Root Cause Analysis of Solar Cell Cracks at Shingle Joints

40 YEARS
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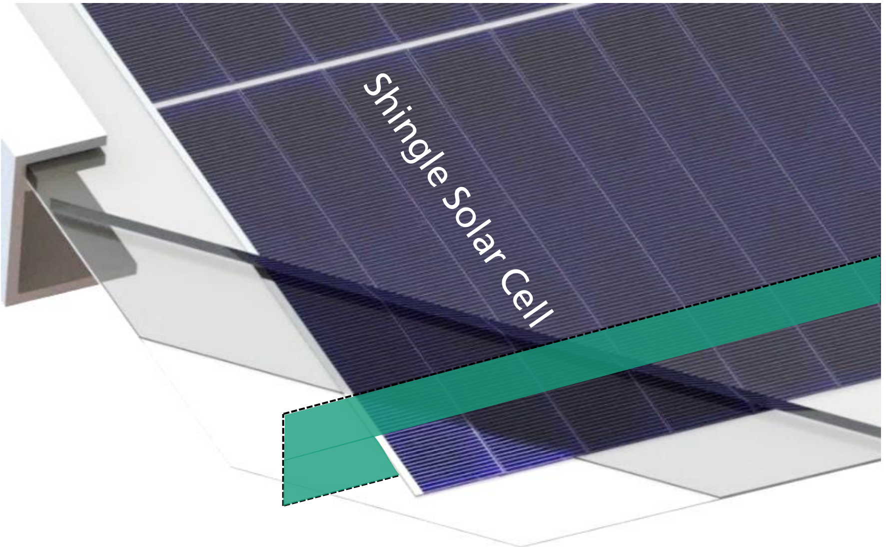
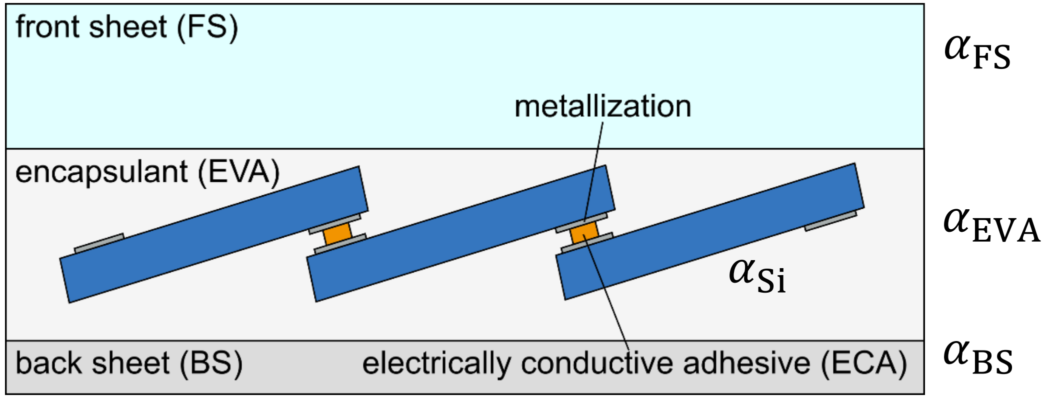
Introduction
Shingled Solar Cell Interconnection



- Overlapping solar cells
- Joint formed by an **e**lectrically **c**onductive **a**dhesive (ECA)

- Challenge
  - Thermomechanical response to temperature changes
  - Mismatch of coefficient of thermal expansion α in laminate layers



$$\varepsilon_{th} = \alpha \Delta T$$

Layer	α / $10^{-6}\ K^{-1}$
FS (Float Glass)	9
Silicon[1]	1.9 – 3.2
BS (TPT)[2]	50
Encapsulant (EVA)*	90 – 270
ECA*	50 – 250

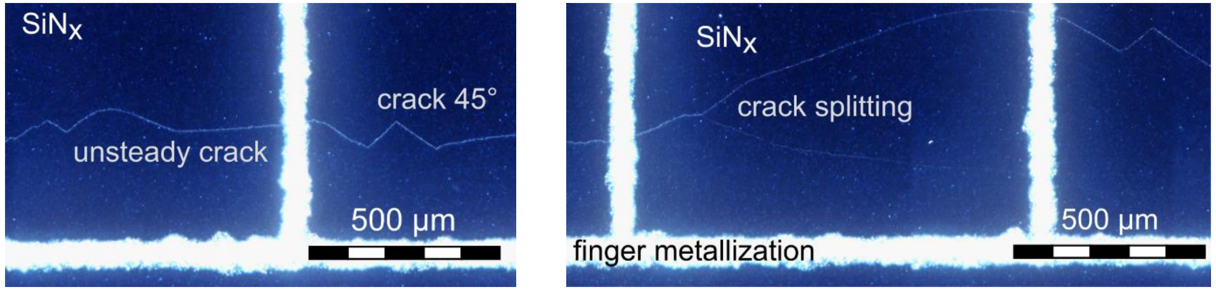
*measured

[1] K. G. Lyon, G. L. Salinger, C. A. Swenson, and G. K. White, "Linear thermal expansion measurements on silicon from 6 to 340 K," *J Appl Phys*, vol. 48, no. 3, pp. 865–868, 1977, doi: 10.1063/1.323747.
[2] U. Eitner, "Thermomechanics of photovoltaic modules," Dissertation, Martin-Luther-Universität, Halle-Wittenberg, 2011.

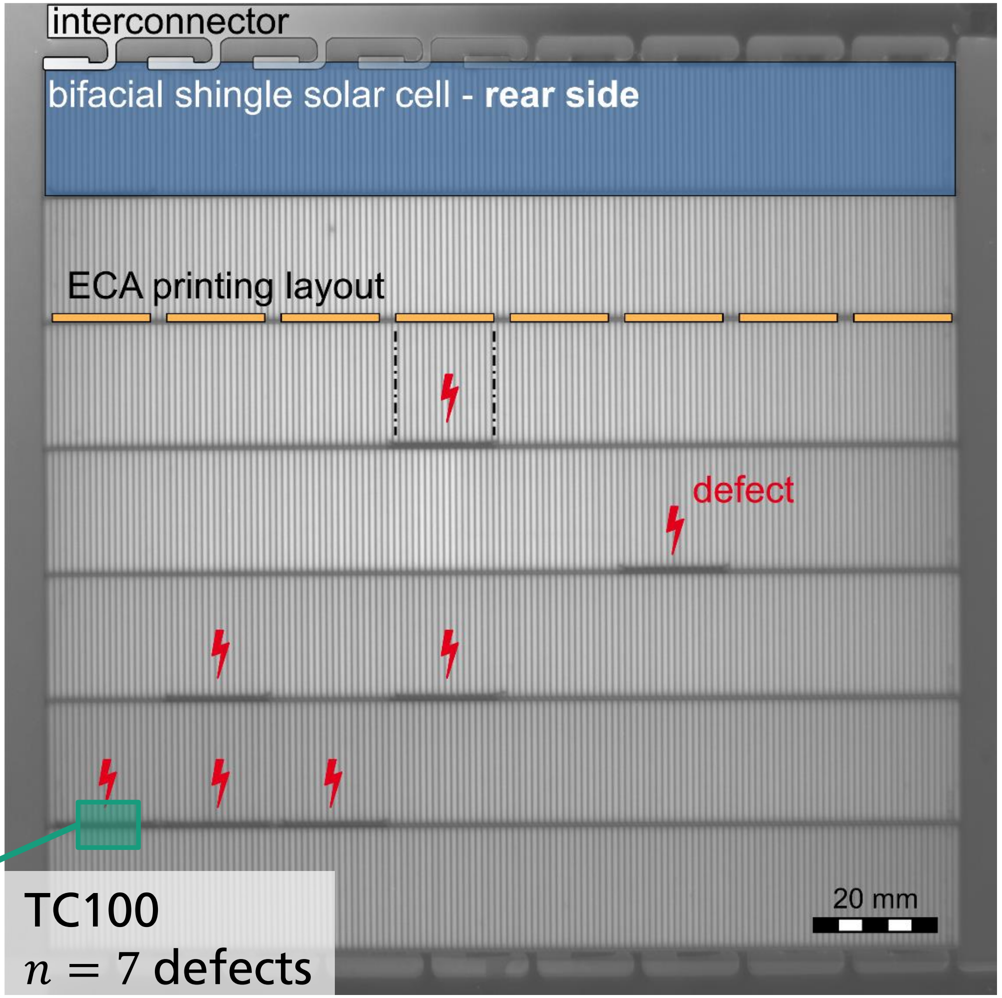
Defect Observation
Thermal Cycling (TC) Experiments[1]

- Defects congruent with printed ECA
- Dominantly on **rear side** of bifacial solar cells
- First occurence between TC0 – TC100

- Cracks outside <111> crystal plane orientation
  - High tensile stresses



Topview microscopy – darkfield mode

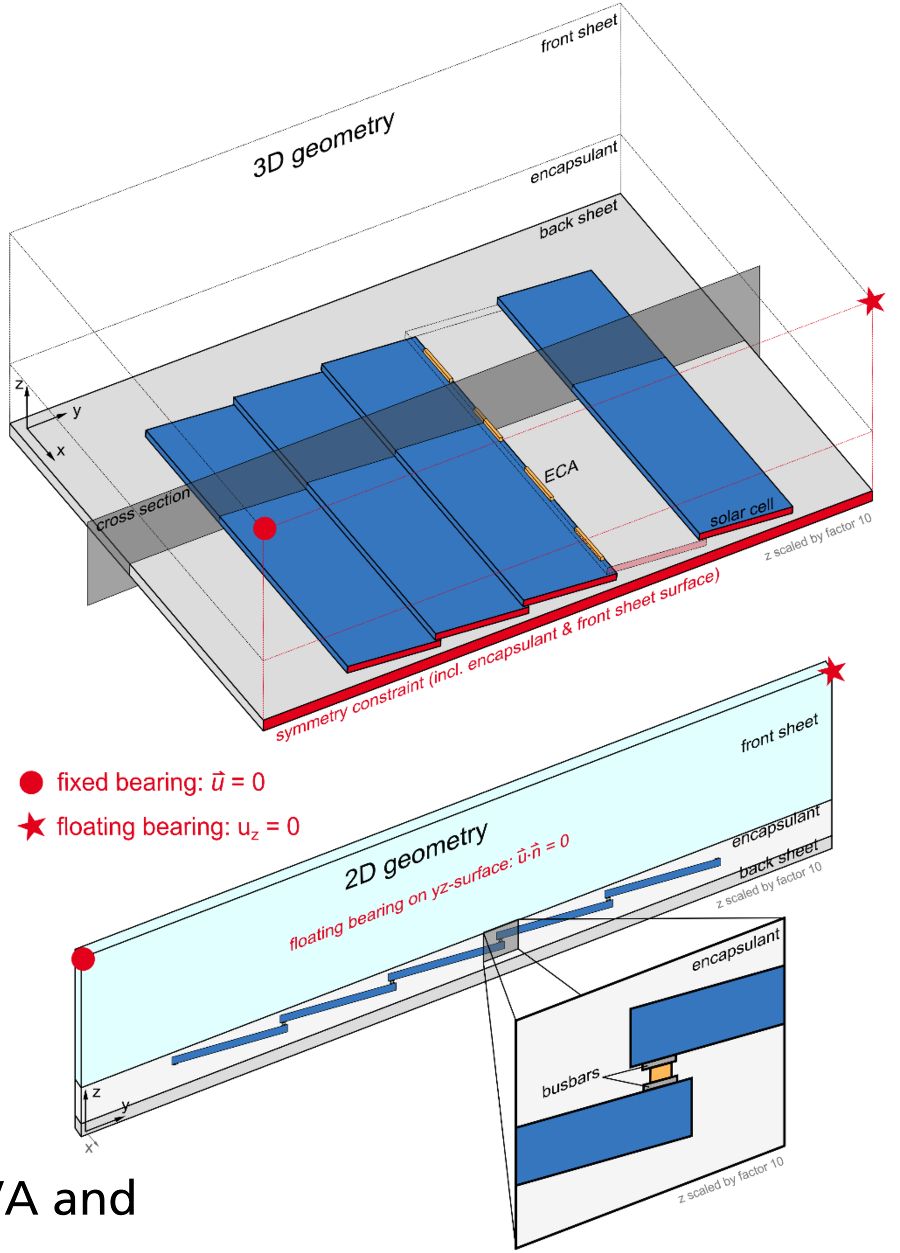


Photoluminescence – rear side

[1] IEC 61215-2:2016, International Electrotechnical Commission (IEC)

Finite Element Simulations
Model Configuration

- Geometries
  - 5 solar cells
  - 3D geometry
  - Pseudo 2D geometry: 1 mesh element in x
- Boundary constraints
  - $\Delta T = -200\ \mathrm{K}$: lamination @ $160\ °\mathrm{C}$ to $-40\ °\mathrm{C}$
  - Suppressed rigid body motion
- Material properties and viscoelastic models for EVA and ECA from previous publication[1]

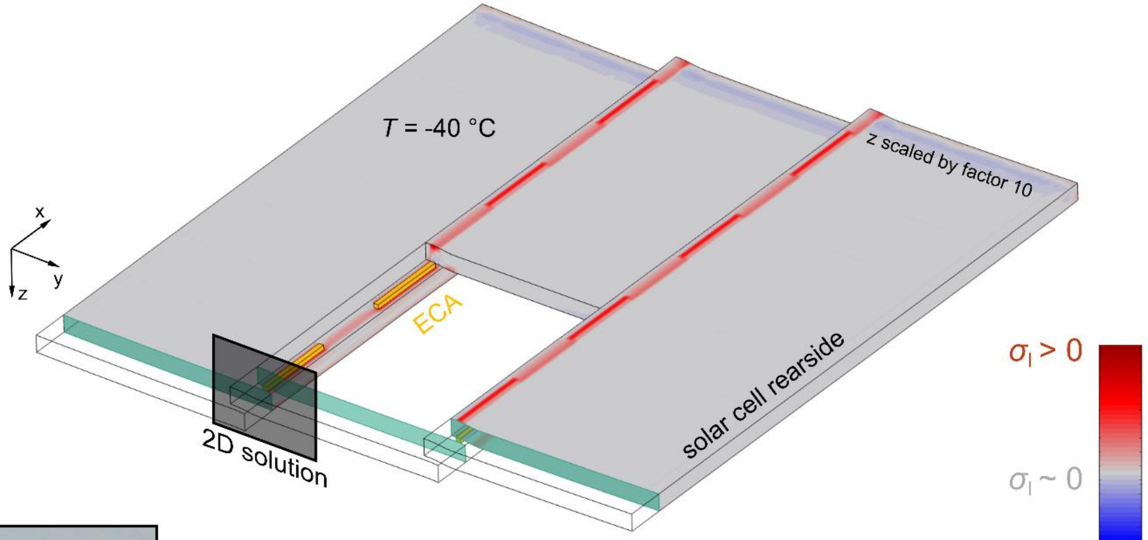


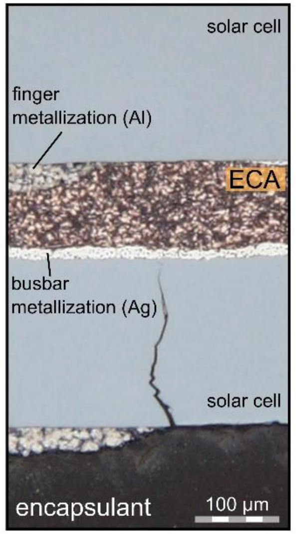
[1] N. Klasen et al. "FEM simulation of deformations in strings of shingled solar cells subjected to mechanical reliability testing," in *8th Workshop on Metallization and Interconnection 2019*, p. 20016.

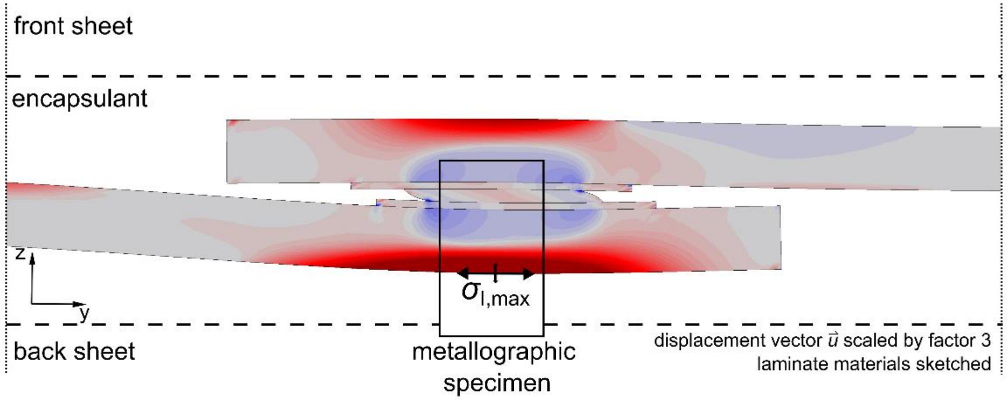
Finite Element Simulations
Results

- First principal stress σ_{I} relevant for crack formation in silicon

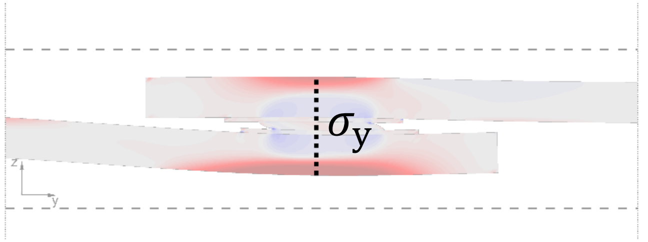
- 3D model:
  - σ_{I} - imprints of ECA pads on solar cell surface
- 2D model:
  - σ_{I} - concentration on rear side
  - $\sigma_{\mathrm{I,max}}$ in joint center below ECA
  - Direction of σ_{I}: parallel to surface
- Metallographic specimens:
  - Crack origin on rear side



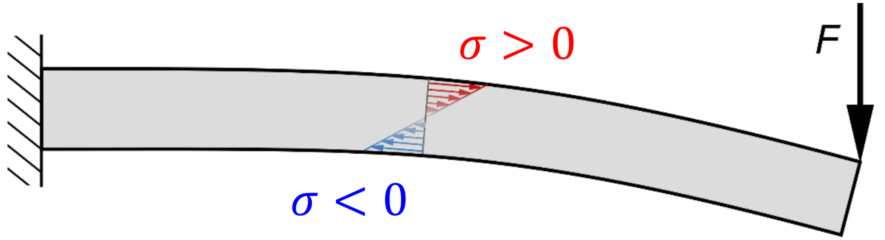




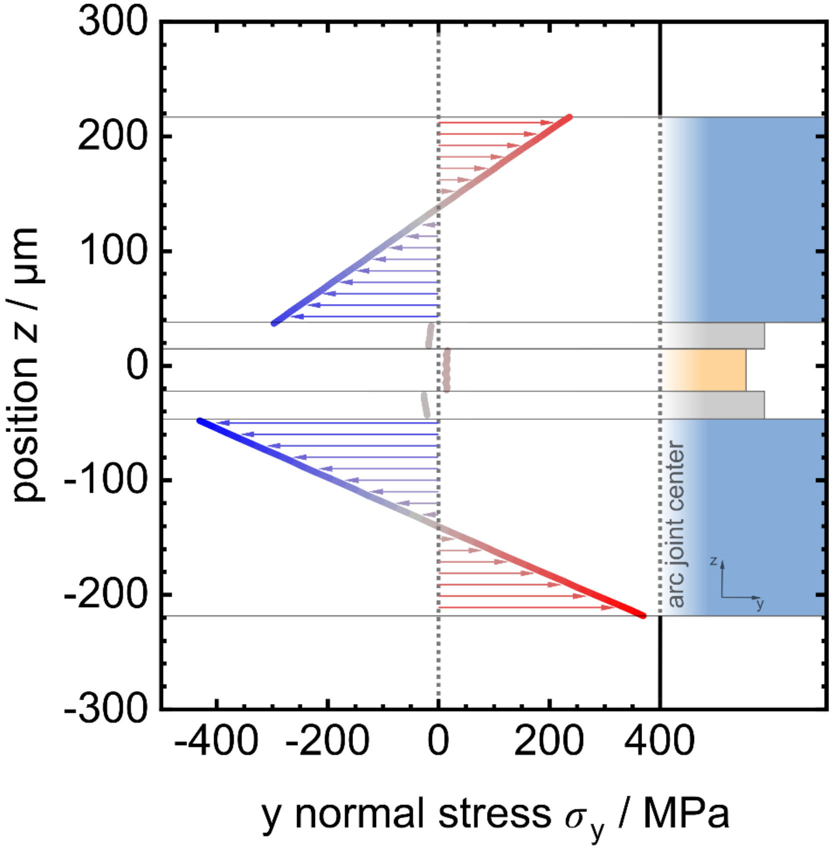
Finite Element Simulations
Bending Moment at Shingle Joint



- Characteristic stress distribution in cross sections under bending forces:

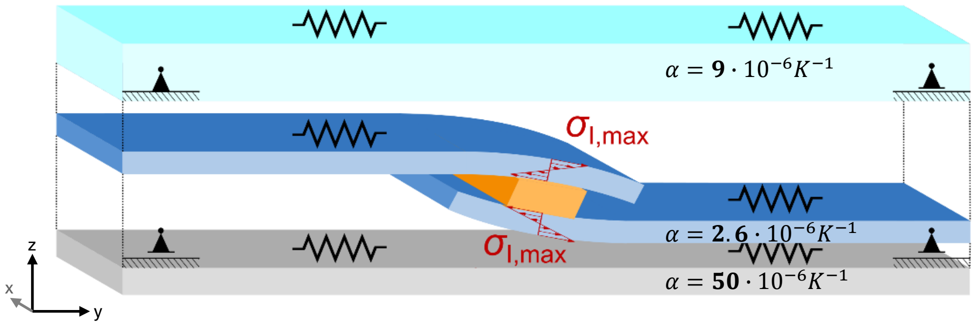


- Bending moment in solar cells at joint center causes high $\sigma_{I,max}$ in outer fiber



Root Cause(s) for Bending of the Solar Cells

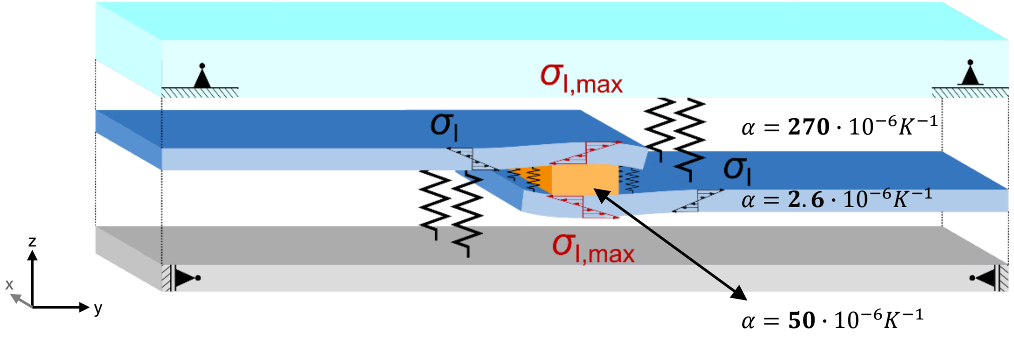
Relative solar cell shift in y

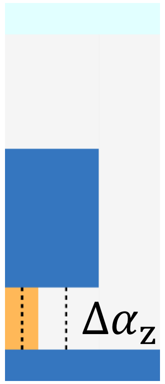


- $\Delta\alpha$ causes relative shift of solar cells[1]
- ECA in joint blocks the shift
- Solar cells bend around joint center

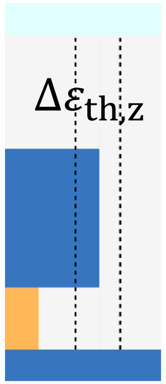
- **Cause: $\Delta\alpha_y$ / solar cell shift**

EVA contraction in z





- Contraction of EVA between solar cells: $\Delta\alpha_z$
- z contraction EVA besides overlap: $\Delta\varepsilon_{th,z}$
- Solar cells bend around joint center

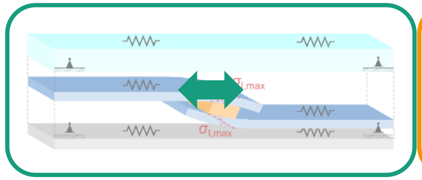


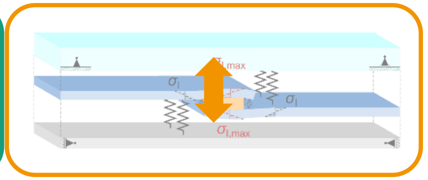
- **Cause: $\Delta\alpha_z$ & $\Delta\varepsilon_{th,z}$**

[1] U. Eitner, "Thermomechanics of photovoltaic modules," Dissertation, Martin-Luther-Universität, Halle-Wittenberg, 2011.

Separation of Defect Mechanisms

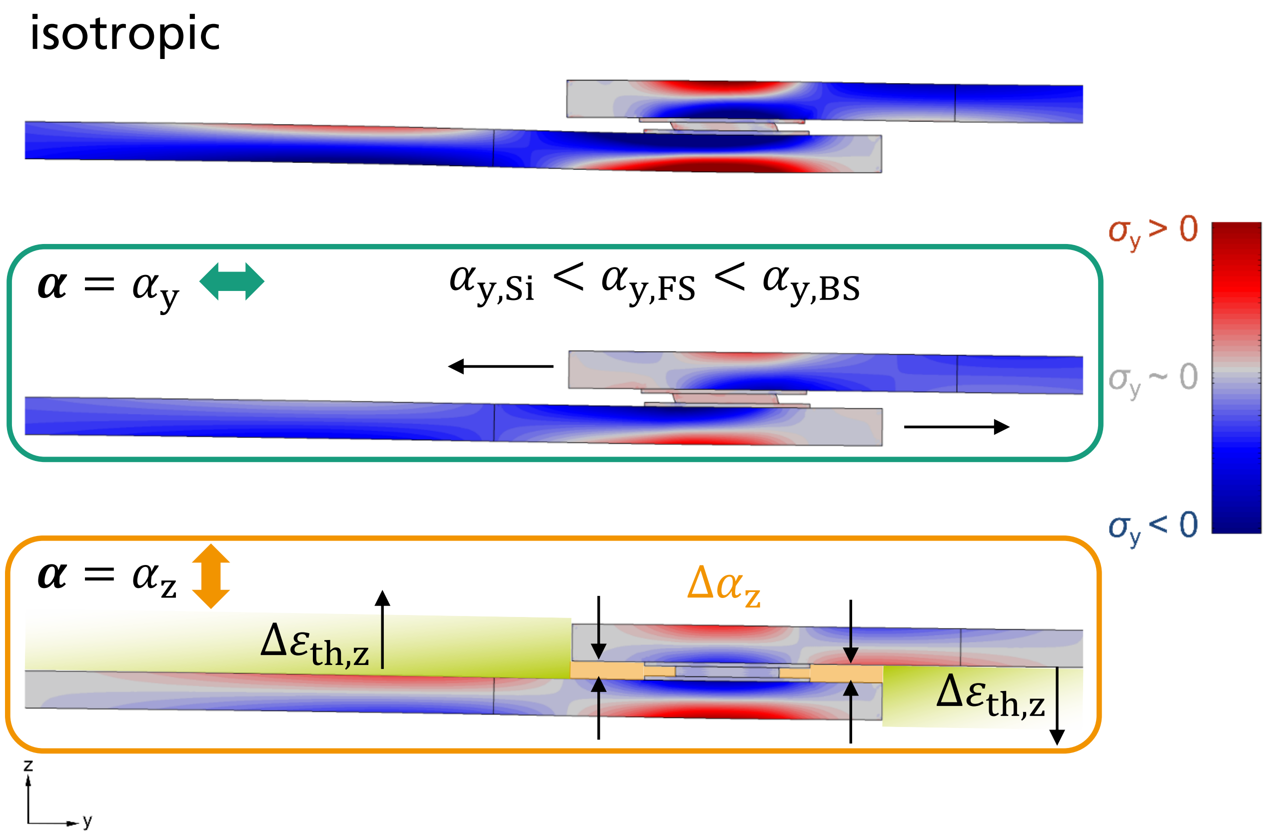
Anisotropic Thermal Expansion



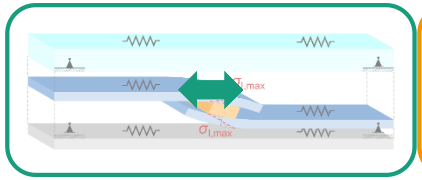


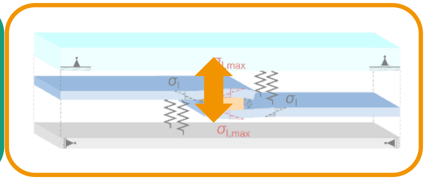
- Superposition of effects

- Separation of mechanisms by anisotropic thermal expansion in all laminate materials:
  - Isotropic: $\boldsymbol{\alpha} = \begin{pmatrix} \alpha_x \\ \alpha_y \\ \alpha_z \end{pmatrix} = \alpha \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$
  - Thermal expansion in y: $\boldsymbol{\alpha} = \alpha \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix}$
  - Thermal expansion in z: $\boldsymbol{\alpha} = \alpha \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$



Cross Check





- According to Eitner[1] solar cell shift becomes $\cong 0$ when $\alpha_{\mathrm{Si}} = \alpha_{\mathrm{FS}}$
- Subsequently $\alpha_{\mathrm{Si}} = \alpha_{\mathrm{FS}} \xrightarrow{\text{yields}} \sigma_{\mathrm{I}} \cong 0$
- Hooks law (isotropic materials):
  - $\vec{\varepsilon} = \boldsymbol{C}^{-1} \cdot \vec{\sigma}$
- $\boldsymbol{\alpha} = \alpha_{\mathrm{y}}$ ➔ σ_{y}
  - Contraction in z: $\varepsilon_{\mathrm{z}} = \frac{1}{E}\sigma_{\mathrm{z}} - \frac{\nu}{E}\sigma_{\mathrm{x}} - \frac{\nu}{E}\sigma_{\mathrm{y}}$
- Poisson ratio ν
  - transversal contraction
  - ➔ z contraction
  - ➔ Solar cell bending

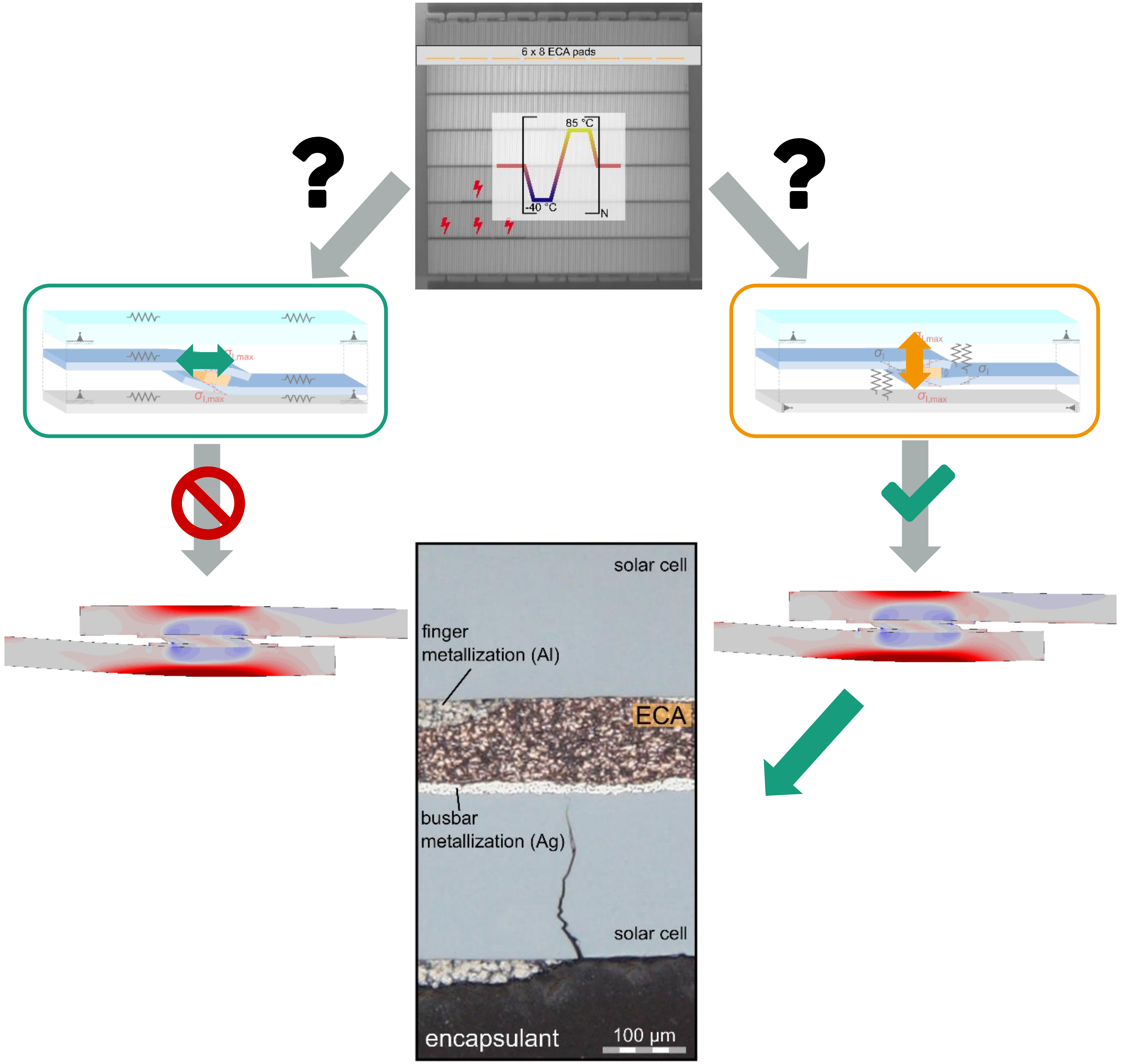
ν(polymers): $0.4 - 0.5$

[1] U. Eitner, "Thermomechanics of photovoltaic modules," Dissertation, Martin-Luther-Universität, Halle-Wittenberg, 2011.

Conclusion and Outlook

- **Summary of talk**
  - $\sigma_{I,rear} \gg \sigma_{I,front}$ cause cracks in TC
  - Driving mechanism: z-contraction of encapsulant
  - Cracks at shingle joints with monofacial solar cells and opaque back sheet might occur unnoticed.

- **Outlook publication**
  - Glass/glass laminates
  - Detailed discussion of both mechanisms
  - Proposals for stress reduction



Thank you for your kind Attention!

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