uncertainty Analysis



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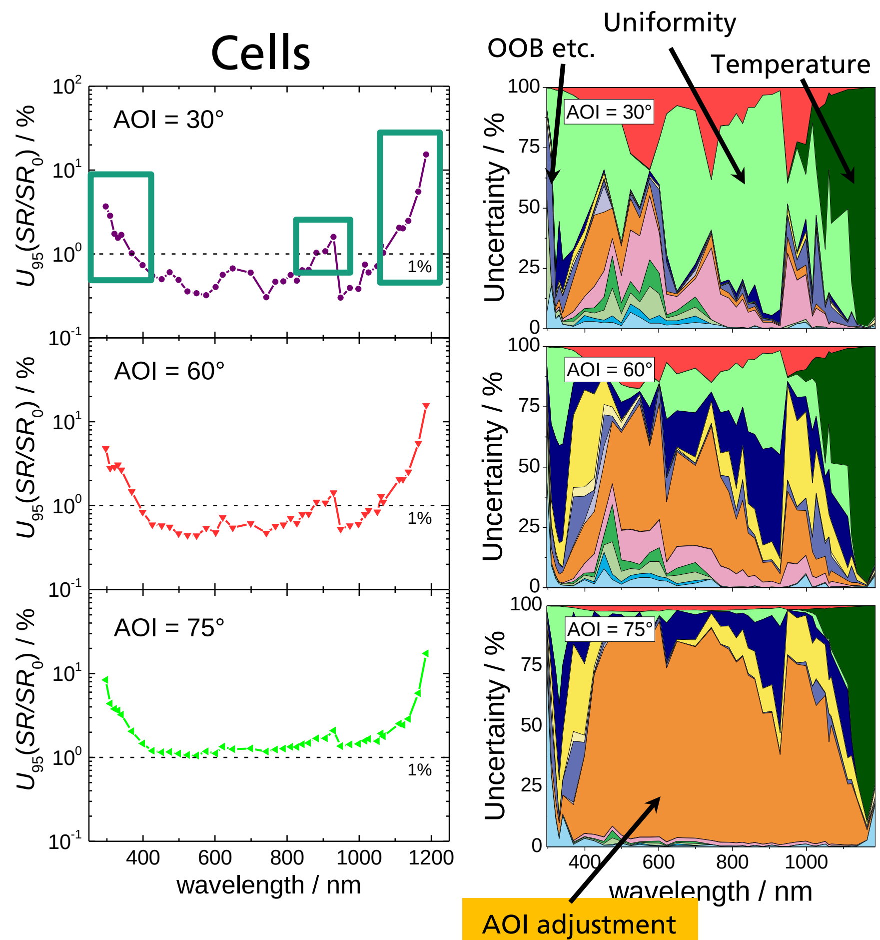
  - Visible/: NIR Position of sample and associated uniformity correction
  - NIR: Temperature
- AOI = 60°: Increasing influence of adjustment of rotating frame (AOI adjustm.)
- AOI = 75°: AOI adjustment dominates



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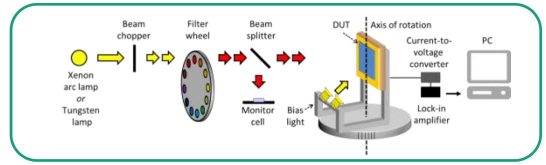
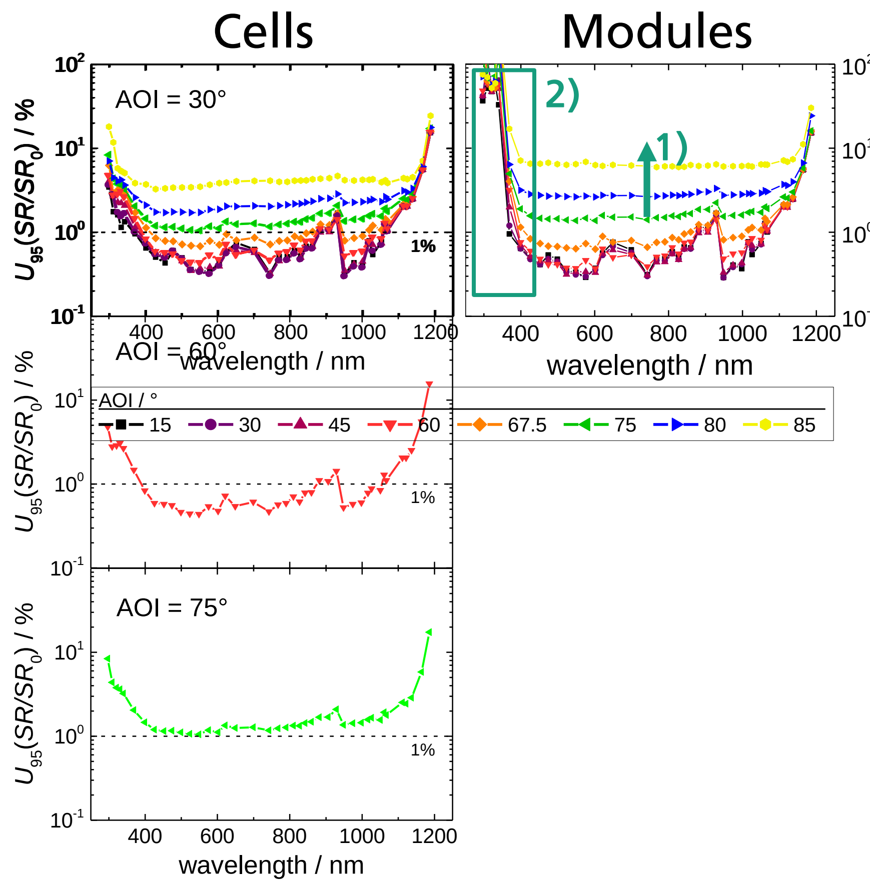
Change in Angular SR
Uncertainty Analysis



- Differences in measurement uncertainty for cells and modules
  - AOIs > 60°: angle adjustment more critical
  - UV: low signal due to EVA



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Change in Angular SR
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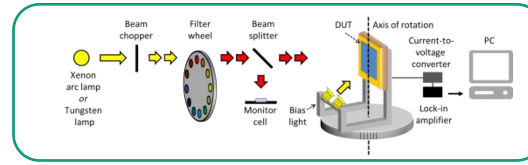

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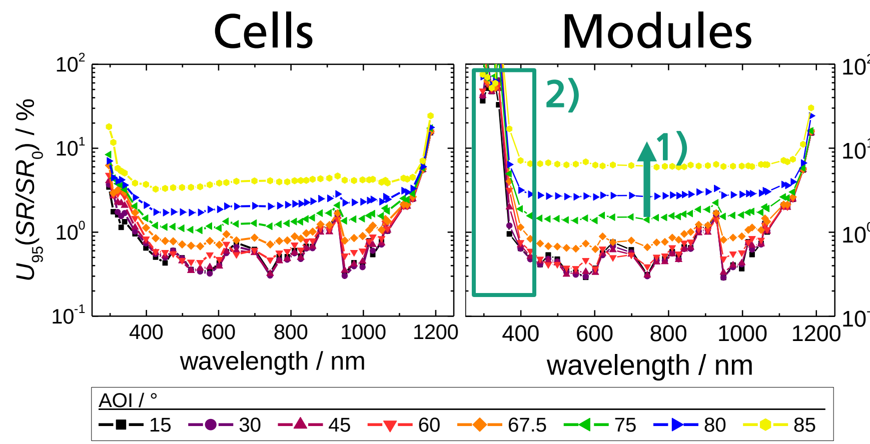
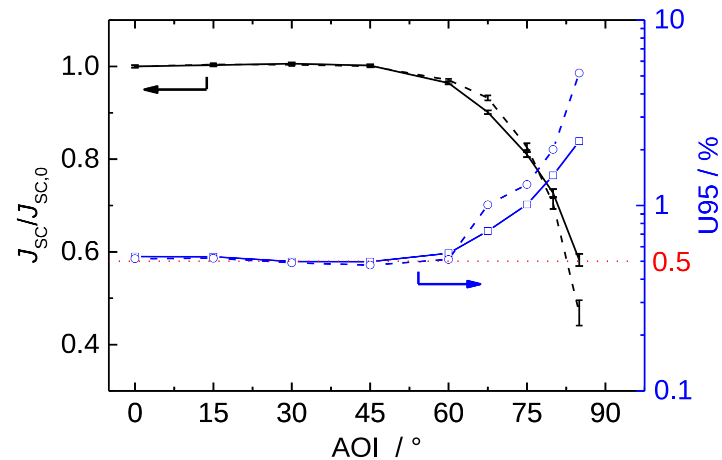


- Change in J_{SC}:
  - Monte Carlo simulation
  - Random walks for correlations w.r.t wavelength
- Lowest measurement uncertainty reported for relative measurement



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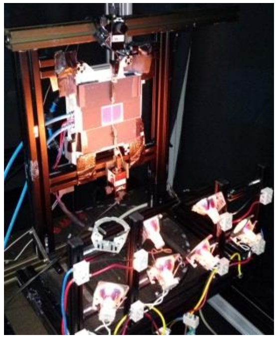
Samples
Cells and Modules

- Six cells
  - Small area 5 x 5 cm²
  - *p*-type Al-BSF
  - Contacted via micromanipu-lators with Kelvin probes



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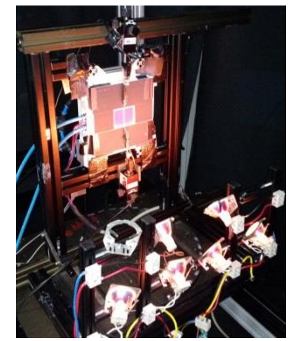
Samples
Cells and Modules

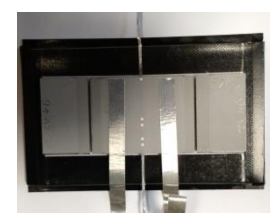
- Six cells
  - Small area 5 x 5 cm^2
  - *p*-type Al-BSF
  - Contacted via micromanipu-lators with Kelvin probes
- Modules
  - Planar glass
  - Dummy half cells
  - Open rear
    - El. conductive tape
    - Th. conductive gray pad



Side view

Front view

Rear view



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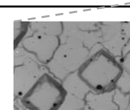
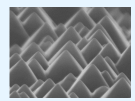
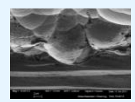
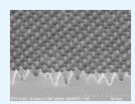
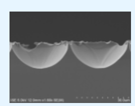
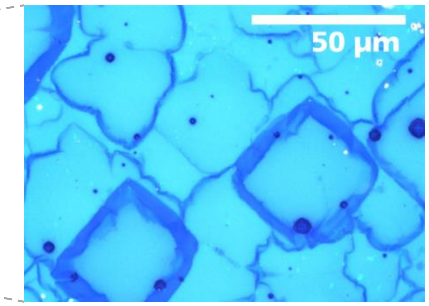
Samples
Front Surface Textures

Texture	Substrate	
PLANAR (chemically polished)	Cz-Si	
RANDOM PYRAMIDS (alkaline-textured)	Cz-Si	
ISOTEXTURE (acidic-textured)	mc-Si	
NIL-HC (nano-imprinted honeycombs) *Volk et al., *IEEE JPV 5*, 1027-1033, 2015	mc-Si	
LW-HC (laser-structured honeycombs) *Volk et al., *28th EUPVSEC*, 1024-1028, 2013	mc-Si	
NANO (shallow nano-textured) *Kafle et al., Solmat 152, 94-102, 2016	mc-Si	



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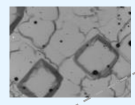
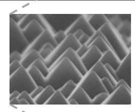
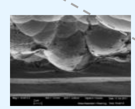
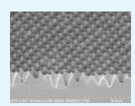
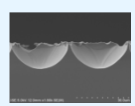
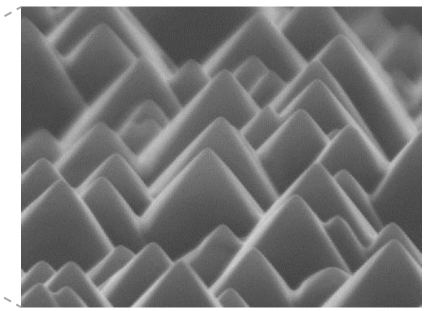
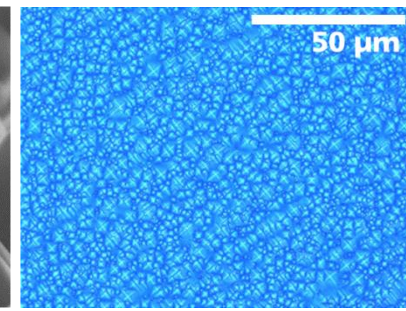
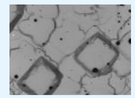
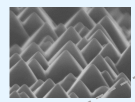
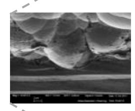
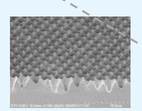
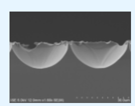
PLANAR (chemically polished)	Cz-Si	
RANDOM PYRAMIDS (alkaline-textured)	Cz-Si	
ISOTEXTURE (acidic-textured)	mc-Si	
NIL-HC (nano-imprinted honeycombs) *Volk et al., *IEEE JPV 5*, 1027-1033, 2015	mc-Si	
LW-HC (laser-structured honeycombs) *Volk et al., 28th *EUPVSEC*, 1024-1028, 2013	mc-Si	
NANO (shallow nano-textured) *Kafle et al., Solmat 152, 94-102, 2016	mc-Si	

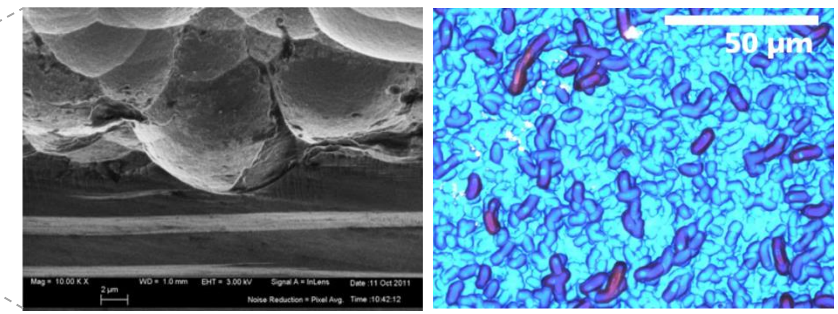




*Geisemeyer et al., Angle Dependence of Solar Cells and Modules: The Role of Cell Texturization, DOI: 10.1109/JPHOTOV.2016.2614120

Samples
Front Surface Textures

Texture	Substrate	
PLANAR (chemically polished)	Cz-Si	
RANDOM PYRAMIDS (alkaline-textured)	Cz-Si	
ISOTEXTURE (acidic-textured)	mc-Si	
NIL-HC (nano-imprinted honeycombs) *Volk et al., *IEEE JPV 5*, 1027-1033, 2015	mc-Si	
LW-HC (laser-structured honeycombs) *Volk et al., 28th *EUPVSEC*, 1024-1028, 2013	mc-Si	
NANO (shallow nano-textured) *Kafle et al., Solmat 152, 94-102, 2016	mc-Si	



**Geisemeyer* et al., Angle Dependence of Solar Cells and Modules: The Role of Cell Texturization, DOI: 10.1109/JPHOTOV.2016.2614120

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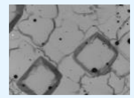
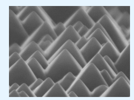
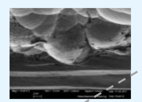
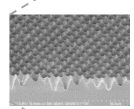
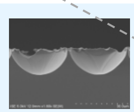
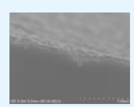
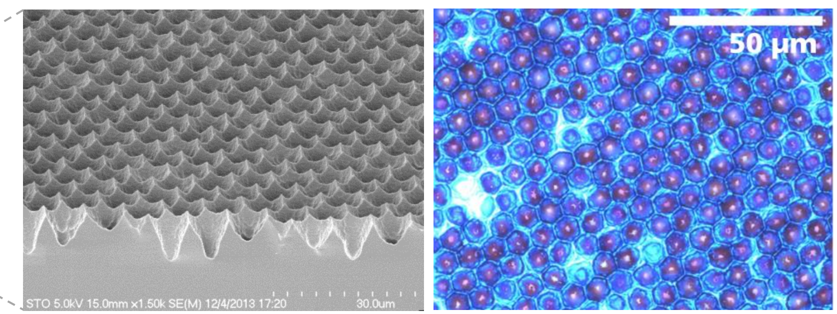
PLANAR (chemically polished)	Cz-Si	
RANDOM PYRAMIDS (alkaline-textured)	Cz-Si	
ISOTEXTURE (acidic-textured)	mc-Si	
NIL-HC (nano-imprinted honeycombs) *Volk et al., *IEEE JPV 5*, 1027-1033, 2015	mc-Si	
LW-HC (laser-structured honeycombs) *Volk et al., 28th *EUPVSEC*, 1024-1028, 2013	mc-Si	
NANO (shallow nano-textured) *Kafle et al., Solmat 152, 94-102, 2016	mc-Si	



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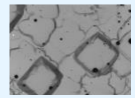
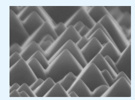
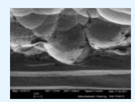
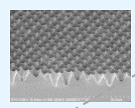
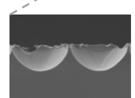
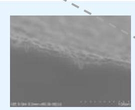
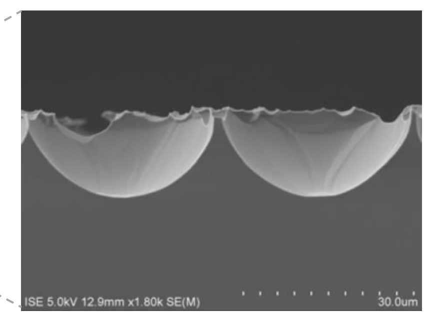
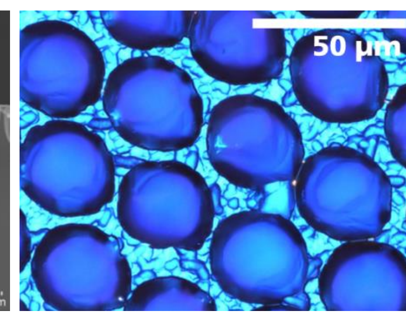
Samples
Front Surface Textures

Texture	Substrate	
PLANAR (chemically polished)	Cz-Si	
RANDOM PYRAMIDS (alkaline-textured)	Cz-Si	
ISOTEXTURE (acidic-textured)	mc-Si	
NIL-HC (nano-imprinted honeycombs) *Volk et al., *IEEE JPV 5*, 1027-1033, 2015	mc-Si	
LW-HC (laser-structured honeycombs) *Volk et al., *28th EUPVSEC*, 1024-1028, 2013	mc-Si	
NANO (shallow nano-textured) *Kafle et al., Solmat 152, 94-102, 2016	mc-Si	





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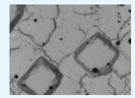
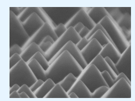
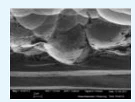
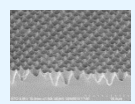
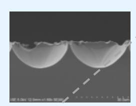
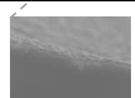
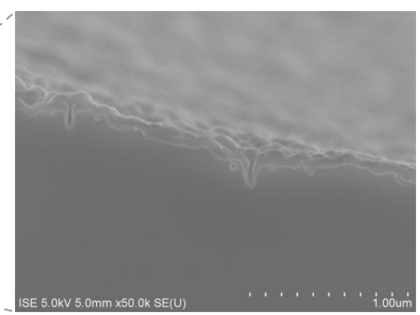
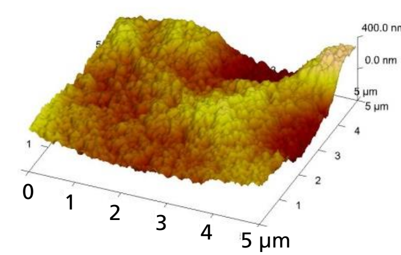
Samples
Front Surface Textures

Texture	Substrate	
PLANAR (chemically polished)	Cz-Si	
RANDOM PYRAMIDS (alkaline-textured)	Cz-Si	
ISOTEXTURE (acidic-textured)	mc-Si	
NIL-HC (nano-imprinted honeycombs) *Volk et al., *IEEE JPV 5*, 1027-1033, 2015	mc-Si	
LW-HC (laser-structured honeycombs) *Volk et al., *28th EUPVSEC*, 1024-1028, 2013	mc-Si	
NANO (shallow nano-textured) *Kafle et al., Solmat 152, 94-102, 2016	mc-Si	





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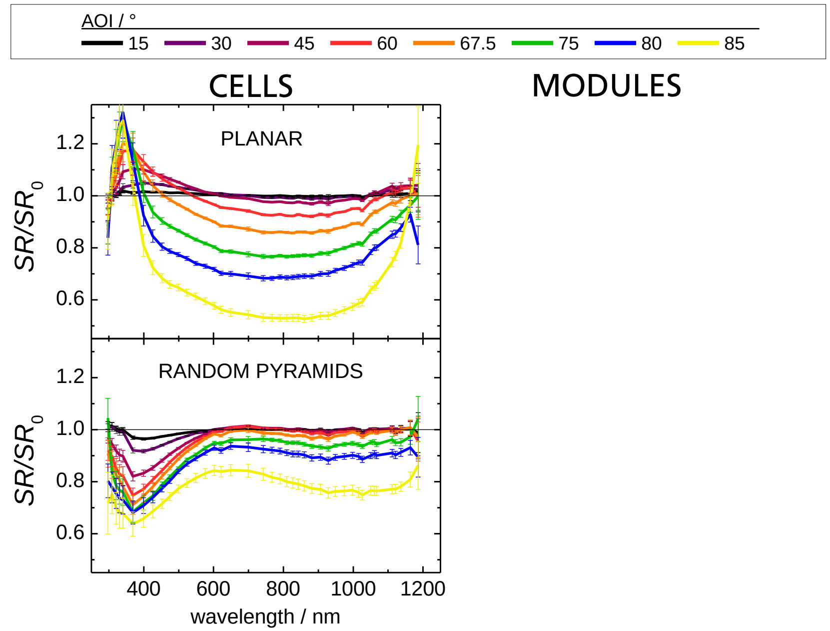
Results
Change in Angular SR



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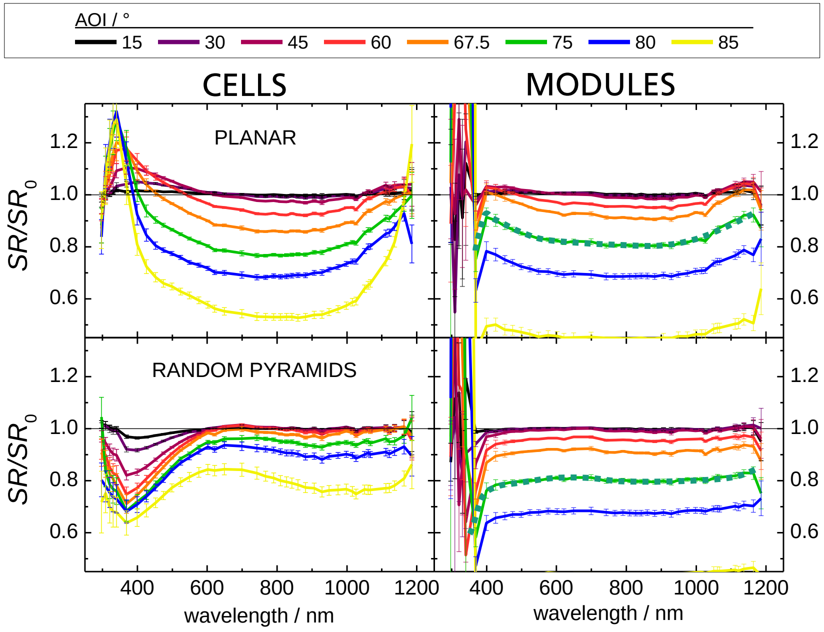
Results
Change in Angular SR

- Module level
  - More similar characteristics
  - Effects of texture still observable



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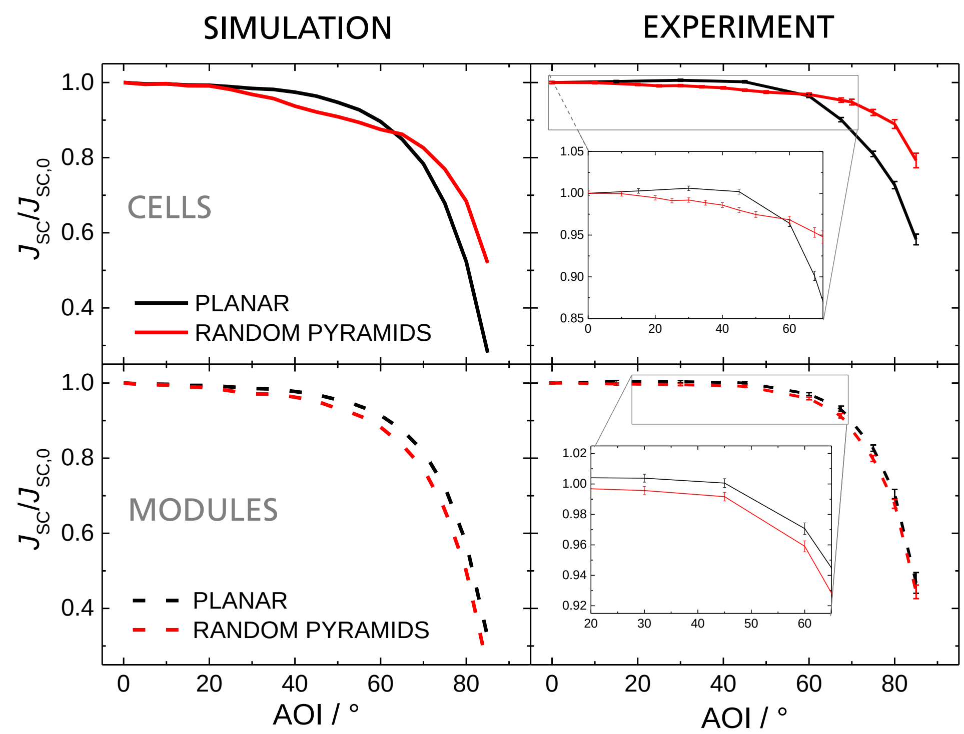
Results
Change in J_{SC}

<u>Cells</u>

- PLANAR: Stronger decrease for AOI > 60°
- RP: Distinct near-linear decrease for AOI > 15°

<u>Modules</u>

- Differences in the range of 1%
- RP: Stronger AOI dependence



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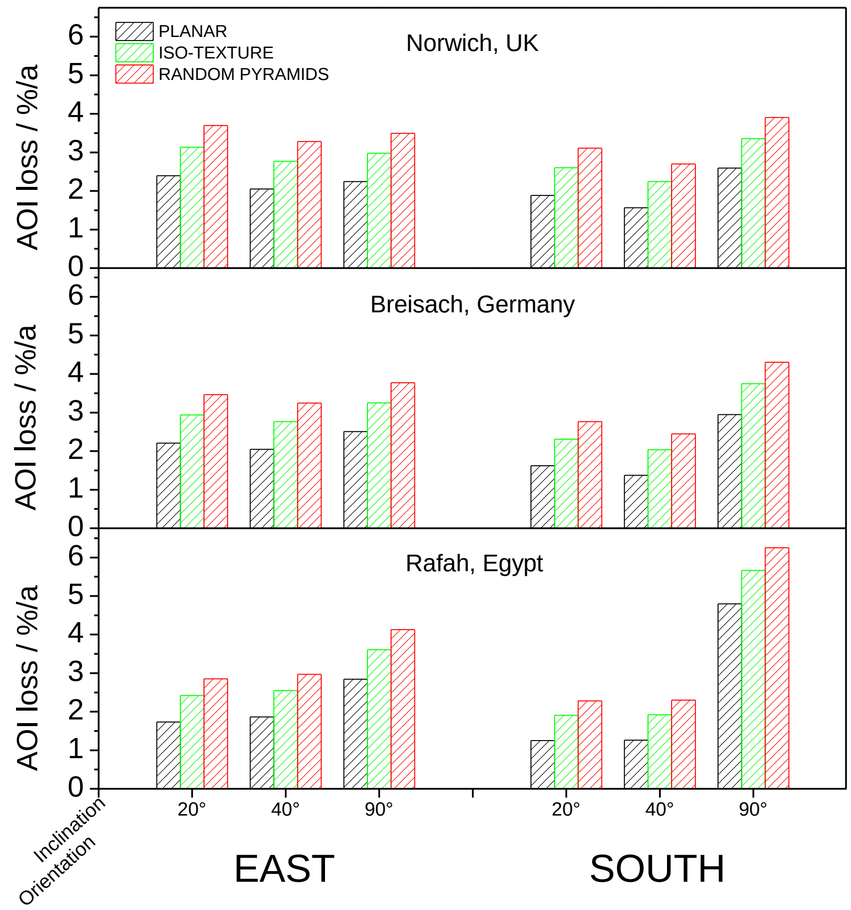
Energy Rating with Measured Data

Change in J_{SC}

- Three different climate zones
- SolarGIS weather data
  - 10 years
  - 15 min resolution
  - Separated direct and diffuse (AOI 55°) irradiation
- Three module orientations
- Three inclination angles



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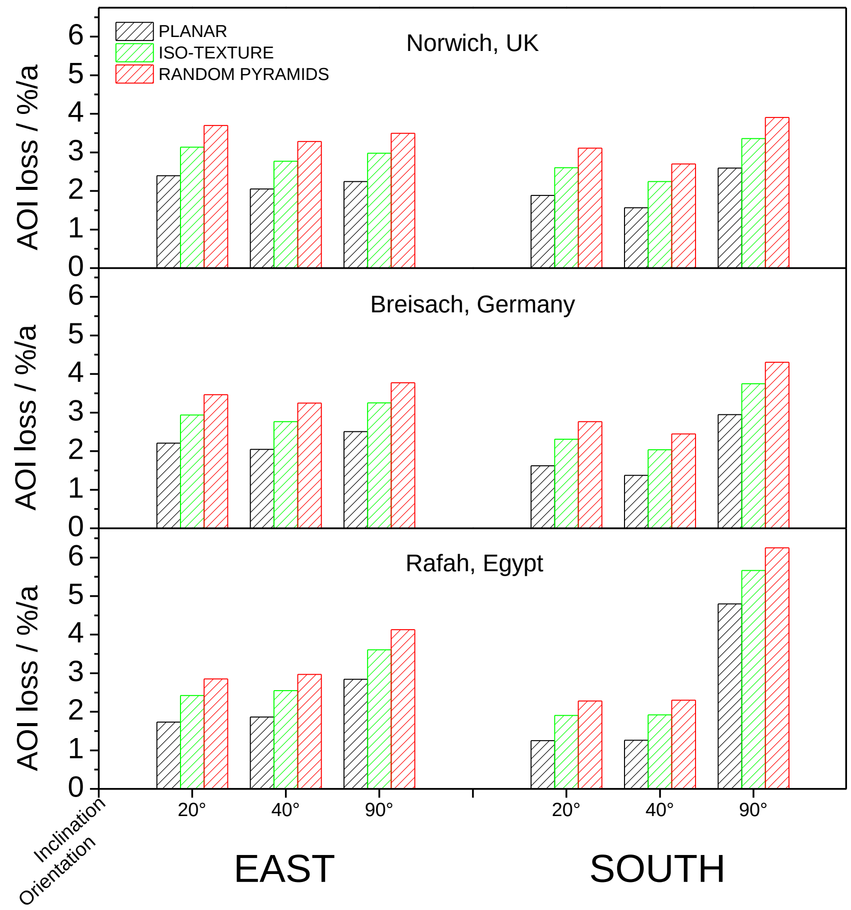
Energy Rating with Measured Data

Change in J_{SC}

- Typically 2-4 % annual loss due to AOI dependence
- Up to 1.5 % difference due to front texture



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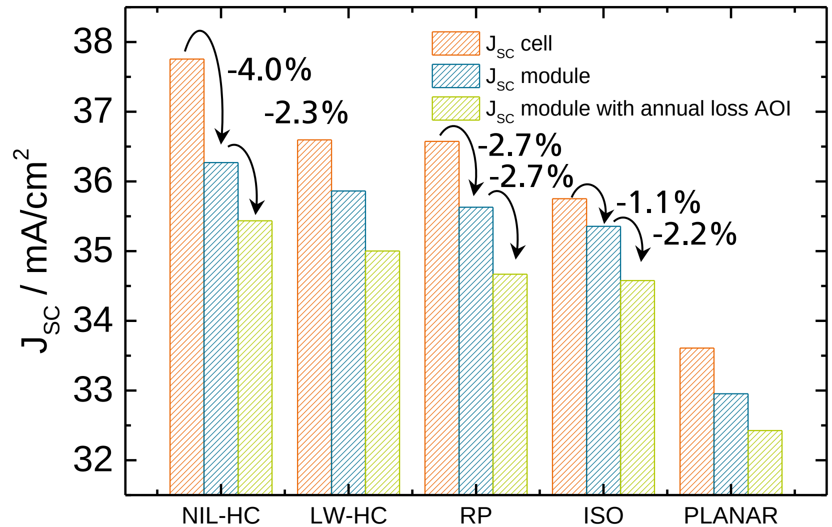
Energy Rating with Measured Data

Cell-to-Module Losses in J_{SC}

- Convolution of SR with AM1.5g (before and after encapsulation)
- Simulated annual AOI loss (based on measured data)
- Cell-to-module:
  - NIL-HC: -4.0 %
  - RP: -2.7 %
  - ISO: -1.1 %
- AOI losses:
  - RP loses initial advantage over ISO almost completely



Norwich (UK), Orientation: South, Inclination: 40°

Small area laboratory cells and mini modules!

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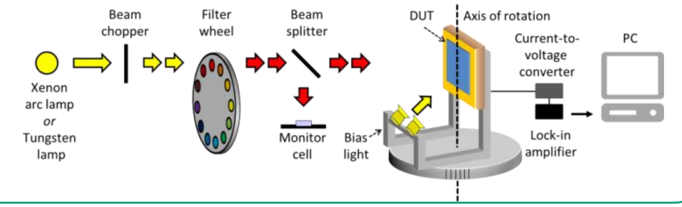
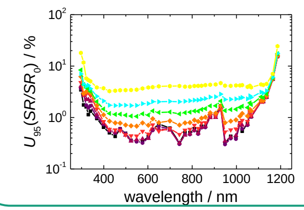
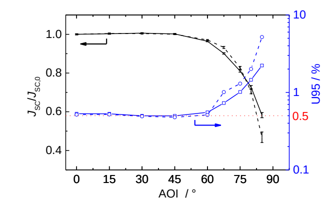
Conclusion

- Measurement setup for angular SR: Bias light rotating with the sample

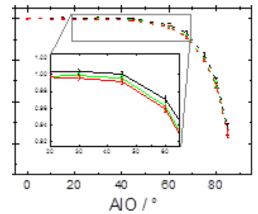


- Uncertainty analysis:
  Change in SR: $U_{95}(AOI < 75°) < 1\%$
  Change in J_{SC}: $U_{95}(AOI < 60°) \approx 0.5\%$

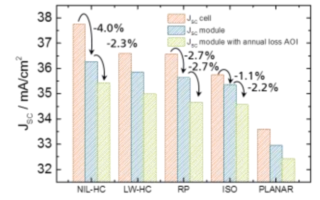




- Results for cells and modules:
  Modules: Differences ≈ 1%



- Combination of CTM and AOI losses: Random pyramids lose initial advantage over isotexture



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Acknowledgment

Thank You Very Much for Your Attention!

This work was partly funded by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (Contract Number 0325447 OHM) and the EMRP ENG55 project “Towards an energy-based parameter for photovoltaic classifi-cation”. The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union.

Jochen Hohl-Ebinger

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