# Evaluating performance limiting defects in novel thin-film materials for solar cells

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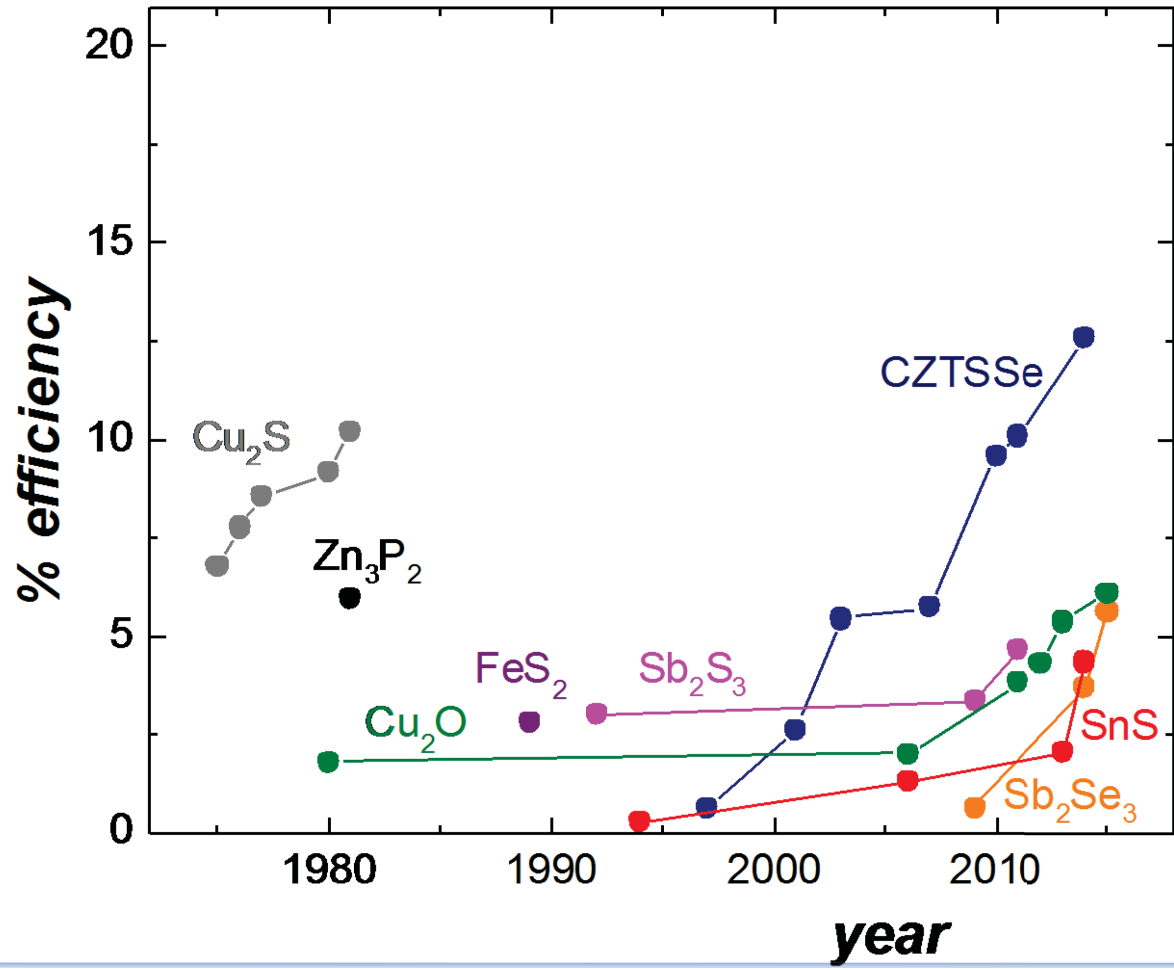
# Development of novel Earth-abundant solar cells

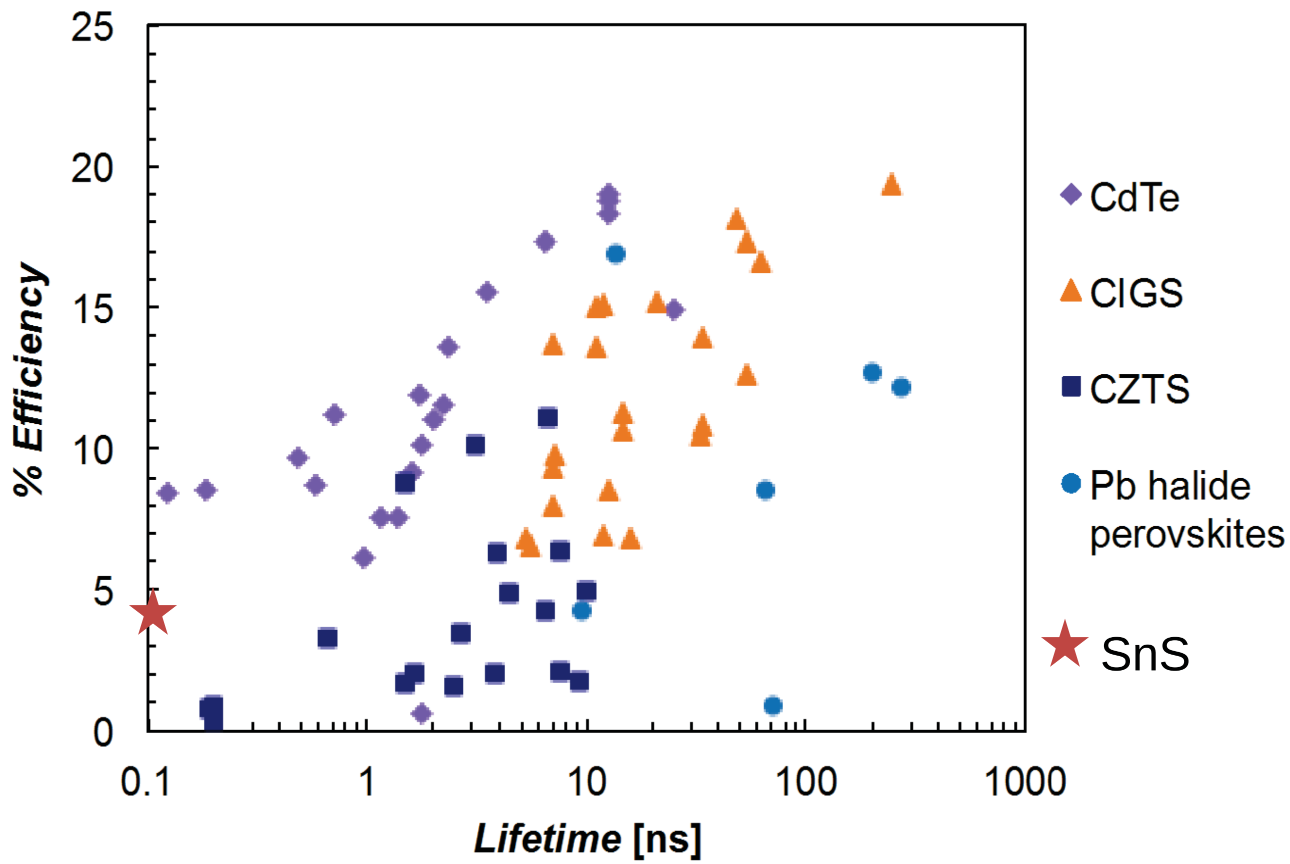
- Many inorganic thin-film materials are underperforming (< 10% laboratory efficiency) despite decades of R&D.




V. Steinmann *et al.*, *Nature Photonics* **9**, 355 (2015).

# High bulk carrier lifetime for high-performance devices

- High bulk carrier lifetime (> 1–10 ns): a pre-requisite for high conversion efficiencies (≥ 10%).




R. Jaramillo *et al.*, submitted (2015).



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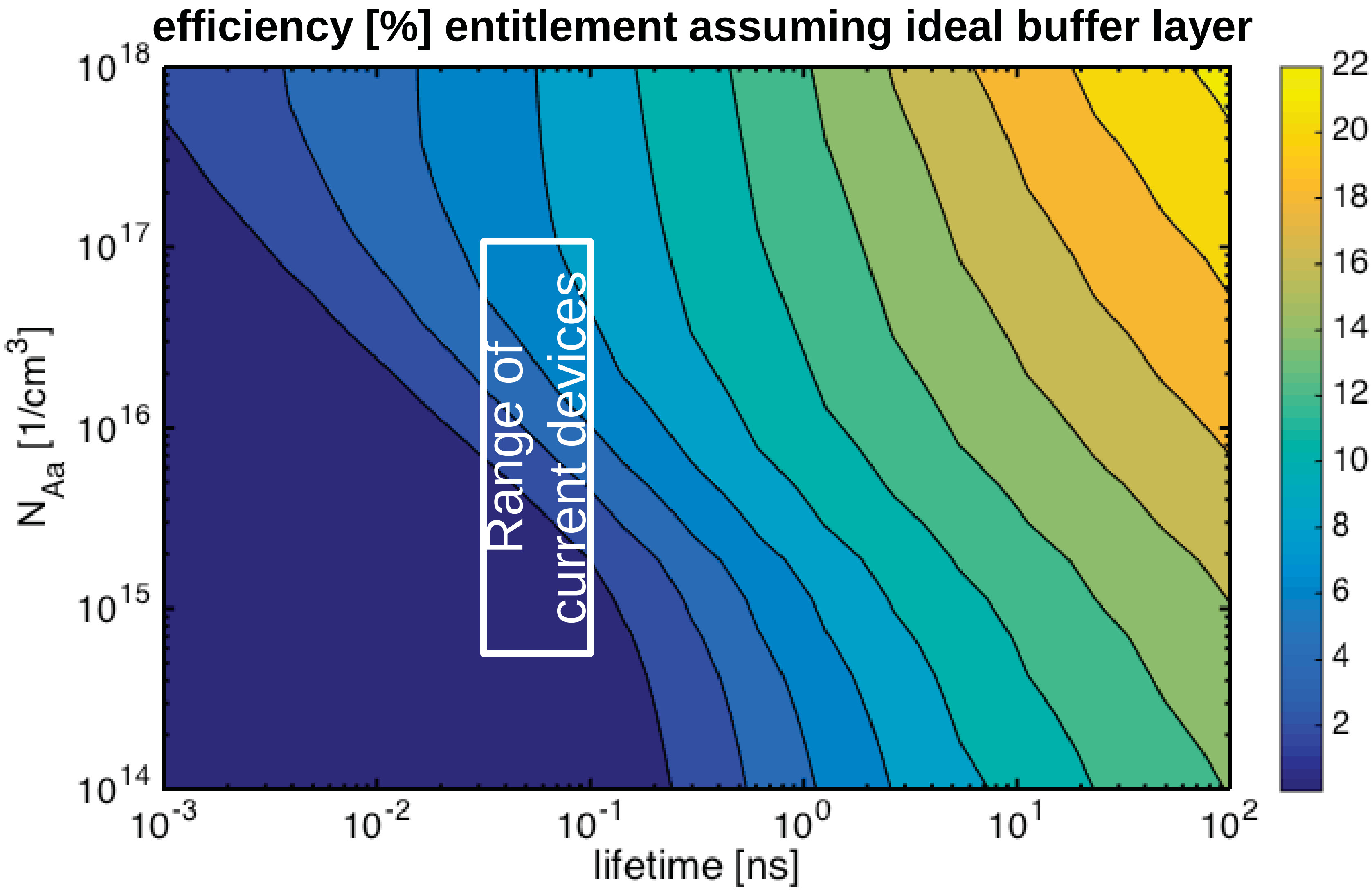
# Bulk carrier lifetime in SnS



# What defects limit the SnS device performance?

- We perform cross-sectional SEM and electron-beam-induced current (EBIC) to study the thin-film morphology and electronic activity.
- Intragranular recombination appears to limit bulk carrier lifetime/diffusion lengths, caused by:
  - Extrinsic defects (impurities)
  - Extended structural defects (stacking folds, dislocations).

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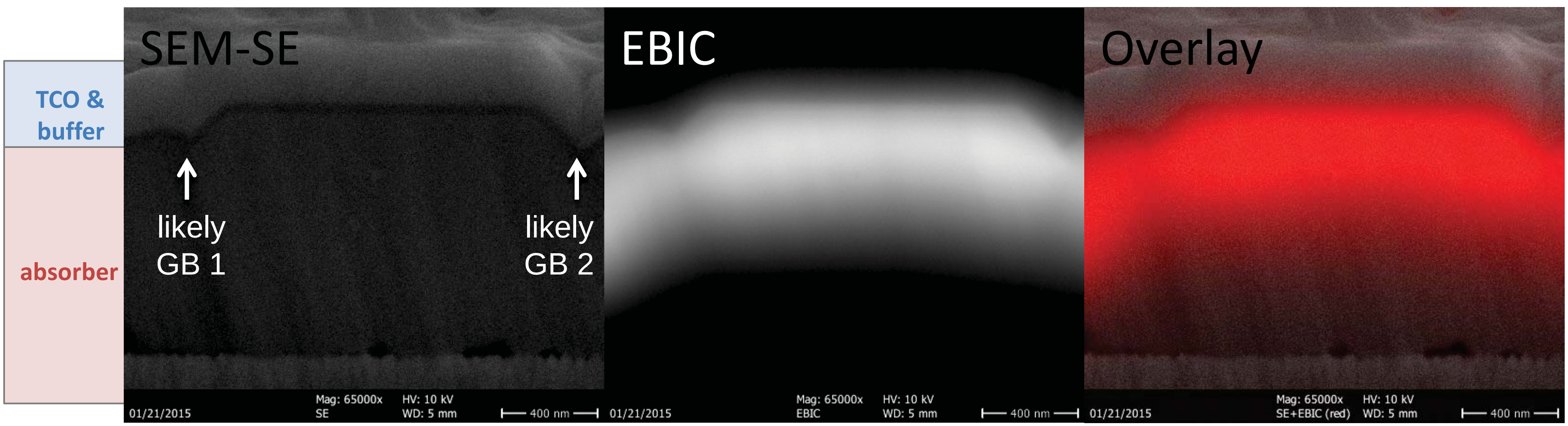


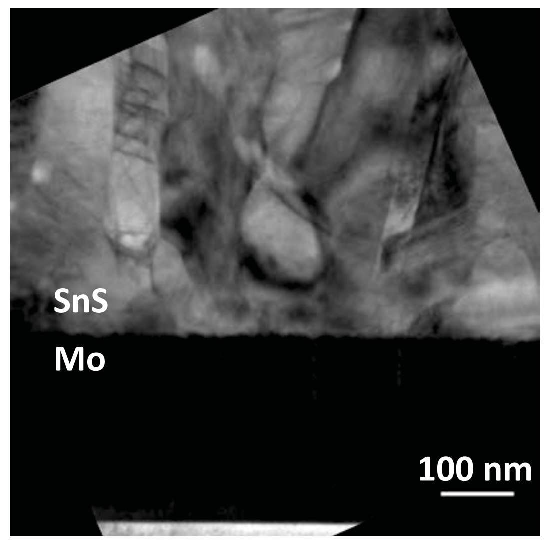

V. Steinmann *et. al., under preparation.*

# Extended structural defects in SnS

- Transmission electron microscopy (TEM) reveals high density of intragranular extended structural defects at $T_{substrate} \sim 0.5\ T_{melt}$ (< 450° C).

- Hypothesis: higher temperature growth may help to reduce the extended structural defect density and improve charge carrier diffusion length.

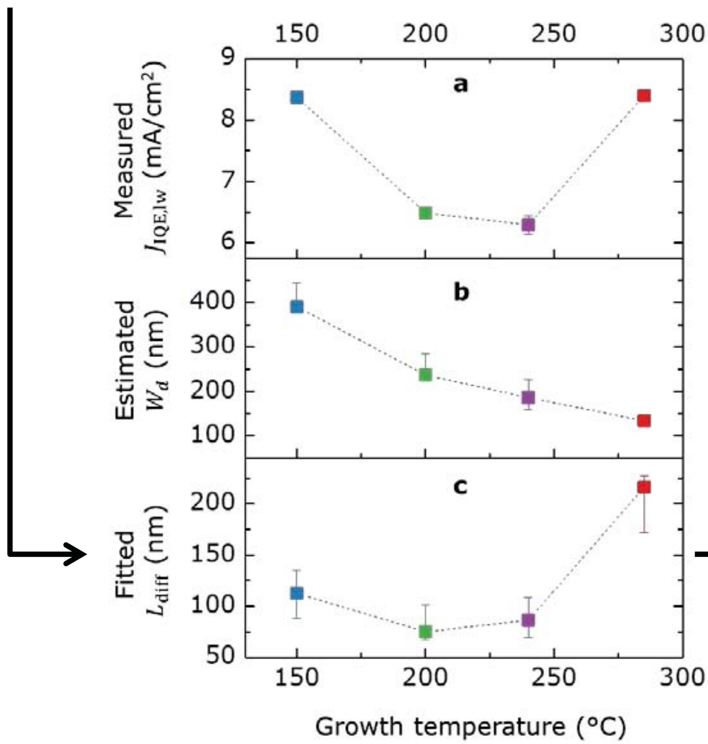
**Growth temperature < 300° C,**
**annealing temperature < 450° C**



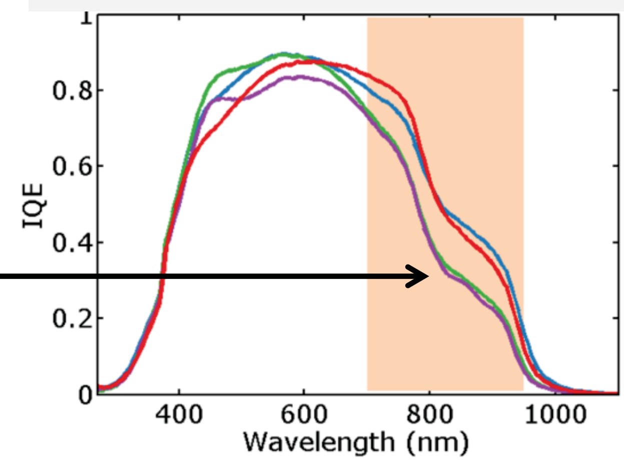

SnS melting point at $T_{melt}$ = 882° C.

# First results show increase in diffusion length

- Explored range of growth temperatures from 150–285° C, annealed at 400° C in 4% $H_2S$ ambient.
- Diffusion length increases with higher growth temperature.




Diffusion length calculated from long-*l* portion of IQE




R. Chakraborty, V. Steinmann *et al.*, *Appl. Phys. Lett*. 2015.



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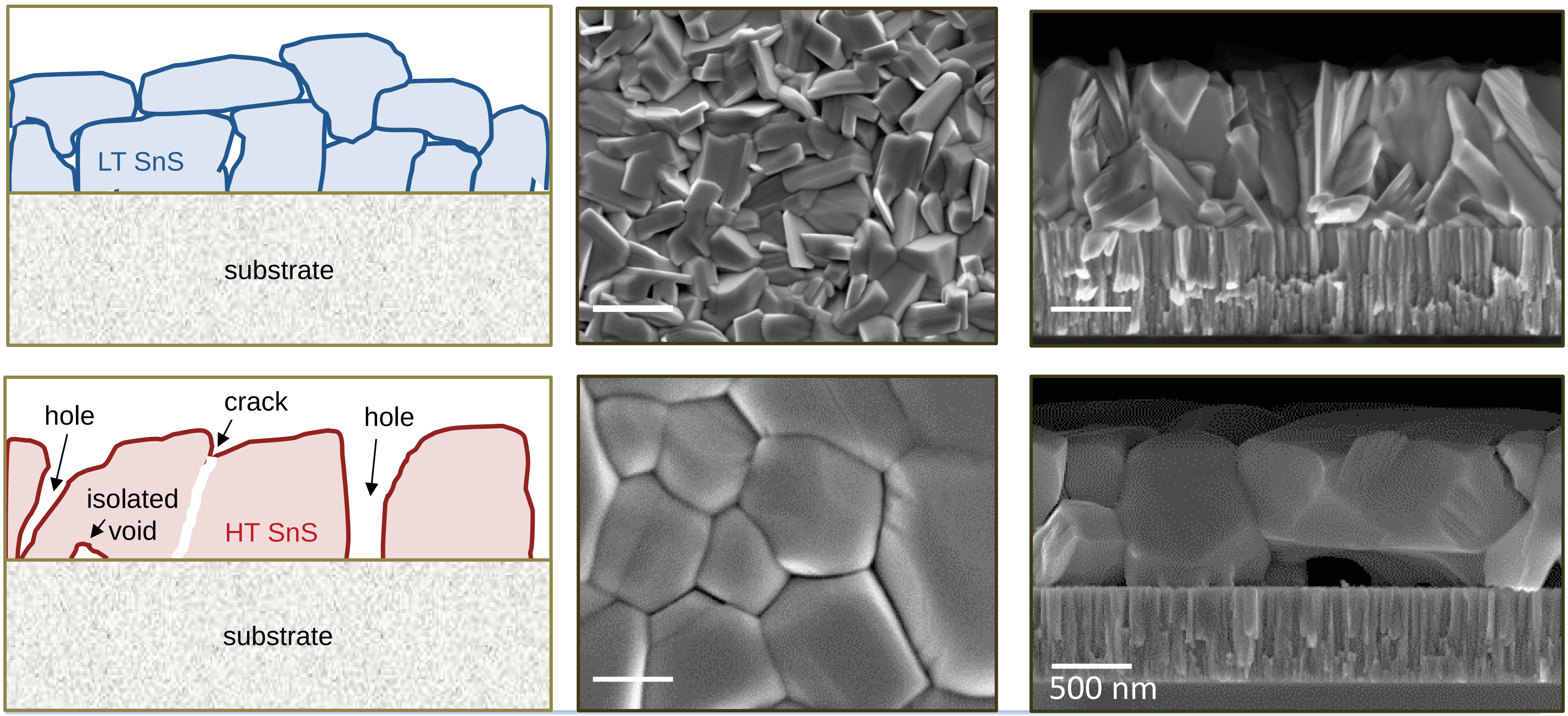
# High-temperature processing causes cracks

- locally unfavorable surface energetics and/or coefficients of thermal expansion make polycrystalline SnS with many different grain orientations especially prone to through-thickness voids.




V. Steinmann *et. al.*, *under preparation.*

LT: low-temperature, HT: high-temperature



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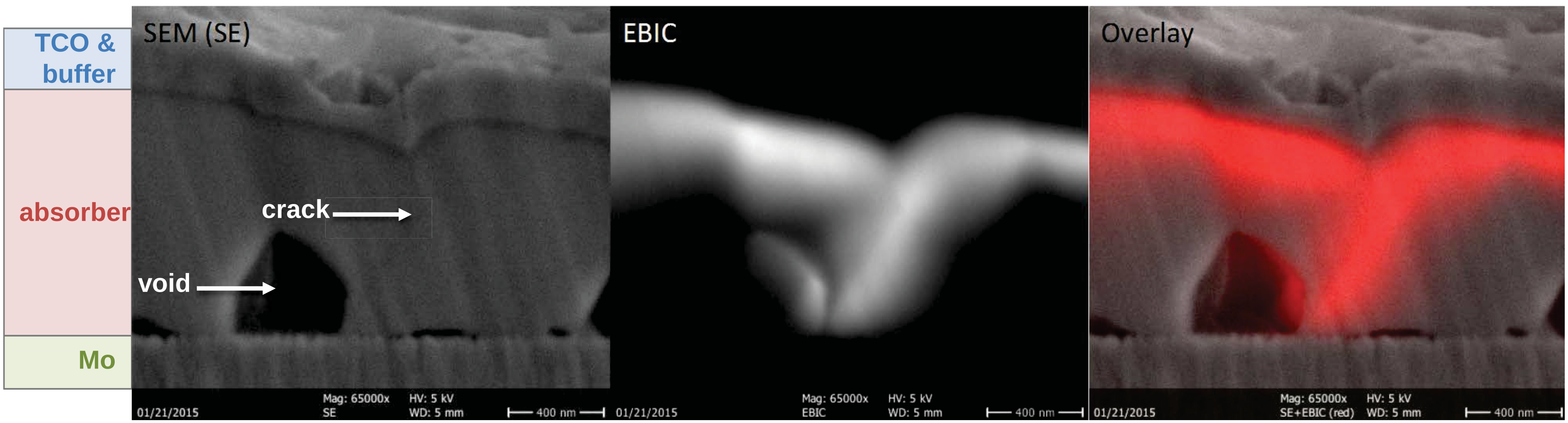
# High-temperature processing causes cracks

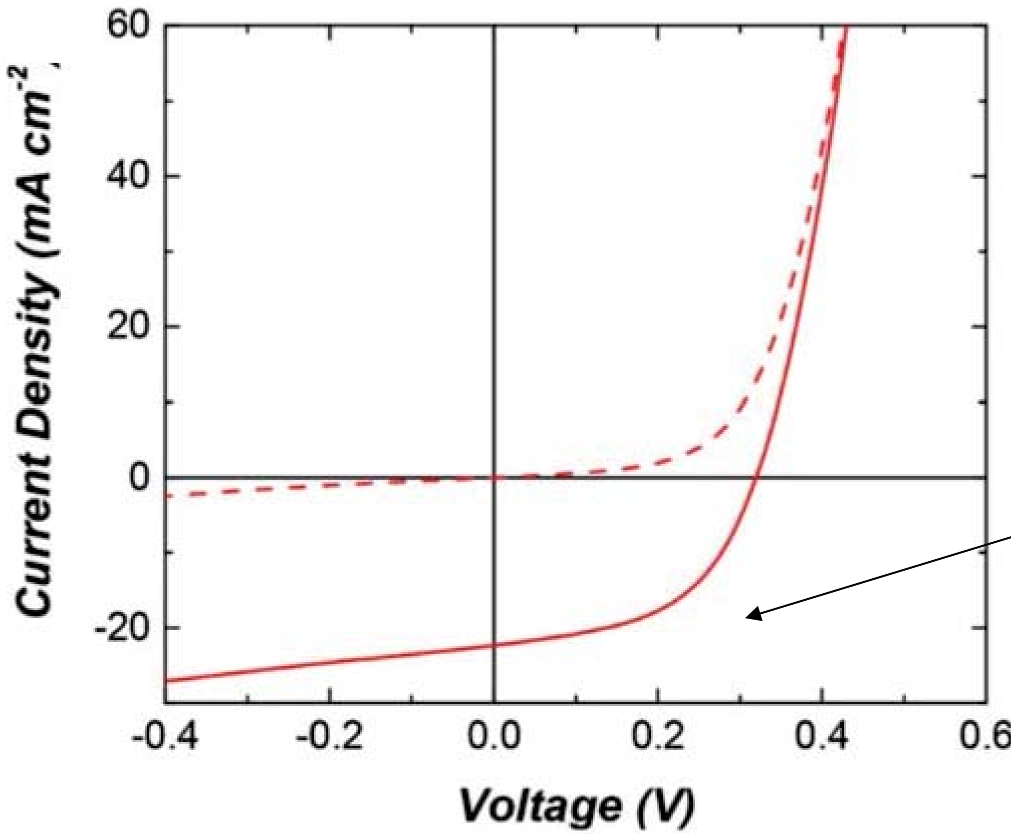
- Cross-sectional electron-beam-induced current (EBIC):
- Cracks can become current pathways  vertically across SnS absorber layer → leading to shunts in devices.




V. Steinmann *et. al., under preparation.*

# Shunting in SnS solar cells

- Cracks across the SnS bulk contribute to low shunt resistance in devices.




$R_{shunt}$ = 74 Ω cm$^2$
$R_{series}$ = 0.66 Ω cm$^2$

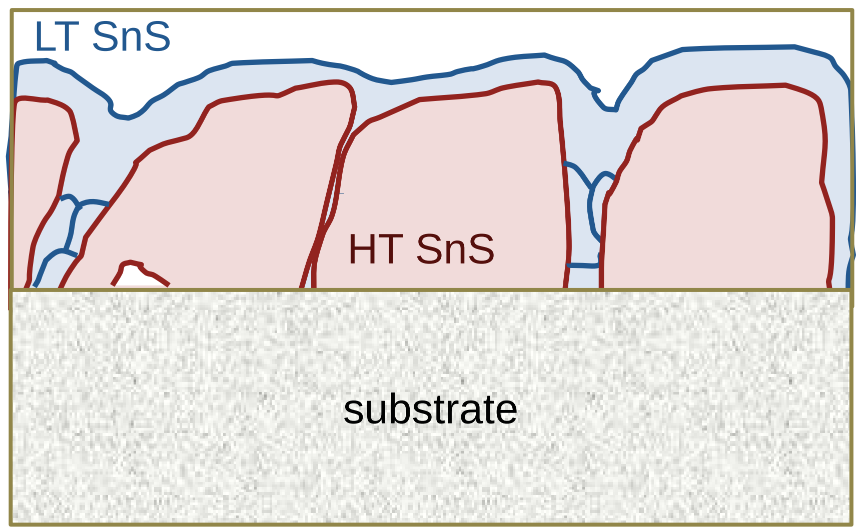
Evidence of shunting in $J$—$V$ characteristics.

$V_{OC}$ = 334.1 mV, $J_{SC}$ = 20.6 mA/cm$^2$, FF = 65.28%, PCE = 3.88%

V. Steinmann *et al. Adv. Mater.* 26, 7488 (2014).

# Two step deposition approach to avoid shunts

- Apply continuous thin absorber coverage at low-temp. to reduce number of shunted devices.
- High-temp. anneal at 400° C + low-temp. deposition at 240° C.

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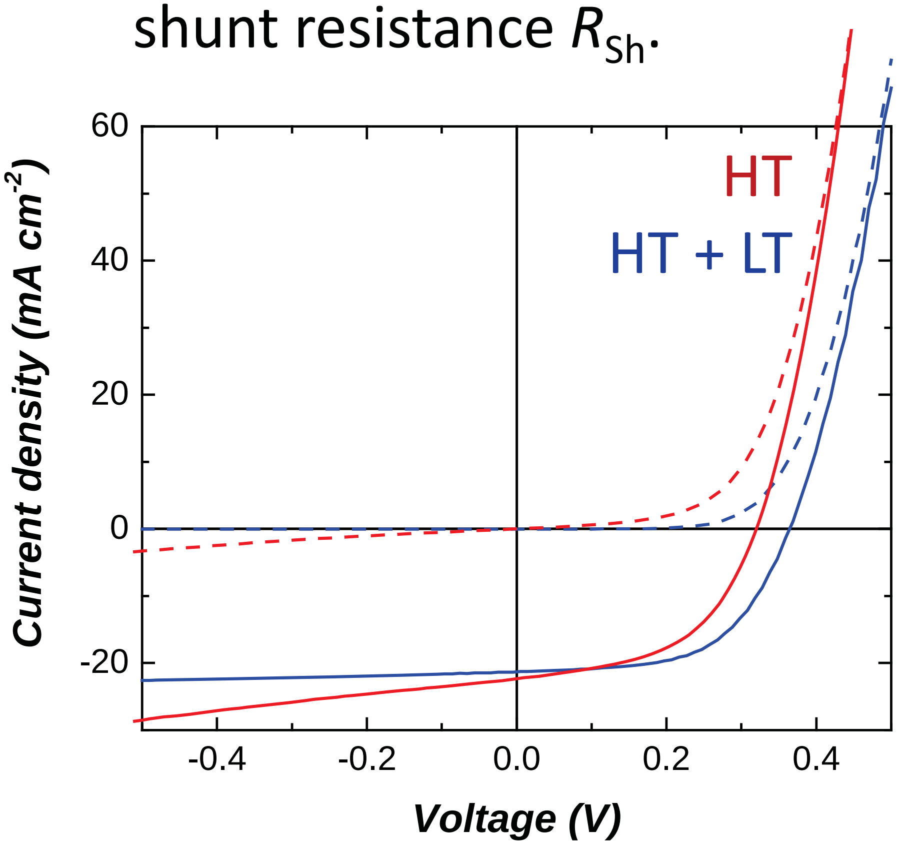
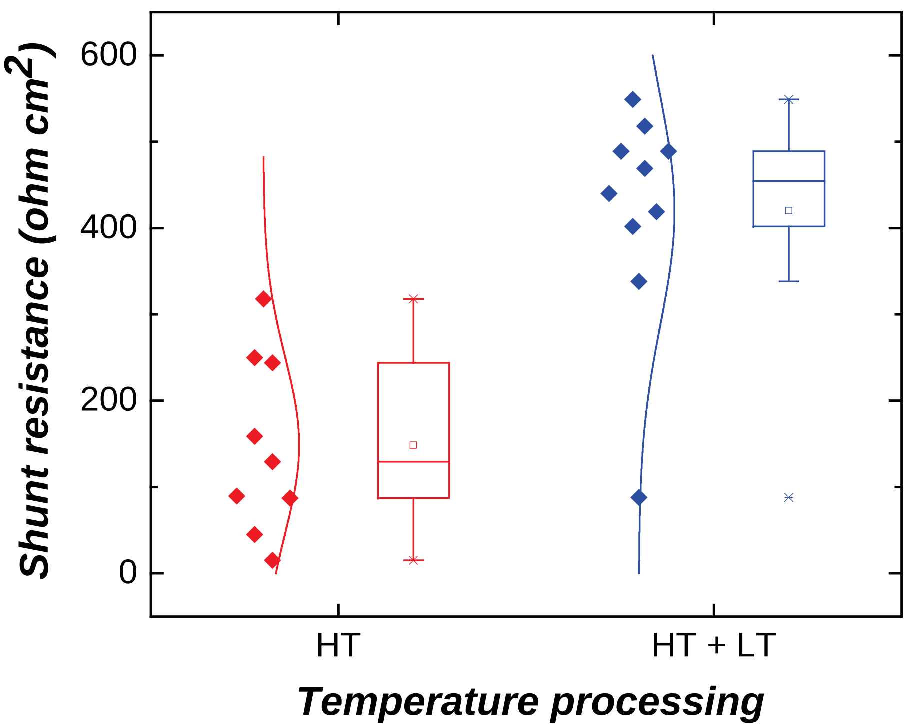
V. Steinmann *et. al*., *under preparation.*

# Shunt reduction by two step deposition approach

- Improved fill factor and open-circuit voltage due to improved shunt resistance $R_{Sh}$.

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# Take-aways

- High bulk carrier lifetime is necessary (but not sufficient) for high-efficiency solar cells.
- Lifetime in SnS thin-films is limited by intragranular recombination.
  - Extrinsic defects
  - Extended structural defects

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- High-temperature processing can reduce extended structural defect density and improve SnS bulk carrier lifetime.
- High-temperature processing causes cracks in SnS thin-film, leading to shunts in devices.
- Two step absorber deposition approach successfully "plugs holes" and improves shunt resistance in devices.

# Acknowledgments


- PVLab at MIT
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- Center for Materials Science and Engineering at MIT

Harvard University Center for Nanoscale Systems

CMSE MIT Center for Materials Science and Engineering

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