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

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

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).

[Graph showing scatter plot with markers for CdTe, CIGS, CZTS, Pb halide perovskites, and SnS]
Bulk carrier lifetime in SnS

efficiency [%] entitlement assuming ideal buffer layer

Range of current devices
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.
- Intragraniular recombination appears to limit bulk carrier lifetime/diffusion lengths, caused by:
  - Extrinsic defects (impurities)
  - Extended structural defects (stacking folds, dislocations).

V. Steinmann et. al., under preparation.
Extended structural defects in SnS

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

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

Growth temperature $< 300^\circ \text{C}$, annealing temperature $< 450^\circ \text{C}$

SnS melting point at $T_{\text{melt}} = 882^\circ \text{C}$. 
First results show increase in diffusion length

- Explored range of growth temperatures from 150–285°C, annealed at 400°C in 4% H₂S ambient.
- Diffusion length increases with higher growth temperature.

Diffusion length calculated from long-/l portion of IQE

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
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.

\[ V_{OC} = 334.1 \text{ mV}, \quad J_{SC} = 20.6 \text{ mA/cm}^2, \quad \text{FF} = 65.28\%, \quad \text{PCE} = 3.88\% \]


\[ R_{\text{shunt}} = 74 \text{ } \Omega \text{ cm}^2 \]
\[ R_{\text{series}} = 0.66 \text{ } \Omega \text{ cm}^2 \]

Evidence of shunting in \( J-V \) characteristics.
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.

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 $R_{\text{Sh}}$.

V. Steinmann et. al., under preparation.
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

- 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.
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