SnS as a solar absorber

- Tin (Sn) and sulfur (S) are non-toxic and abundant in nature
- SnS is conducive to thermal evaporation (TE), which has potential for high-throughput manufacturing
- Strong optical absorption (> 10^4 cm^-1 above 1.4 eV)

SnS carrier collection deficit

- Recently achieved 3.88% conversion efficiency with TE SnS-based solar cell
- Leading loss mechanism is recombination at long wavelengths
- Increasing SnS growth temperature $T_g$ may improve charge-carrier collection

Goal of this work

- Determine the effect of $T_g$ on structural and electrical properties of SnS films, and on long-wavelength internal quantum efficiency (IQE) of devices
- Explain the variation in long-wavelength IQE as a function of $T_g$ through optoelectronic modeling
- Determine a path toward higher-current SnS devices

SnS growth conditions & device stack

- Substrate temperature was varied while deposition rate and thickness were kept constant at 1 A/S and 1 µm, respectively
- Used a previously reported device stack

<table>
<thead>
<tr>
<th>SnS growth temperature (°C)</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>150</td>
<td>200</td>
<td>240</td>
<td>285</td>
</tr>
</tbody>
</table>

Electronic properties

- Lower $p$ and higher $L_{diff}$ necessary to achieve maximum $\eta_{IQE, LW}$
- Decreasing $p$ has more limited improvement capacity than increasing $L_{diff}$ in current parameter space

SnS device performance and modeling

- Device simulation with $p$, $\mu$ values from measurements; other material parameter values from literature
- Fit IQE in 700-950 nm range, with $L_{diff}$ as free parameter

Conclusions

- Grain size, $\mu$, and $p$ increase with $T_g$
- Increasing $p$ leads to decreasing drift-assisted collection
- At the highest $T_g$ of 285°C, carrier collection recovers due to an increase in diffusive minority-carrier transport
- Higher carrier collection may be achievable by simultaneously decreasing carrier concentration while increasing diffusion length

Future directions

- Higher $T_g$ with optimized deposition geometry (CSS-like)
- Co-optimization of growth conditions with post-deposition annealing

Acknowledgements

The authors are thankful to Mariela Lizet Castillo for helping with substrate preparation. The authors also thank Luka Barrena and Kelsey Doodliffe for helping with the grain size analysis and anisotropic calculations, respectively. This work is supported by the U.S. Department of Energy through the SunShot Initiative under contract DE-EE0005129, and by Robert Bosch LLC through the Bosch Energy Research Network under grant 02.10.AN.21. V. Steinmann, H. Jaramillo, K. Hartman, and R.E. Brandt acknowledge the support of the Alexander-von-Humboldt Foundation, a DOE/DOE Postdoctoral Research Award, an Intel PhD Fellowship, and an NSF GRFP Fellowship respectively. This work made use of the MRSEC Shared Experimental Facilities at MIT that is supported by the National Science Foundation (NSF) under award DMR-1502796, and the Center for Nanoscale Systems that is supported by the NSF under award ECS-0903242.