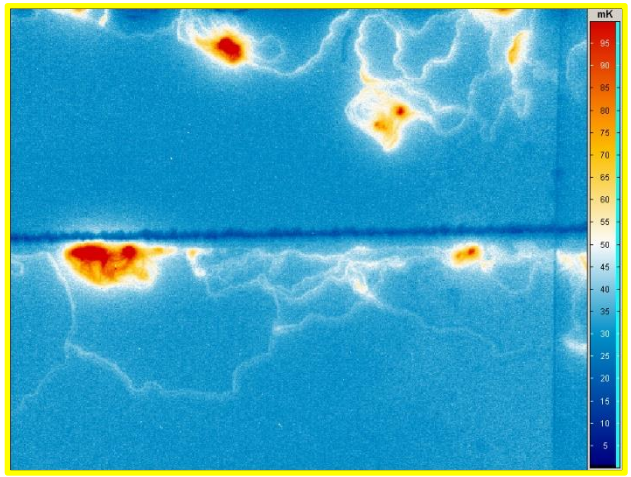
# Study of wormlike defects induced by shading on a commercial $Cu(In,Ga)(S,Se)_2$ module

R. Aninat, G. Campillay Ott, L. Jouard, K. Bakker, M. Theelen



# About our institute

# TNO part of Solliance: 3 Research Programs

From Lab to Fab

Through the value chain

New Seeds

**PSC**

efficiency, stability, up-scaling untill packaged standard modules

**Thin Film PV Module & Packaging Technologies**

lower cost processes, customized modules, thin-film packaging

**Thin Film PV Integration Technologies** for:

IIPV, BIPV, VIPV*

COMPETENCIES - PROJECTS

- Front-end /Deposition technologies
- Back-end / Customization
- Encapsulation technologies
- Integration Concept development
- Life time testing & modelling
- Business Case & Cost modelling
- Mechanical & electrical integration


*IIPV: Infrastructure Integrated PV
BIPV: Building Integrated PV
VIPV: Vehicle Integrated PV

# Introduction:

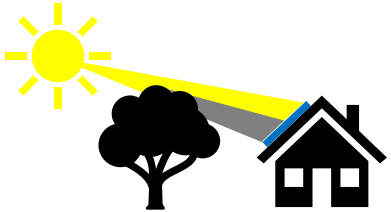
# wormlike defects creation

## *(relevant literature here [1-7])*

*[1] Bakker, K., et al. (2019). IEEE J. Photovoltaics 9(6): 1868-1872.*
*[2] Bakker, K., et al. (2019). J. Mat. Res. 34(24): 3977-3987.*
*[3] Bakker, K., et al. (2020). Sol. Mat. 205: 110249.*
*[4] Palmiotti, E., et al. (2018). Solar En. 161: 1-5.*
*[5] Johnston, S., et al. (2018). 2018 IEEE WCPEC*
*[6] Johnston, S., et al. (2017). 2017 IEEE PVSC*
*[7] Lee, J. E., et al. (2016). PIP, 24(8): 1035-1043*

# How does it happen?

- **Partial shading**



Residential

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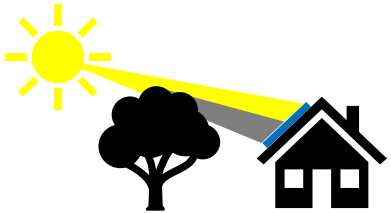

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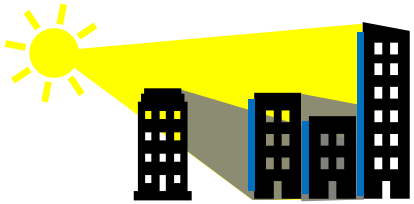

BIPV

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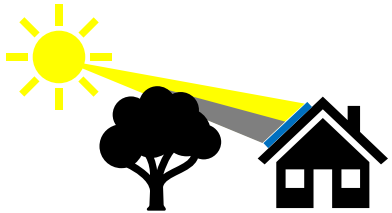

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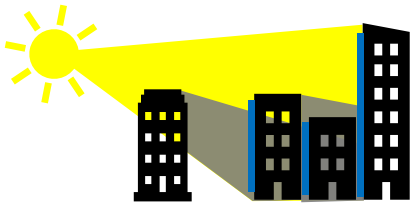
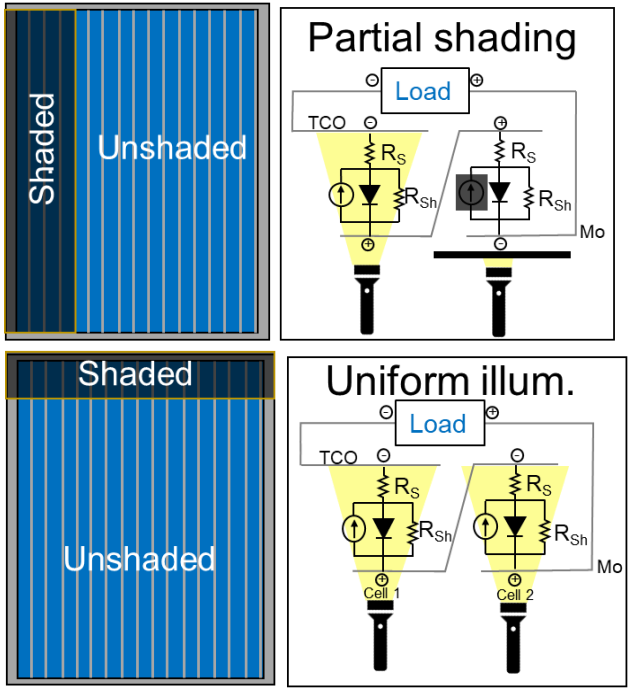


BIPV

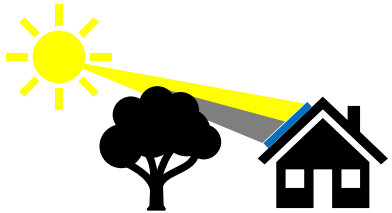
# What is it?

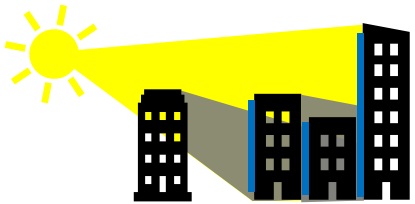
- **Two extreme scenarios**



# How does it happen?

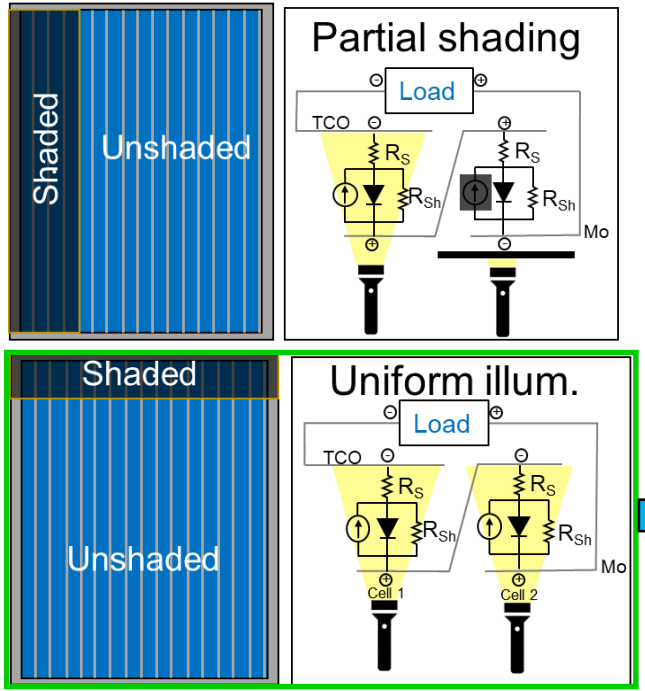
- Partial shading





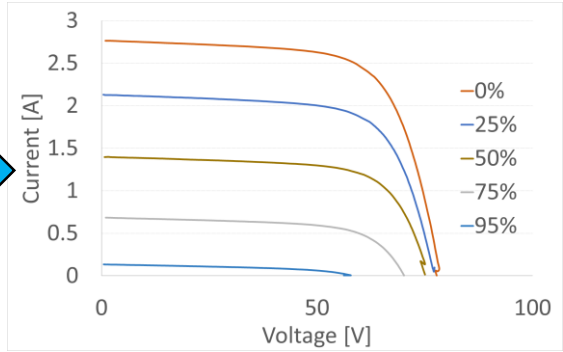
# What is it?

- "Landscape" shading:




- Best case scenario

Uniform shading in I-V
No damage



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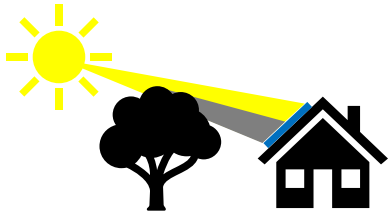
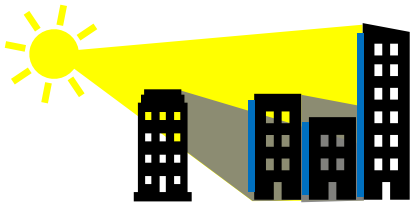
# How does it happen?

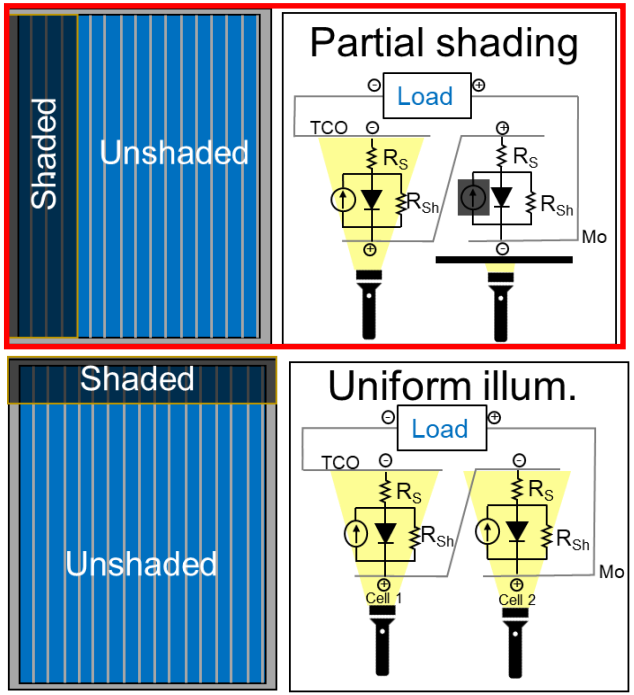
- Partial shading





# What is it?

- “Portrait” shading



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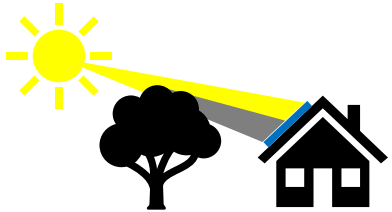

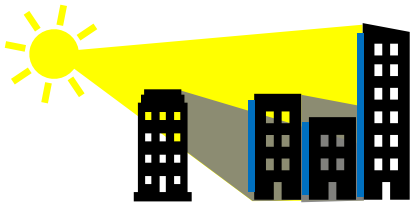

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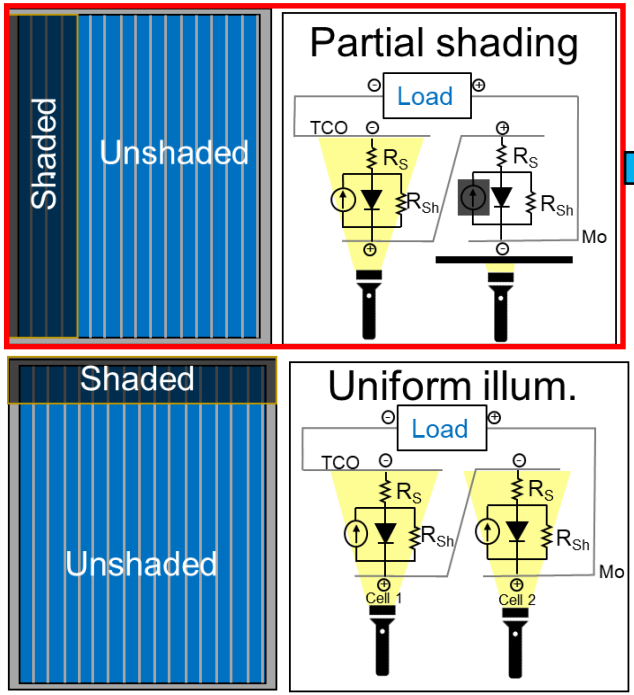
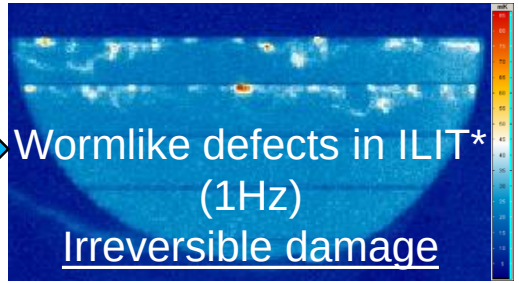


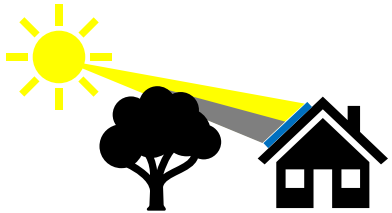

- Worst case scenario




** ILIT: Illuminated lock-in thermography*

# How does it happen?

- Partial shading



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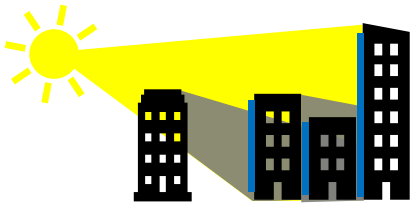
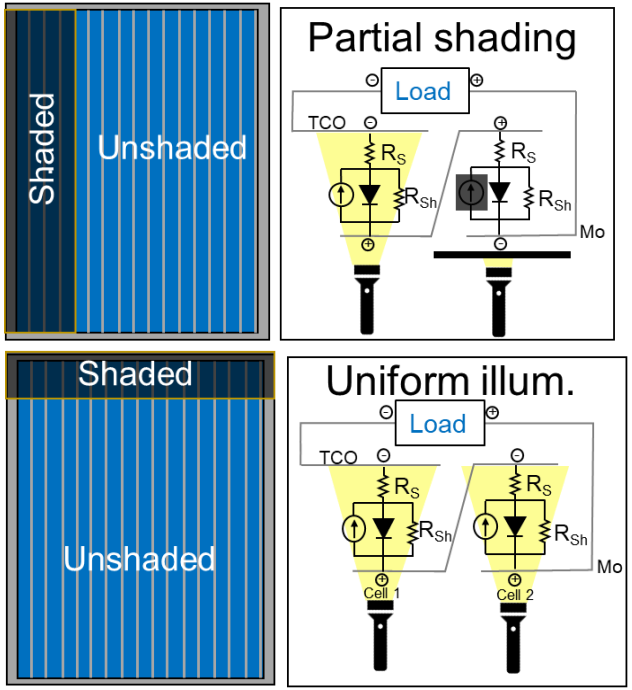


BIPV

# What is it?

- Wormlike defects

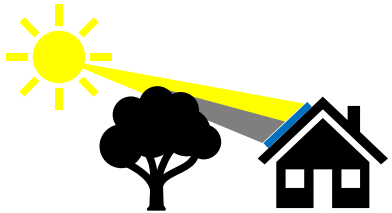



# What is our approach?

- Scale down

# How does it happen?

- **Partial shading**



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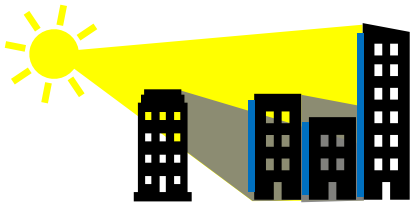

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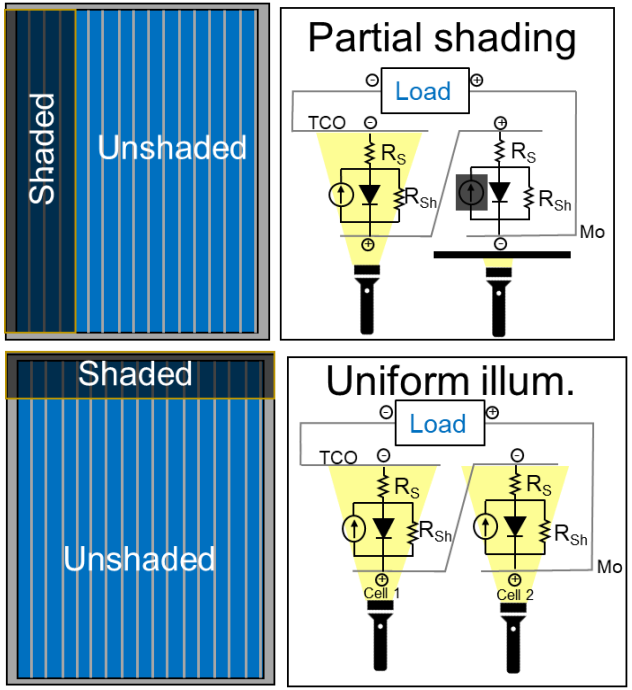


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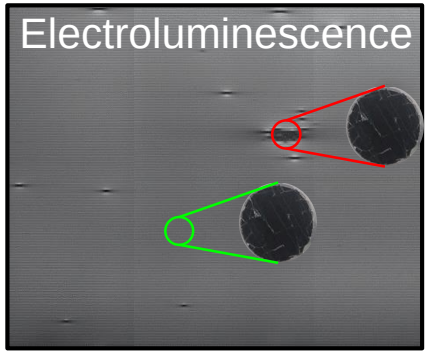

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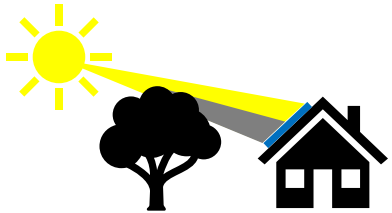

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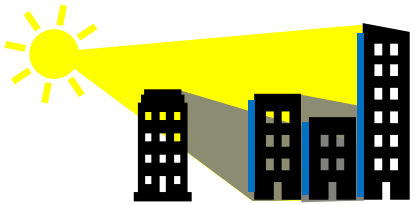

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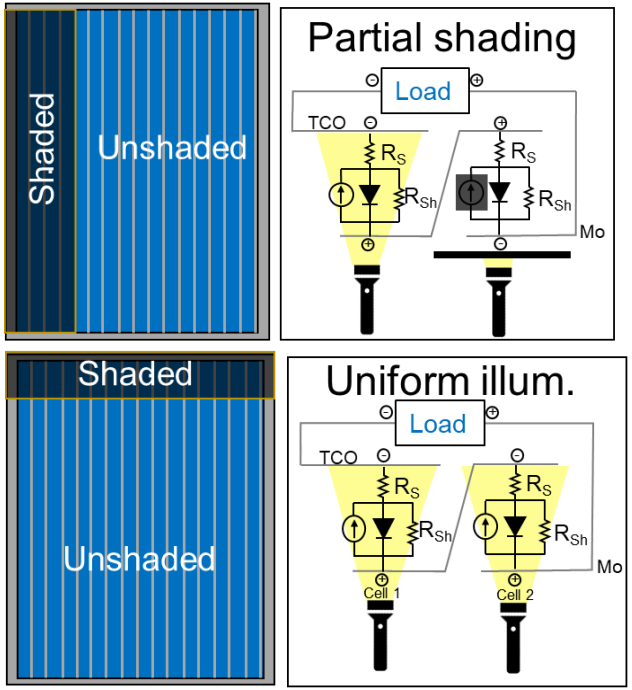


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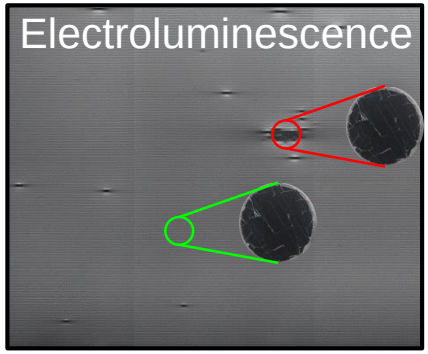


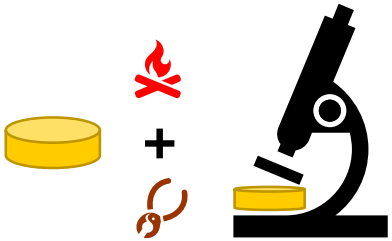



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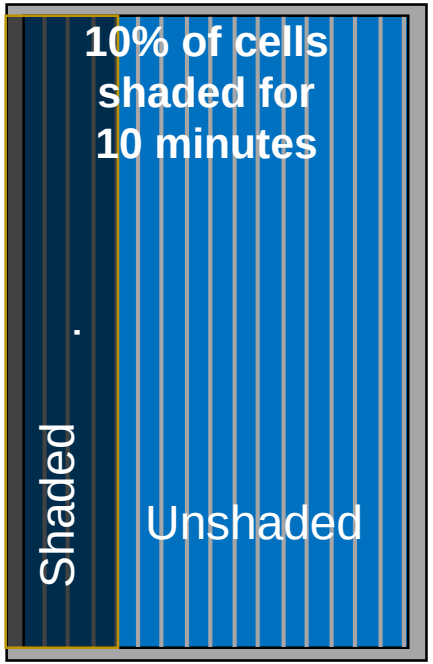
# Sequence Followed

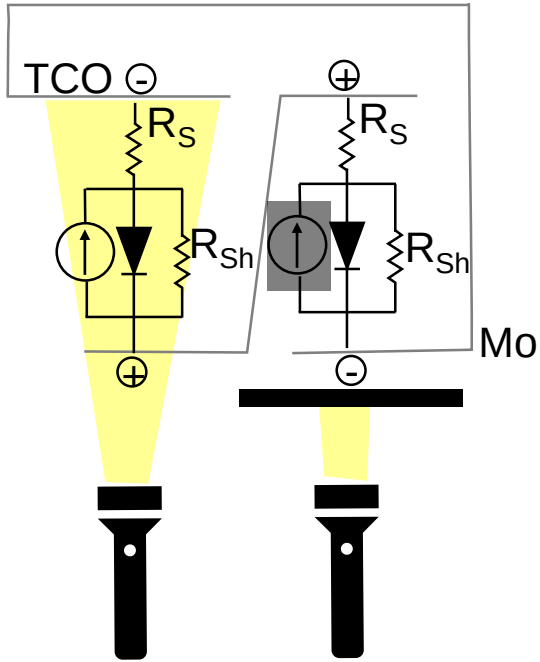


- **Initial steps:**
  - **Select commercial module**
  - **EL on full module**

# Sequence Followed

- Initial steps:
  - Select commercial module
  - EL on full module
- **Stress:**
  - **Partial shading at Jsc**
  - **Reverse bias on shaded cells**
  - **Wormlike defect generation**

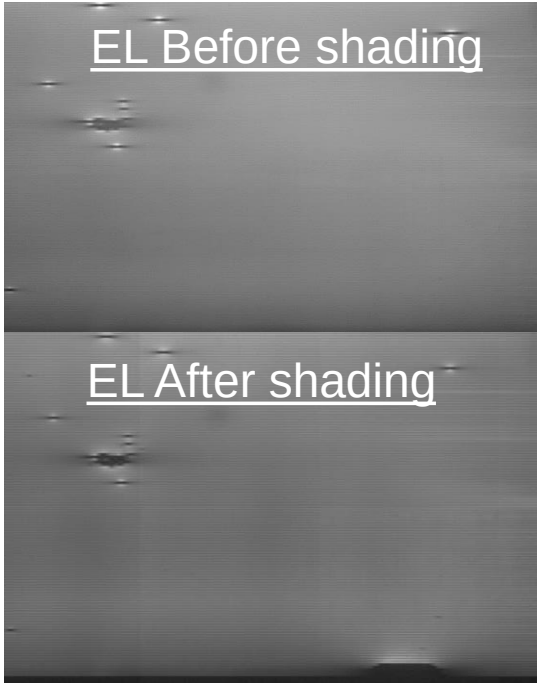



Partially shaded circuit of 2 cells

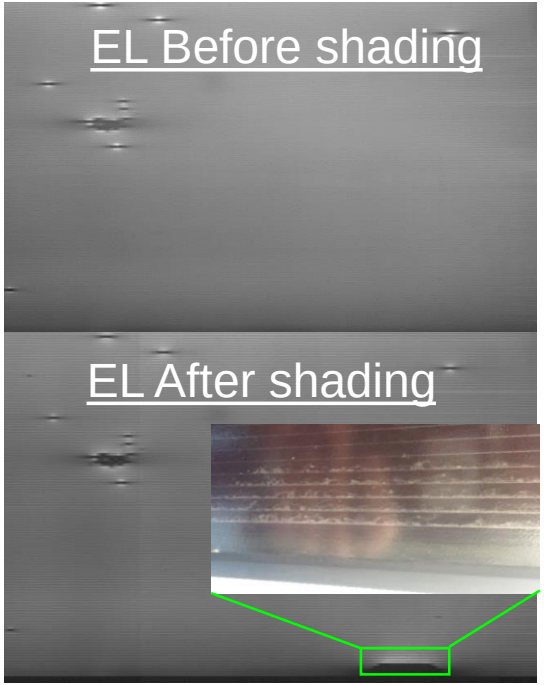
# Sequence Followed

- Initial steps:
  - Select commercial module
  - EL on full module
- Stress:
  - Partial shading
  - Reverse bias on shaded cells
  - Wormlike defect generation
- **Select and prepare the samples:**
  - **EL on full module**



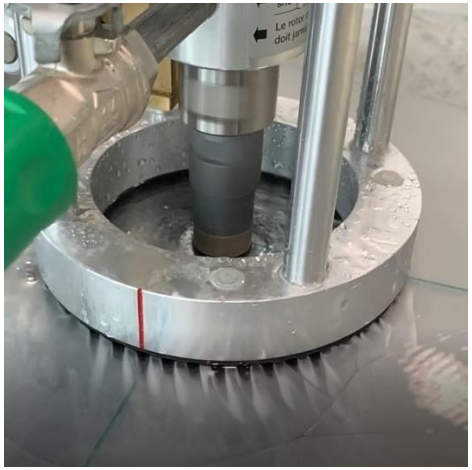
# Sequence Followed

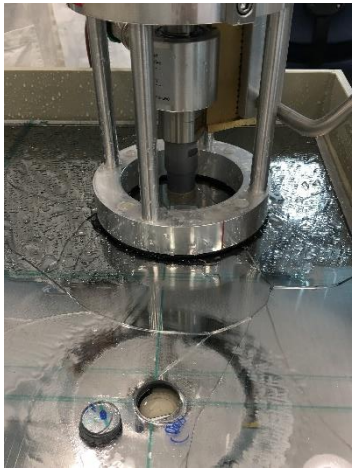
- Initial steps:
  - Select commercial module
  - EL on full module
- Stress:
  - Partial shading
  - Reverse bias on shaded cells
  - Wormlike defect generation
- **Select and prepare the samples:**
  - EL on full module
  - **Locate generated defects**



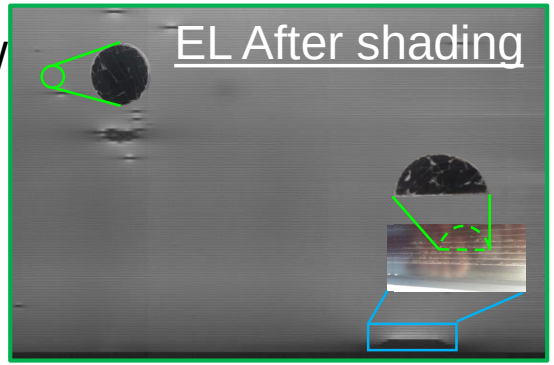
# Sequence Followed

- Initial steps:
  - Select commercial module
  - EL on full module
- Stress:
  - Partial shading
  - Reverse bias on shaded cells
  - Wormlike defect generation
- **Select and prepare the samples:**
  - EL on full module
  - Locate generated defects
  - **Core the samples (wormy & worm-free)**





Sample NW (*worm-free*)



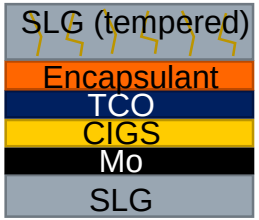

Sample W (*"wormy" area*)

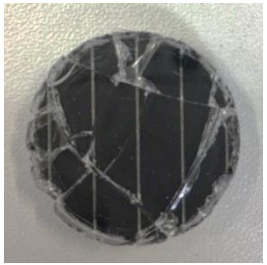
# Sequence Followed



- Initial steps:
  - Select commercial module
  - EL on full module
- Stress:
  - Partial shading
  - Reverse bias on shaded cells
  - Wormlike defect generation
- **Select and prepare the samples:**
  - EL on full module
  - Locate generated defects
  - Core the samples (wormy & worm-free)
  - **Unpackage the samples**

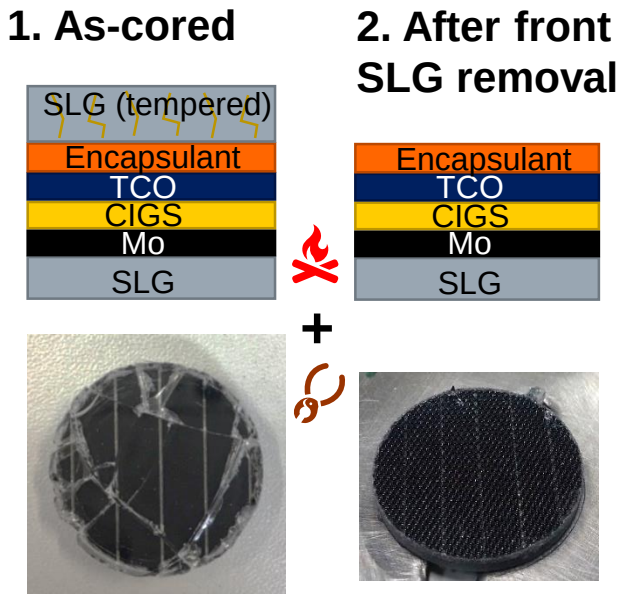
**1. As-cored**



# Sequence Followed

- Initial steps:
  - Select commercial module
  - EL on full module
- Stress:
  - Partial shading
  - Reverse bias on shaded cells
  - Wormlike defect generation
- **Select and prepare the samples:**
  - EL on full module
  - Locate generated defects
  - Core the samples (wormy & worm-free)
  - **Unpackage the samples**



# Sequence Followed

- Initial steps:
  - Select commercial module
  - EL on full module
- Stress:
  - Partial shading
  - Reverse bias on shaded cells
  - Wormlike defect generation
- **Select and prepare the samples:**
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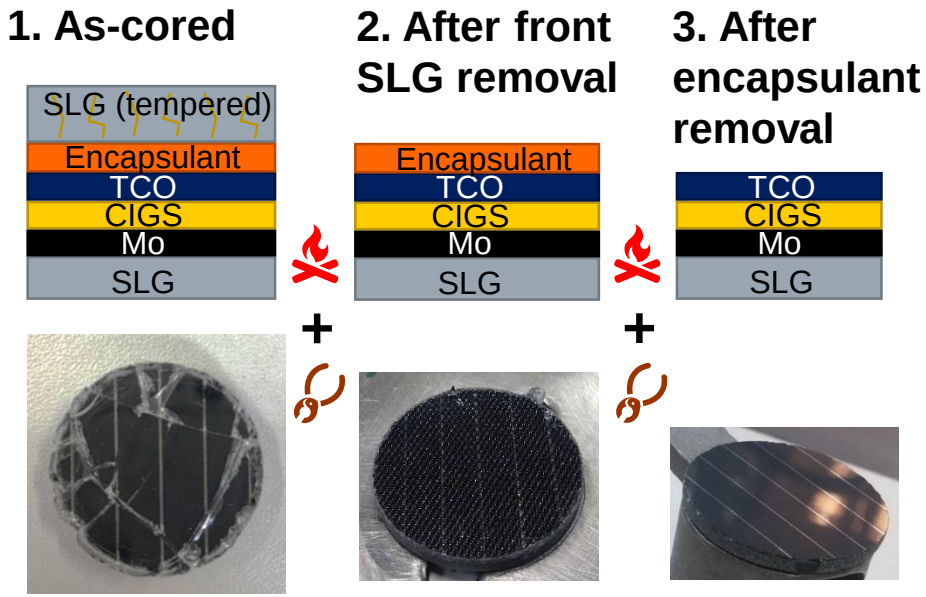
  - Locate generated defects
  - Core the samples (wormy & worm-free)
  - **Unpackage the samples**

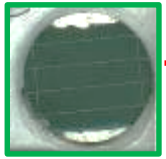


# Sequence Followed



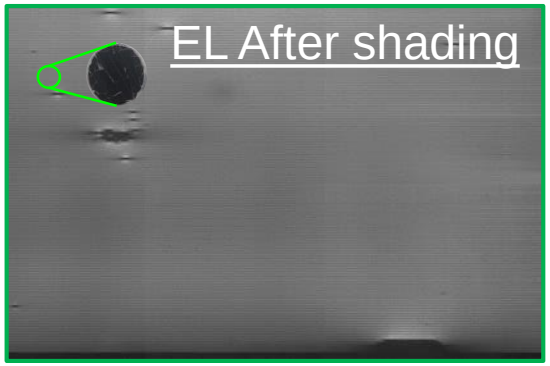
- Initial steps:
  - Select commercial module
  - EL on full module
- Stress:
  - Partial shading
  - Reverse bias on shaded cells
  - Wormlike defect generation
- Select and prepare the samples:
  - EL on full module
  - Locate generated defects
  - Core the samples (wormy & worm-free)
  - Unpackage the samples
- **Characterise the samples:**
  - **PL, ILIT, I-V, SEM, etc...**

# Results: Reference sample NW





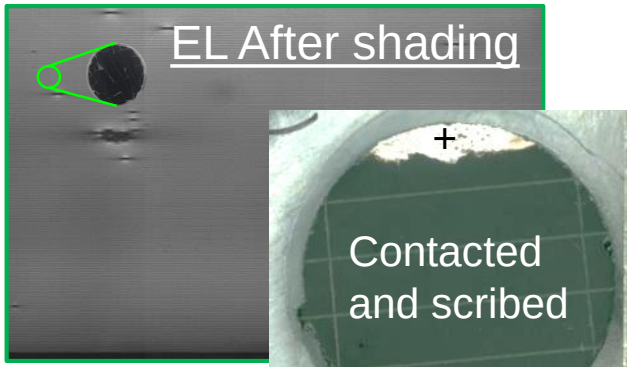
Core NW
(*worm-free*)



# Results: Reference sample NW

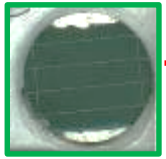


Core NW
(*worm-free*)

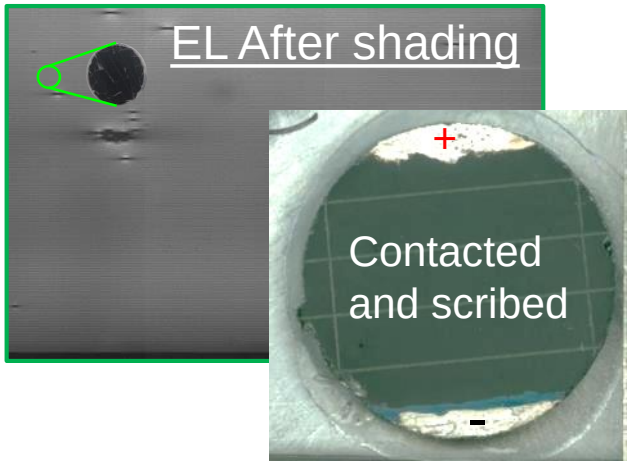


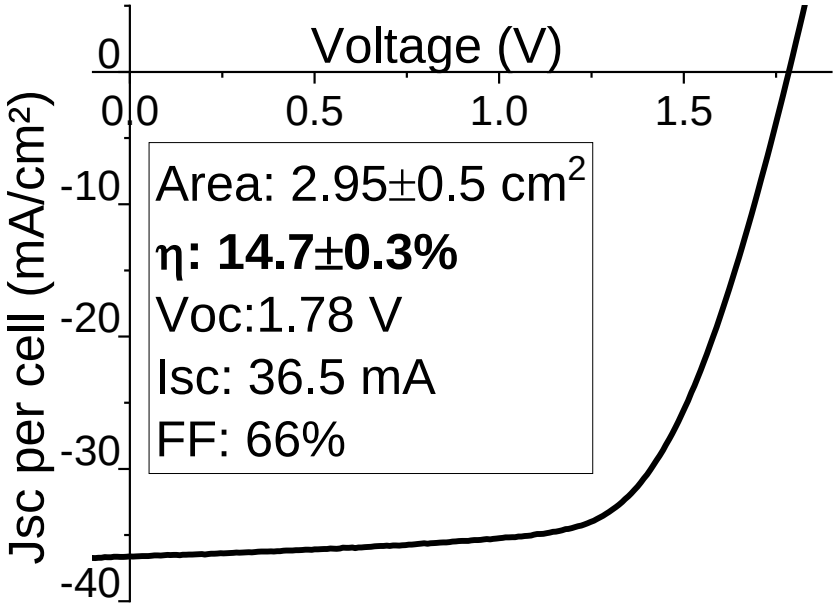
# Results: Reference sample NW





Core NW
(*worm-free*)



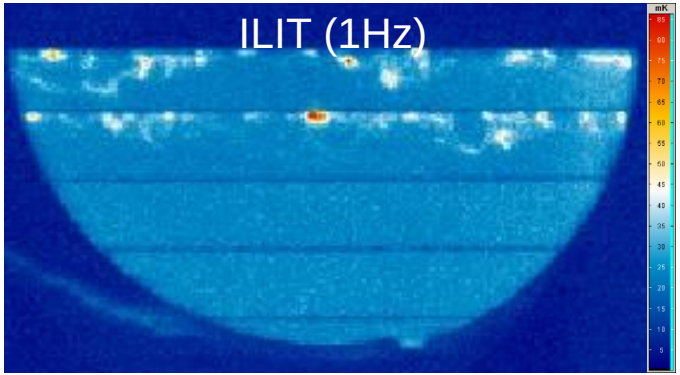



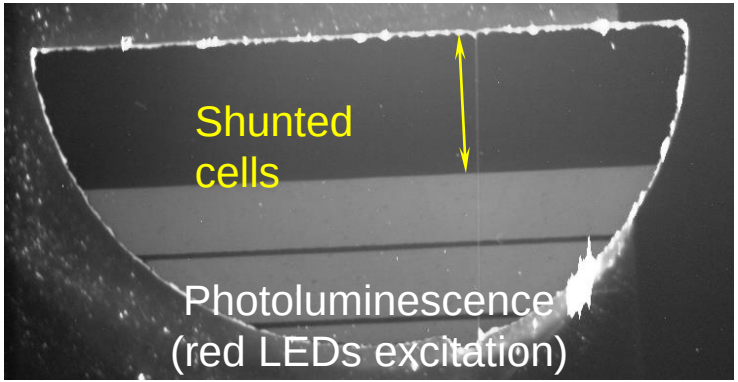

Good performance of the reference sample

→ The coring and unpackaging did little to no damage to the active layers

# Results: ”wormy” sample



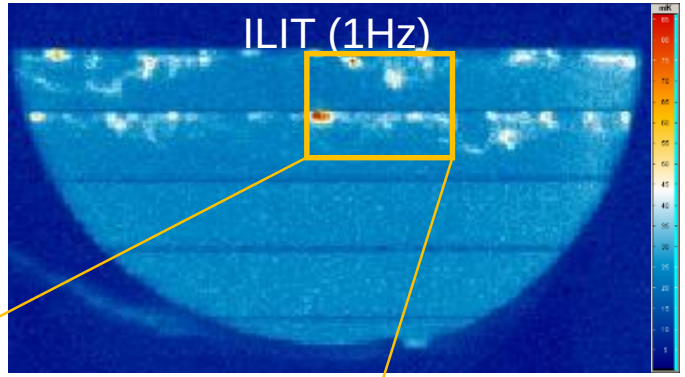


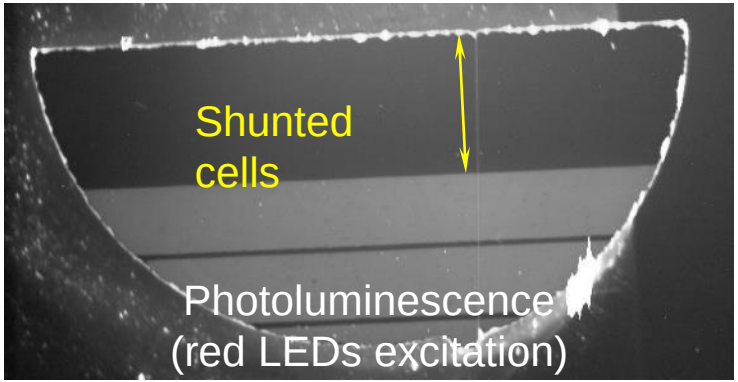



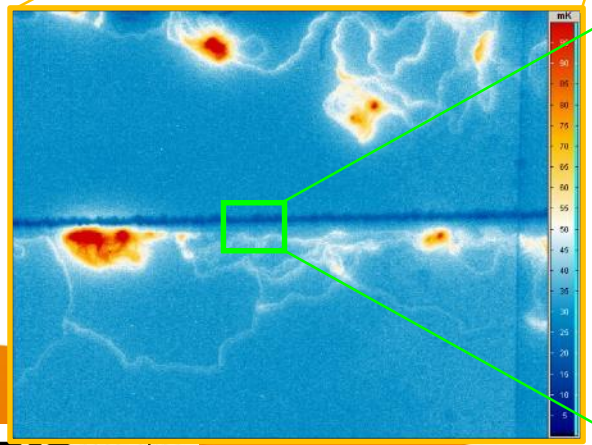

- The worms cause strong shunting

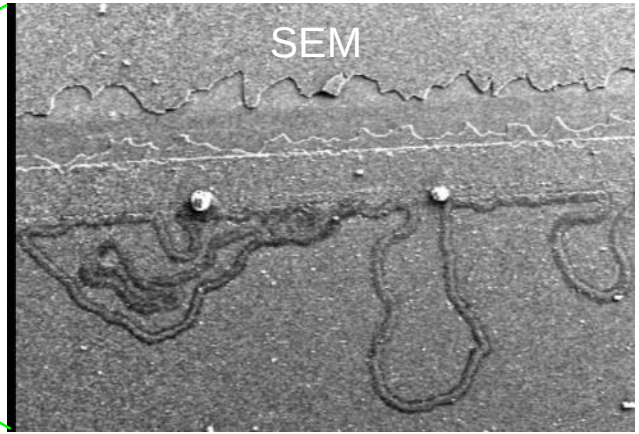
# Results: ”wormy” sample





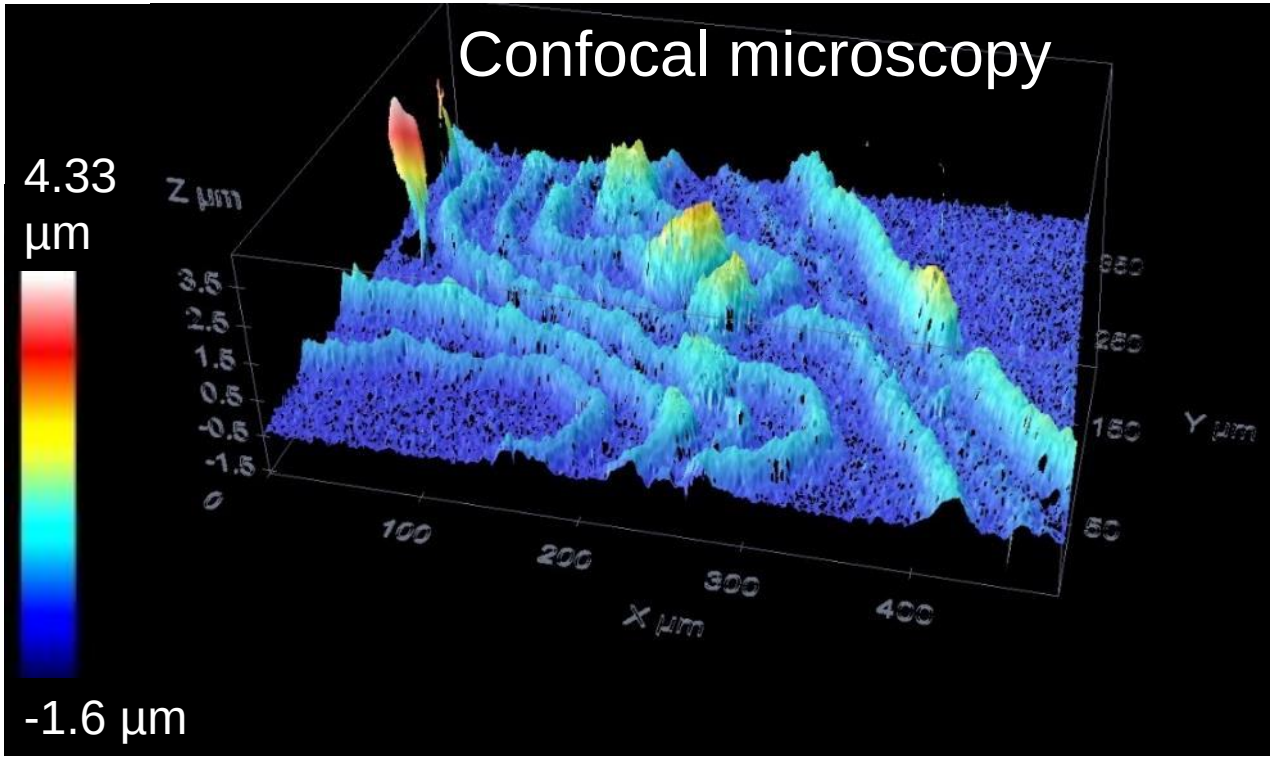






- The worms cause strong shunting
- They propagate close to the P1 interconnects, in line with literature on lab-scale devices

# Results: ”wormy” sample






- Wormlike defects protrude by 0.5 µm - 1.0 µm
- More continuous worm ridge than [1], likely due to TCO thickness

*[1] Bakker, K., et al. (2020). Sol. Mat. 205: 110249.*

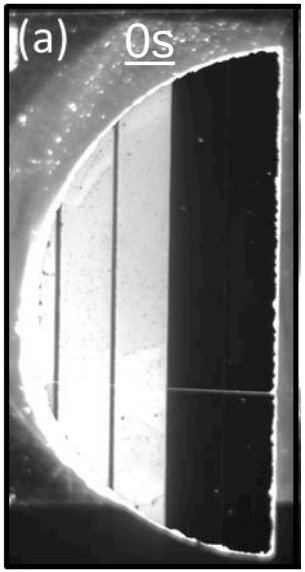
# Results: ”wormy” sample



Photoluminescence imaging before/after TCO etch

TCO

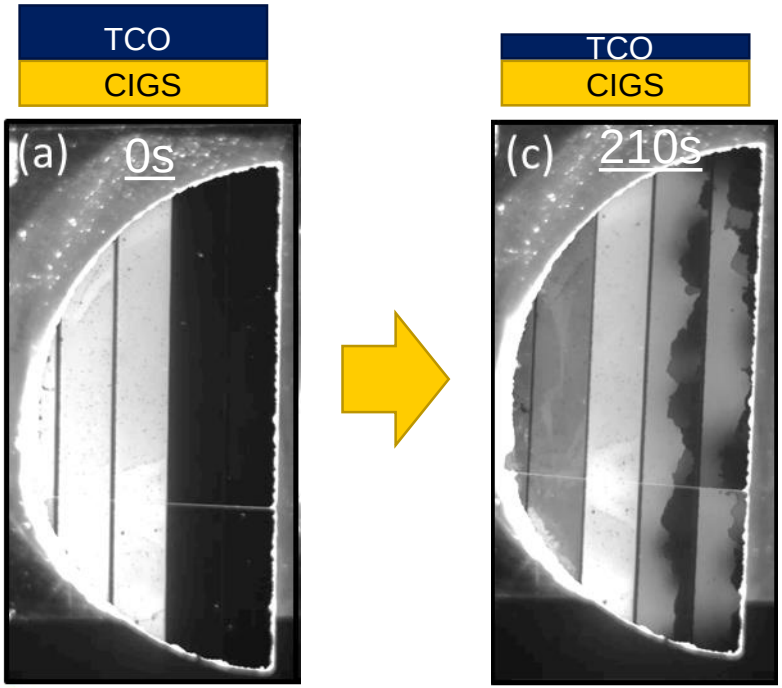
CIGS



# Results: ”wormy” sample



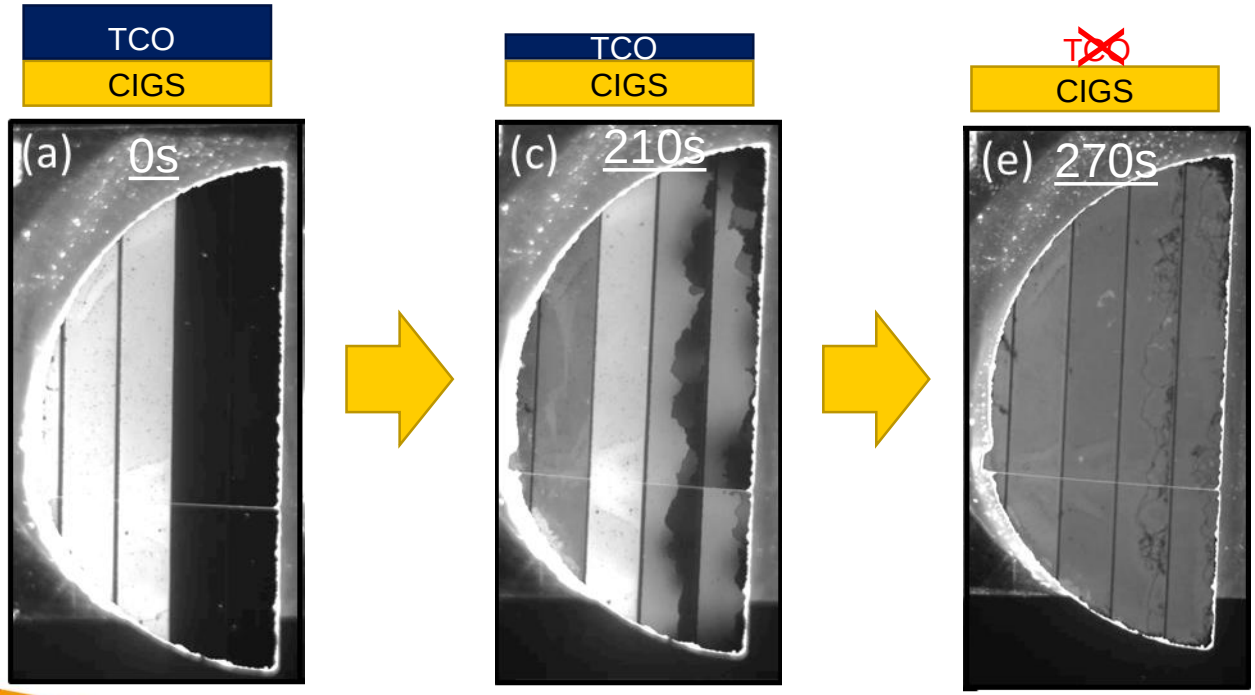
Photoluminescence imaging before/after TCO etch



# Results: ”wormy” sample

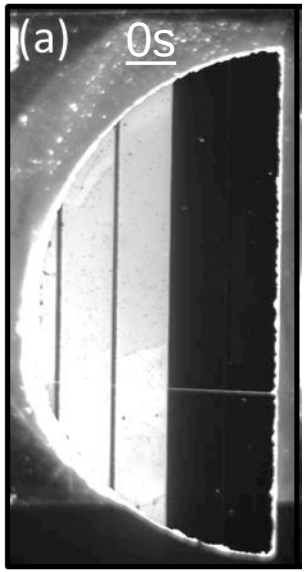


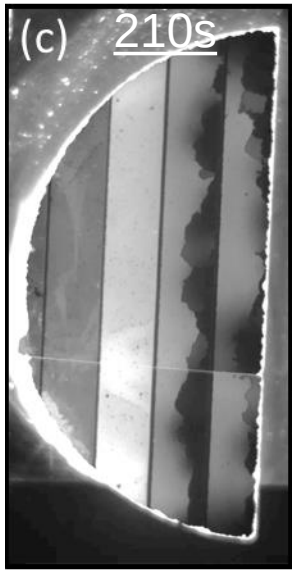
Photoluminescence imaging before/after TCO etch

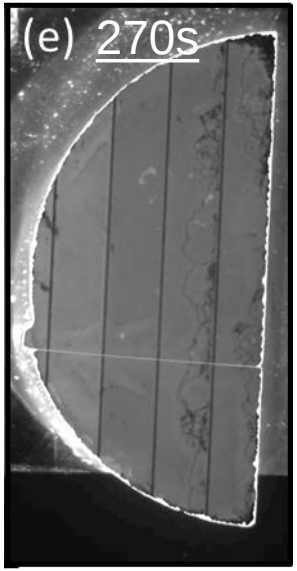


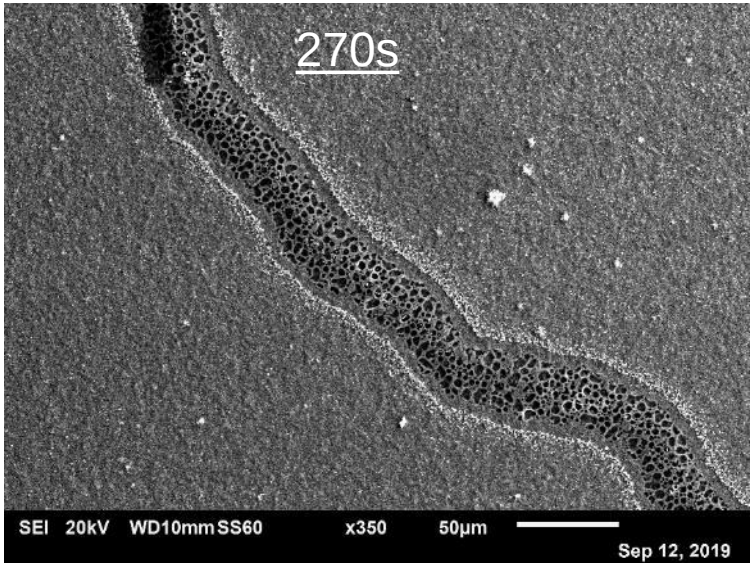
# ”wormy” sample: ascetic acid etching





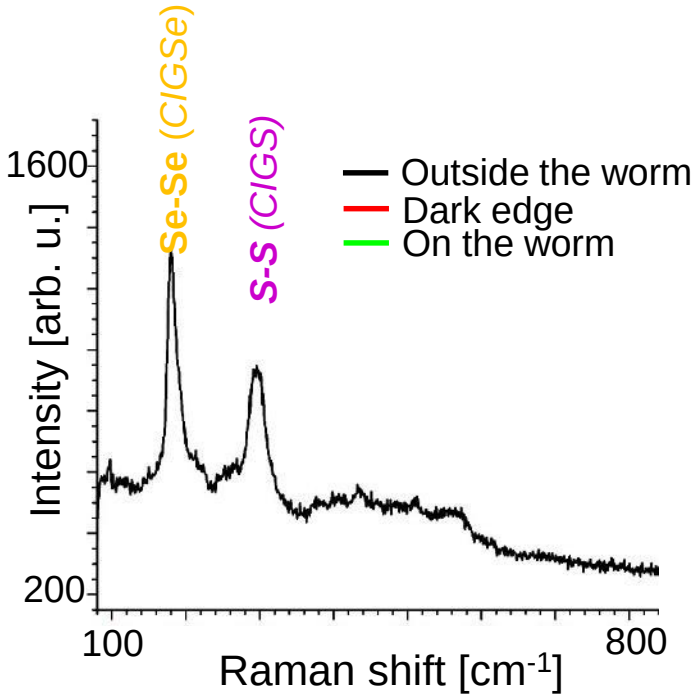

Upon TCO etching:

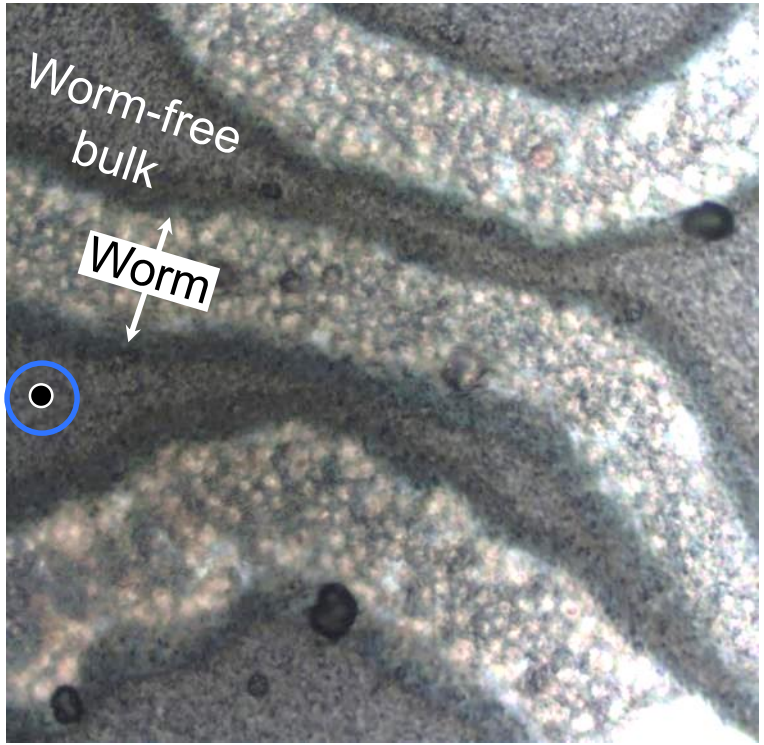
- No longer shunting in PL (for explanation, see [1])
- Etched worm are porous due to expansion

*[1] Bakker, K., et al. (2019). IEEE Journal of Photovoltaics 9(6): 1868-1872.*

# ”wormy” sample: Raman

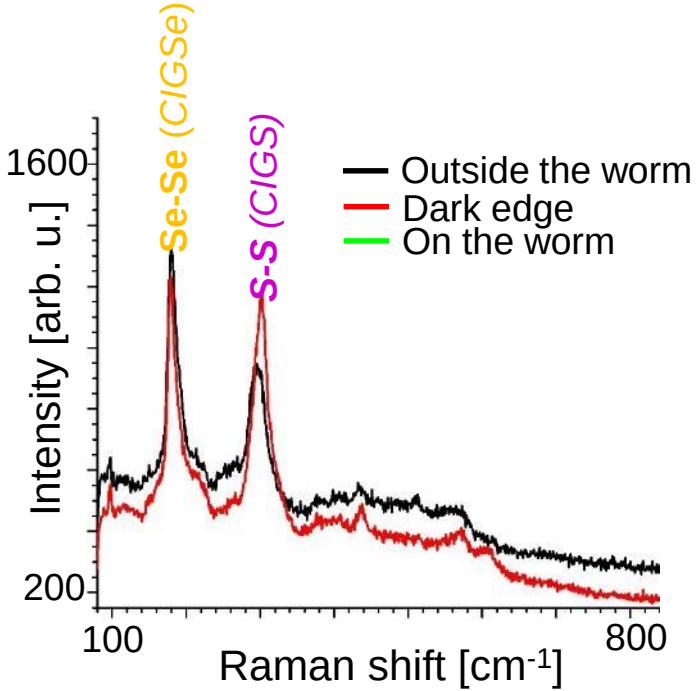


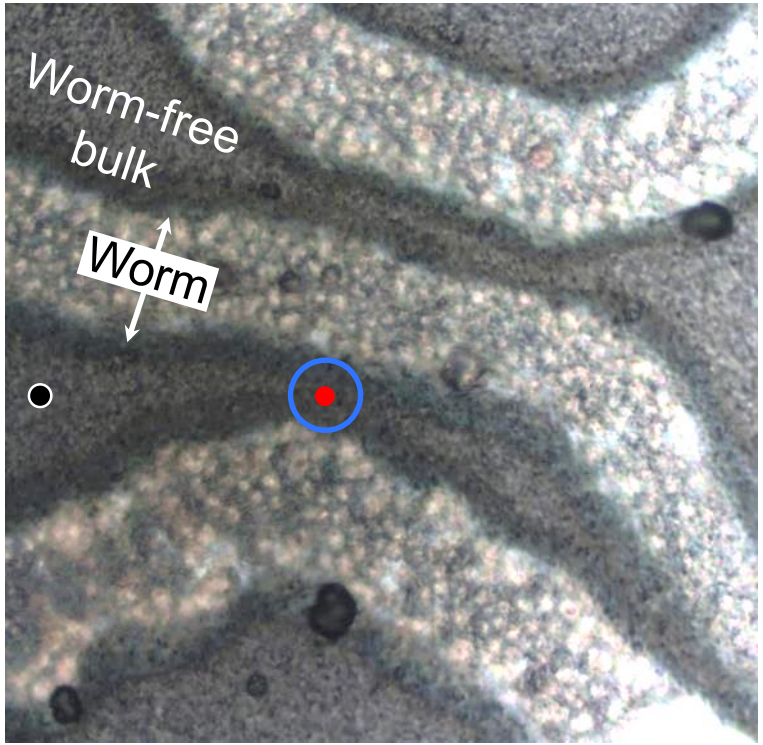


# ”wormy” sample: Raman

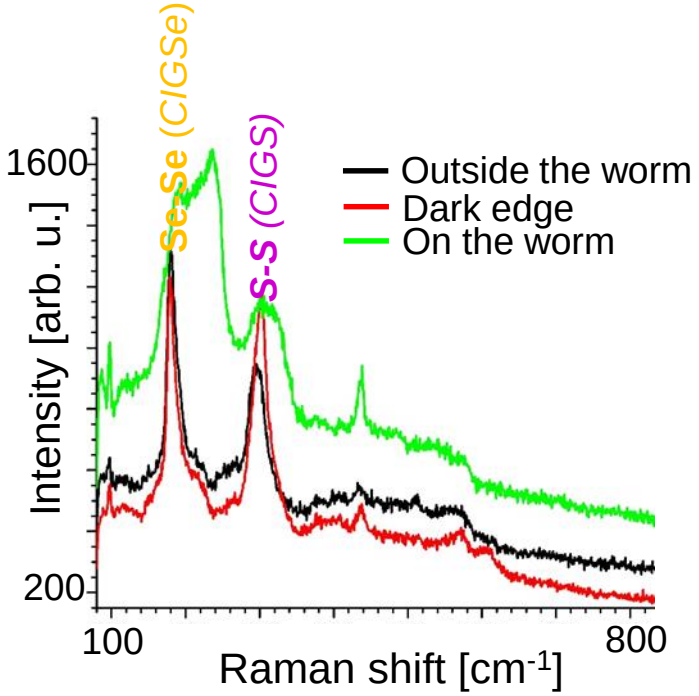


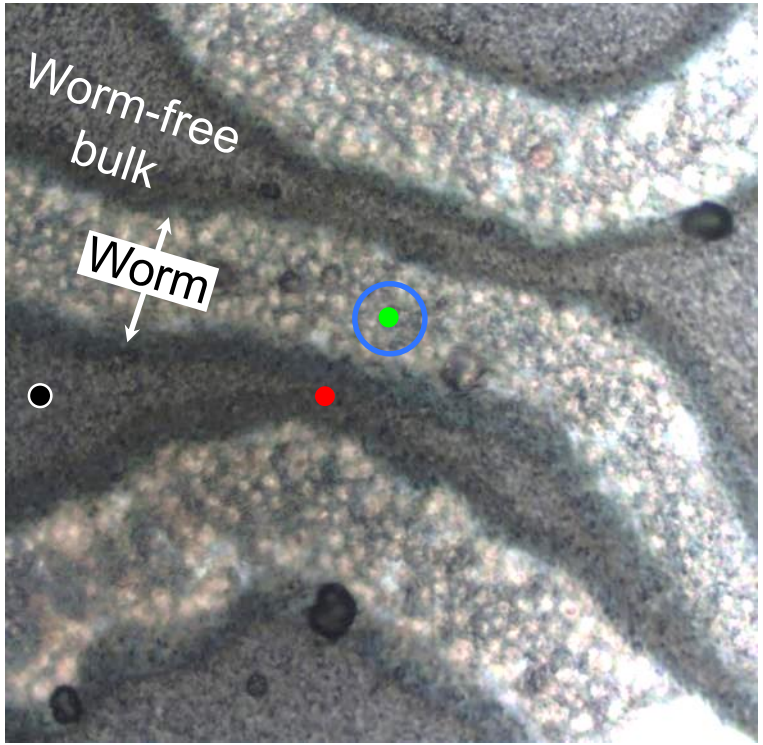


# ”wormy” sample: Raman

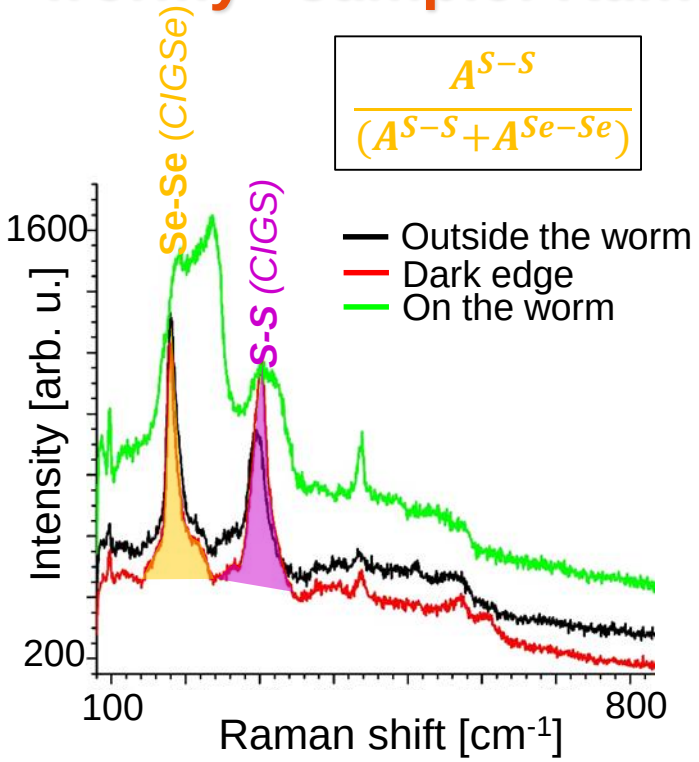


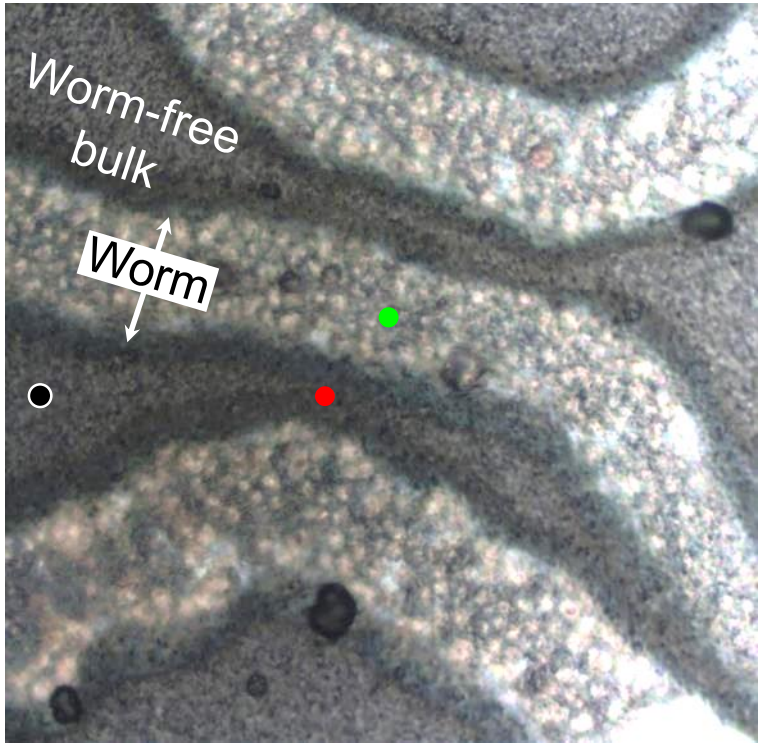


# ”wormy” sample: Raman

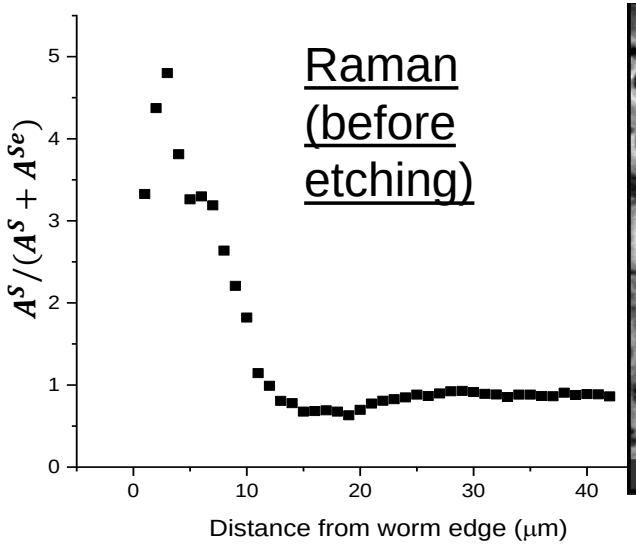


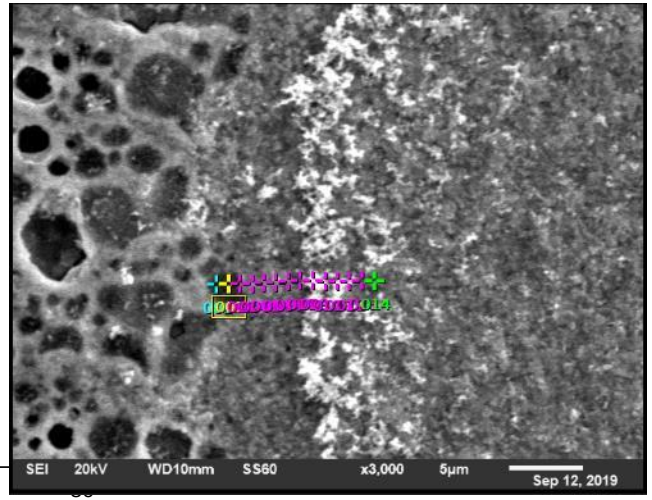


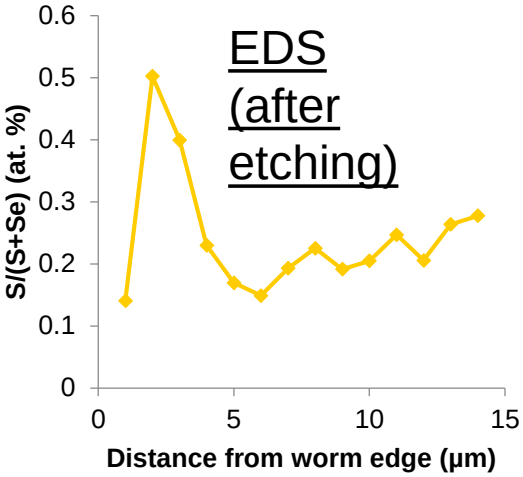



# “wormy” sample: Raman vs SEM/EDS






- Raman & EDS both show increased S/Se ratio near worm edge, as in [1]
- Worm morphology similar to reported wormlike defects

*[1] Bakker, K., et al. (2019). IEEE J. Photovoltaics 9(6): 1868-1872*

# Conclusion

1. Wormlike defects were generated by controlled partial shading in a commercial module

2. Samples were extracted from the module without damage to the active layers, usable for electrical and material characterisation

3. The samples with wormlike defects was etched and studied:
    a. the wormlike defects are porous and protrude from the surface by ≈1µm
    b. An increase of the sulphur content is observed at the edge of the worm, both by Raman and EDS

4. Results are comparable to lab scale results published in the past

# Thanks!

# I’d be happy to hear (or read) you questions