Radiation Tolerance and Annealing Capabilities of 2MeV Proton-irradiated, Ultra-thin InP Solar Cells

Space Photovoltaics Group

James H. Shin [1], Venkata S. A. Chaluvadi [1], Toluwalase Agoro [1], Stefan Diesing [2], and Louise C. Hirst [1]

[1] **University of Cambridge**
[2] University of Sheffield

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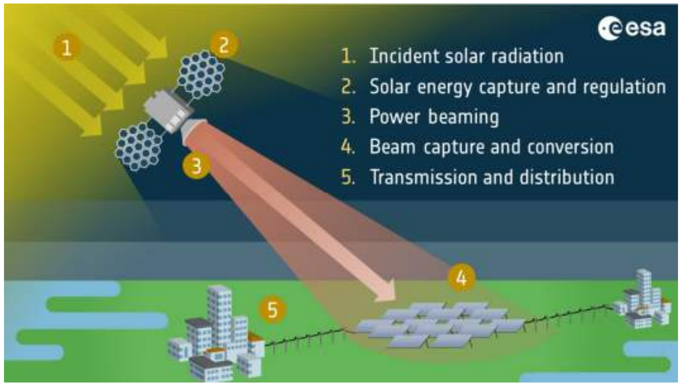
Motivation: Enabling Resilient, Novel Space Architecture

- **Current Major Players in Photovoltaics for Space Applications:**
  - Silicon: Low Cost
  - III-V Multijunction: High Performance, High Cost

- **Novel Space Architecture and Mission Profiles Require Continual Advancements in Reliable, Resilient Power Generation**
  - longer operational lifetimes
  - establishing cislunar and lunar architecture
  - space based solar power
  - orbital data centers



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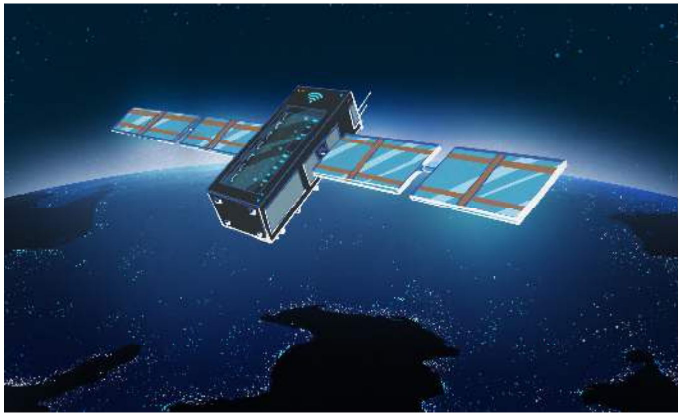

[2]

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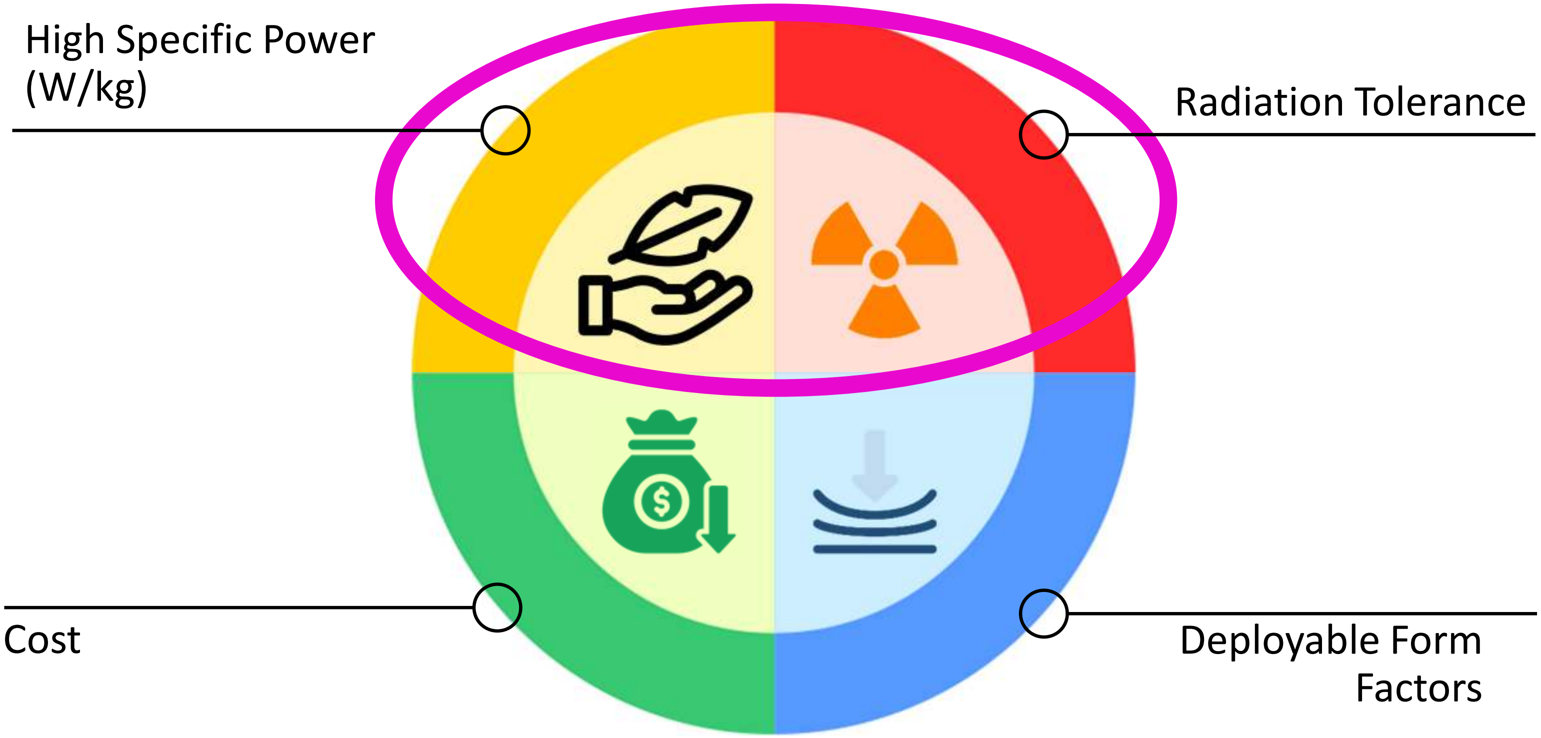
[1] ESA Stages of space-based solar power, European Space Agency, Jun. 30, 2023.

[2] Tyler August, “Space-Based Datacenters Take The Cloud Into Orbit,” Hackaday, Jun. 19, 2025.

Motivation: Enabling Resilient, Novel Space Architecture



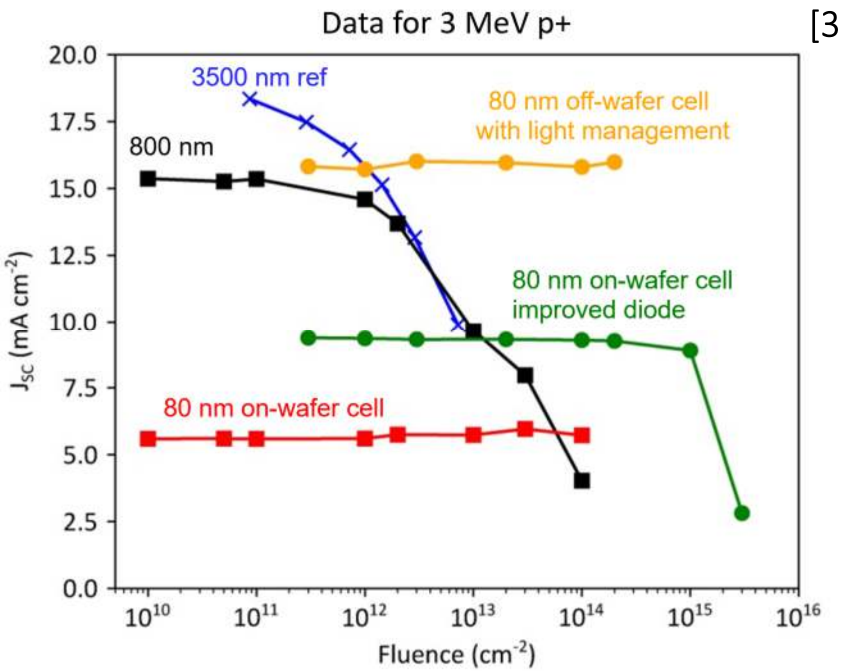
High Specific Power (W/kg)

Radiation Tolerance

Cost

Deployable Form Factors

Background: Radiation Tolerance of Ultra-thin Solar Cells



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- ○ **Radiation Induced Defects Reduce Minority Carrier Lifetime**
- ○ **Ultra-thin Devices Reduce Carrier Collection Distance**
  - – can tolerate greater reductions in minority carrier lifetime
- ○ **Challenges Associated With Thin Absorber:**
  - – absorption
  - – increased surface recombination

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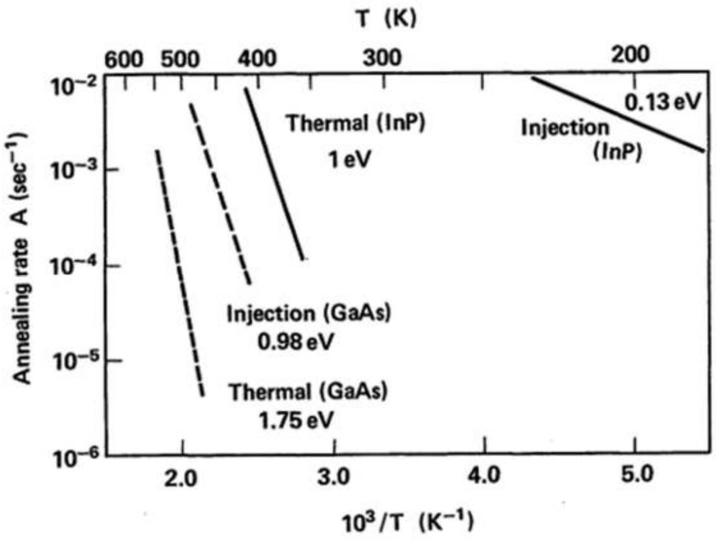
[3] A. Barthel et al., “Radiation effects in ultra-thin GaAs solar cells,” J. Appl. Phys., vol. 132(18), 184501, 2022.

Background: Indium Phosphide Solar Cells

- **Non-ionizing Energy Loss (NIEL) Values for InP are the Lowest Amongst Space Solar Cell Materials [4]**
    - ~10^{-2} MeV cm^2/g for 3 MeV protons

- **Indium Phosphide Displays Thermal Annealing and Minority-carrier Injection Annealing**

- **Device Structure, Fabrication, and Radiation Particle Impact Annealing Capabilities**
    - diffused junction vs. epitaxy
    - electron vs. proton



[5]

[4] R. Walters et al., “Space radiation effects in InP solar cells,” IEEE Transactions on Nuclear Science, vol. 38(6), pp. 1153-1158, 1991.

[5] Yamaguchi et al., “Radiation Resistance of InP-Related Materials,” Jpn. J. Appl. Phys. 34:6222, 1995.

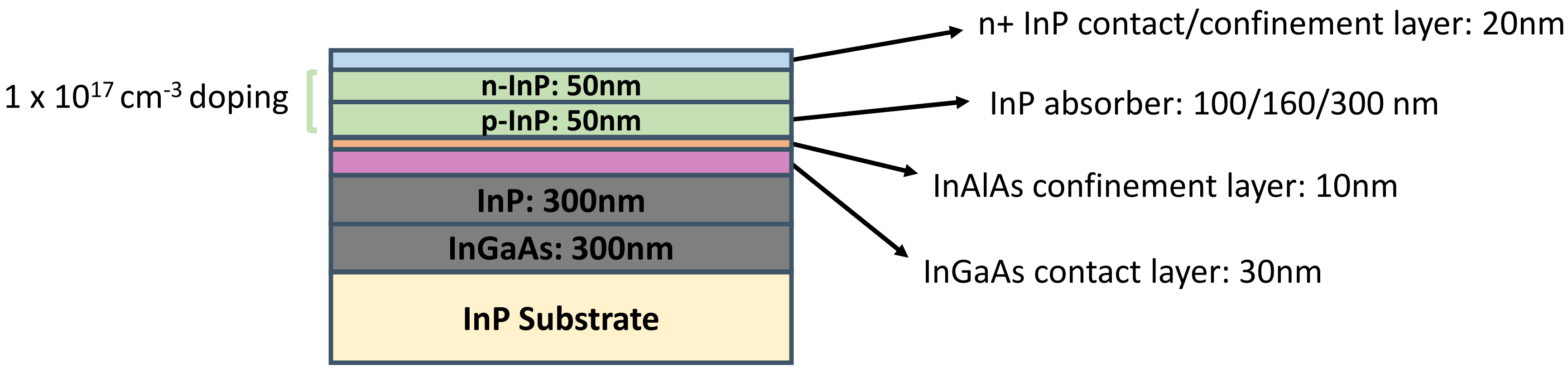
Overview

1. **Can we harness Indium Phosphide within an ultra-thin geometry to increase its absorber thickness relative to GaAs while maintaining radiation resilience?**

2. **Does ultra-thin Indium Phosphide exhibit minority-carrier injection and thermal annealing?**

Ultra-thin InP Stack up and Fabrication

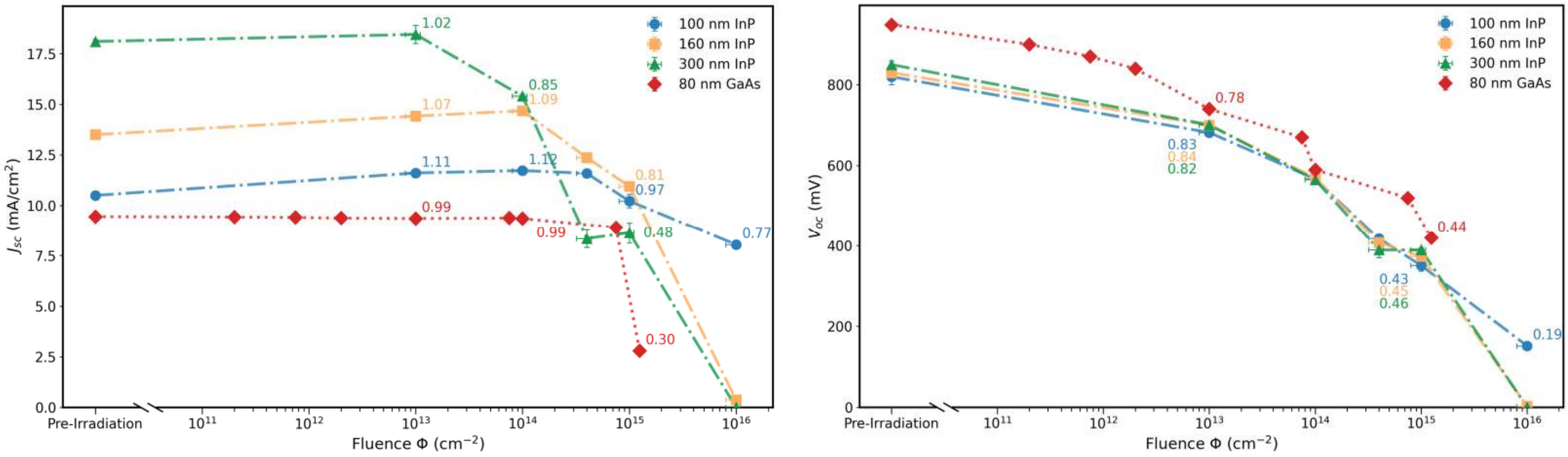
Epitaxially Grown Ultra-thin InP (via MOCVD)



Cell Growth Completed by IQE

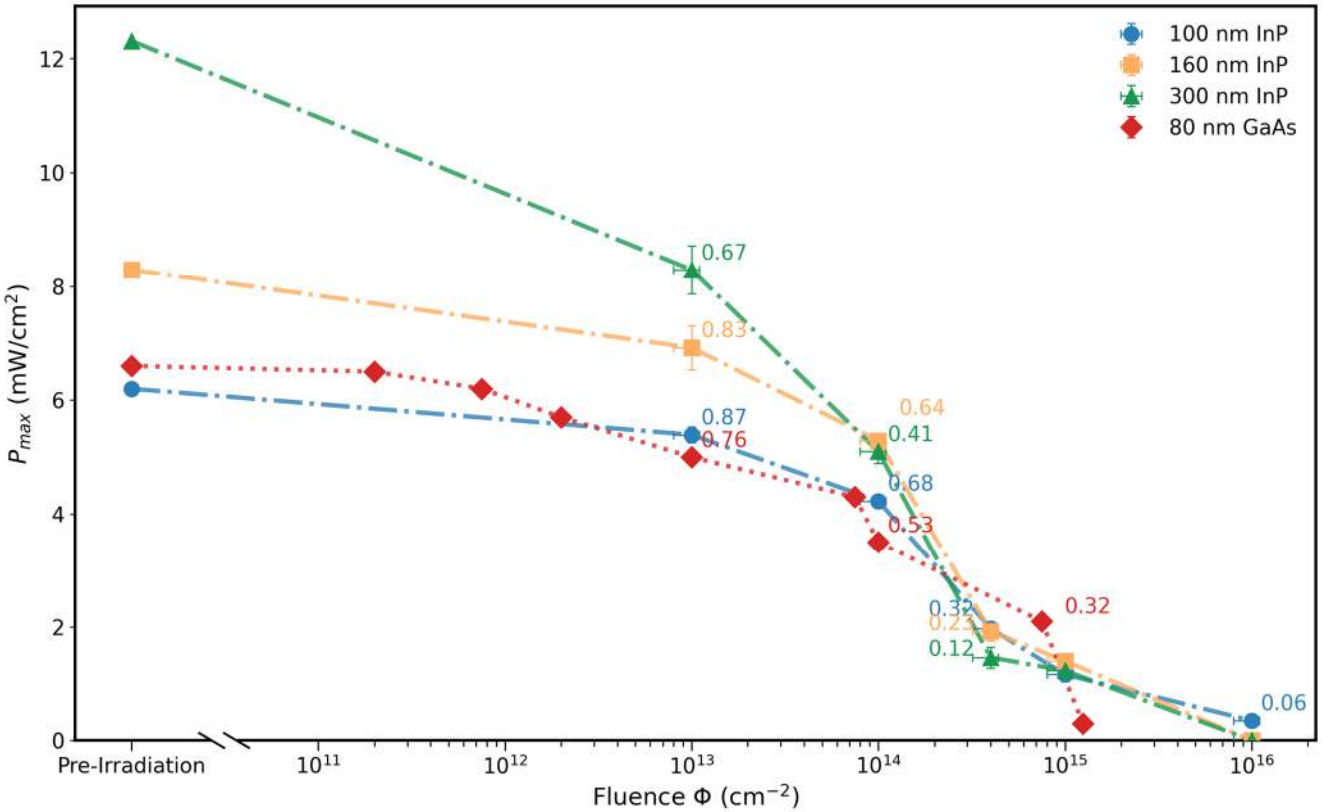
2MeV Proton Irradiation at EPSRC UK National Ion Beam Centre

Device Parameters Across Fluence: LIV



Labels on markers indicate remaining factor

Device Parameters Across Fluence: LIV



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Orbit Equivalents

Putting Fluences into Perspective

*Without any additional shielding

2MeV p+ Fluence (cm^{-2})	Equiv. Years on Orbit: **GEO**	Equiv. Years on Orbit: **GPS**
10^{14}	0.37	0.060
10^{15}	3.65	0.60
10^{16}	36.5	6.05

← ~1.2 Years: 80nm GaAs

← ~6 Years: 100nm InP

Calculated using **SPENVIS**

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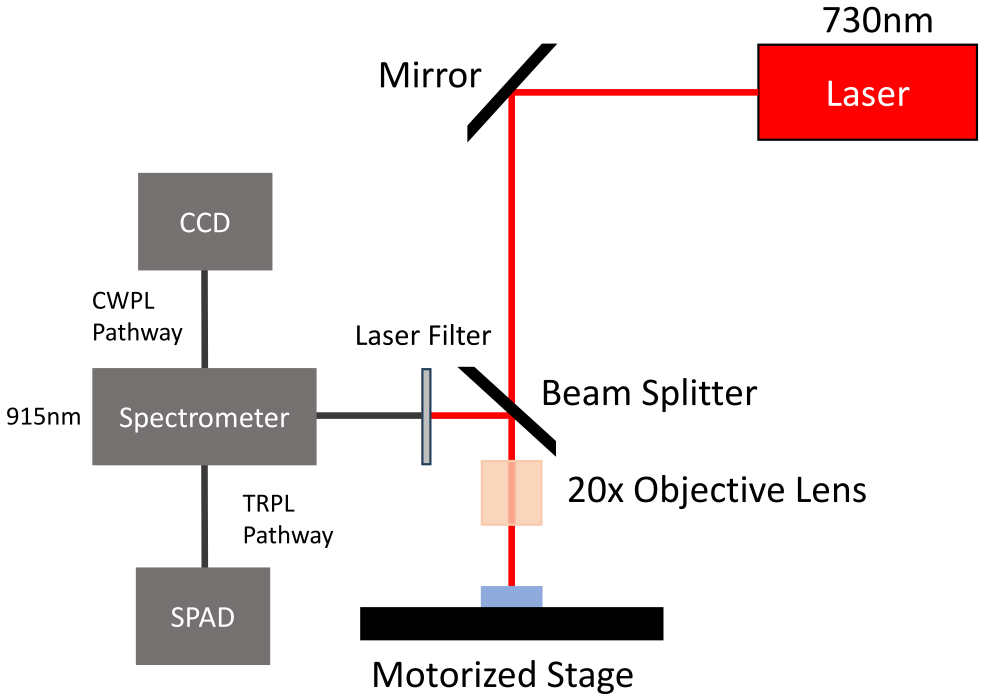
Time-Resolved and Continuous Wave Photoluminescence

- **Characterizing Annealing Using Photoluminescence in Addition to Device Measurements**
  - **time-resolved photoluminescence (TRPL)** to measure effective carrier lifetime
  - **continuous wave photoluminescence (CWPL)** provides insight into recombination pathways, defect states, temperature effects

- **Photoluminescence Provides Non-Contact, Non-Destructive Characterization**



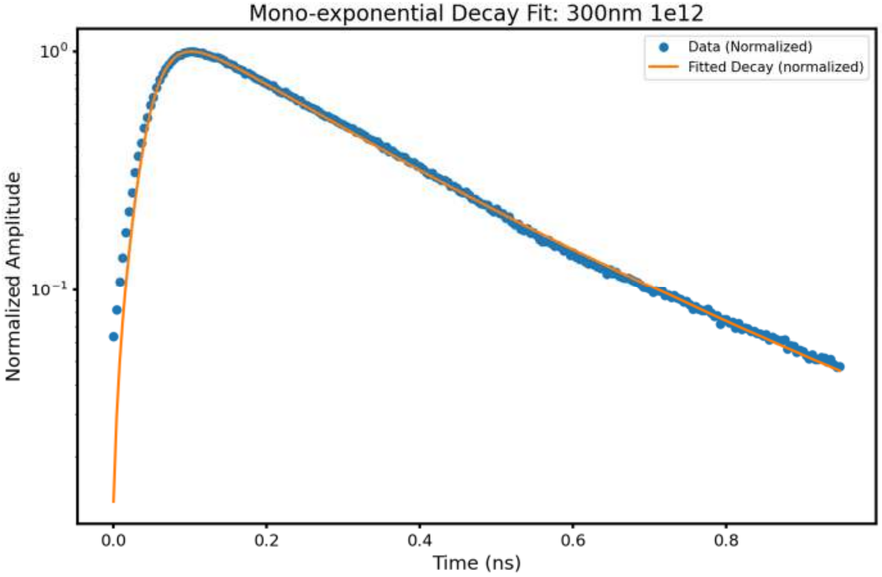
Predicting Radiation-Induced Device Failure

- ○ Jsc collapse occurs when **carrier lifetime (τ) becomes comparable to transit time (t_{tr})** in the device
  - – solcore used to calculate electric field (E) and drift velocity (v_d) [6]
  - – integrated across absorber width (W)

$$v_{d_{e/h}} = \frac{\mu_{e/h}E}{\left[1+\left(\frac{\mu_{e/h}E}{v_{sat}}\right)^{\beta}\right]^{\frac{1}{\beta}}}$$

$$t_{tr} = \int_0^W \left(v_{d_{e/h}}\right)^{-1} dx$$

Instrument Response Function (IRF) Convolved Mono-exponential Decay Fit



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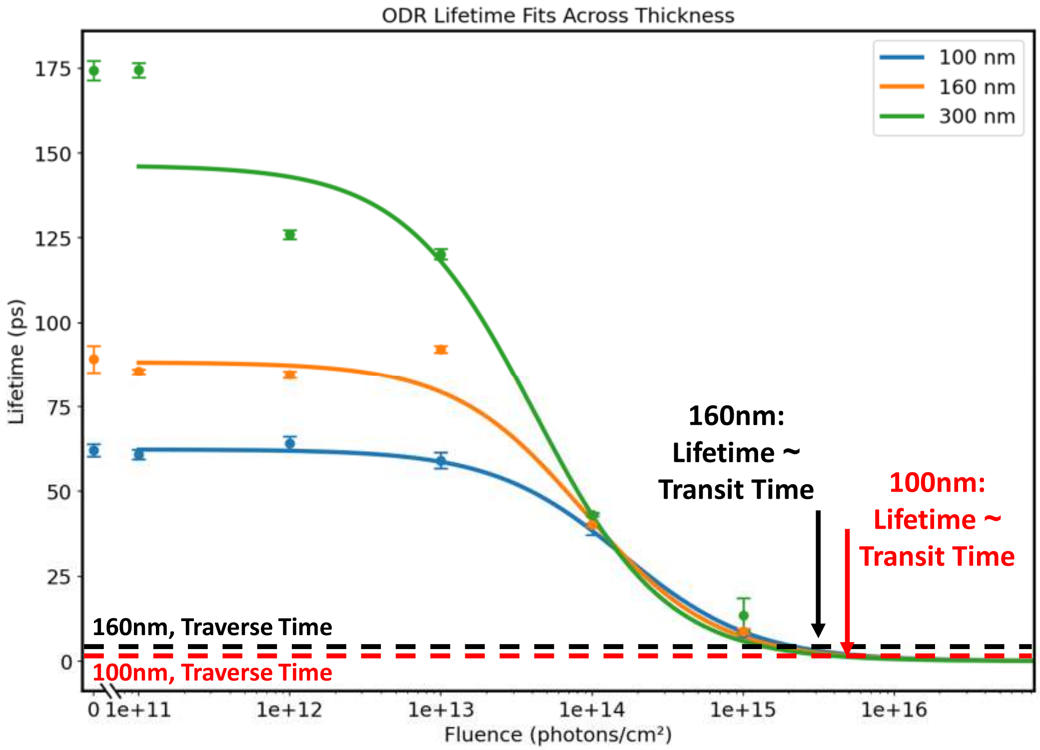
[6] D. Alonso-Álvarez et al., “Solcore: a multi-scale, Python-based library for modelling solar cells and semiconductor materials,” *J. Comput. Electron.*, vol. 17, no. 3, pp. 1099–1123, Apr. 2018.

TRPL across Fluence

TRPL across 64 positions on each sample



160nm: Lifetime ~ Transit Time

100nm: Lifetime ~ Transit Time

160nm, Traverse Time

100nm, Traverse Time

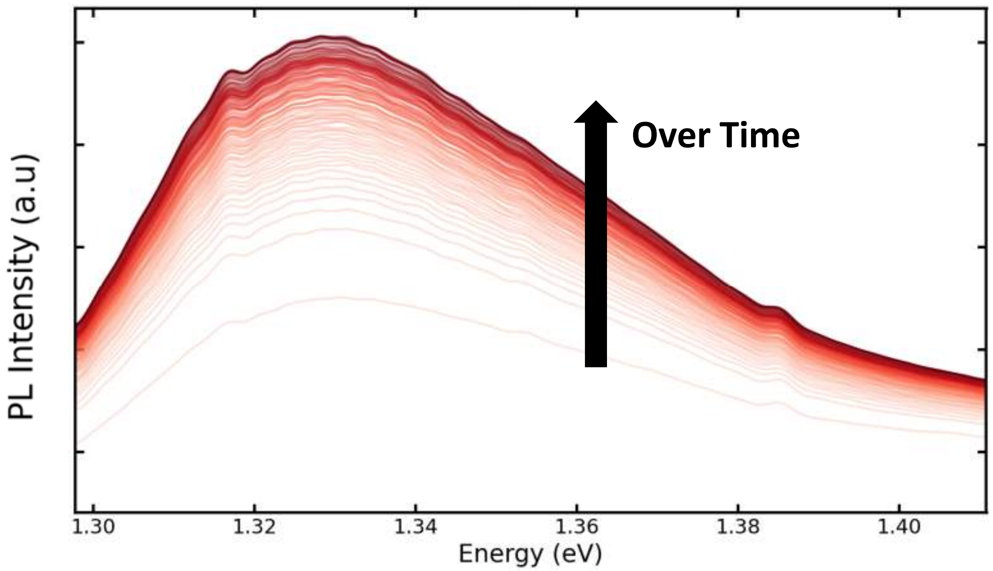
$$\frac{1}{\tau} = \frac{1}{\tau_0} + K_\tau \phi$$

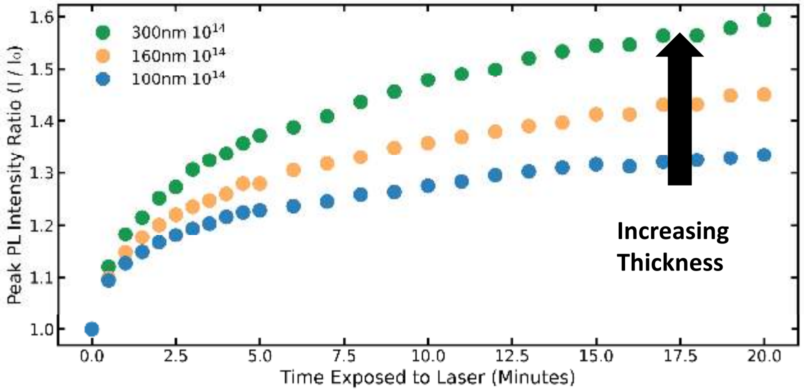
Absorber Thickness (nm)	Lifetime Damage Constant $(cm^2 s^{-1})$ K_τ	Pre-irradiation Lifetimes (ps) τ_0
300	**1.64×10^{-4}** $\pm$ 2.99×10^{-5}	**146.37** $\pm$ 10.1
160	**1.30×10^{-4}** $\pm$ 1.32×10^{-5}	**86.64** $\pm$ 2.32
100	**9.97×10^{-5}** $\pm$ 9.53×10^{-6}	**62.354** $\pm$ 0.797

80nm GaAs K_τ: **8.3×10^{-4}** $\pm$ 9×10^{-5}

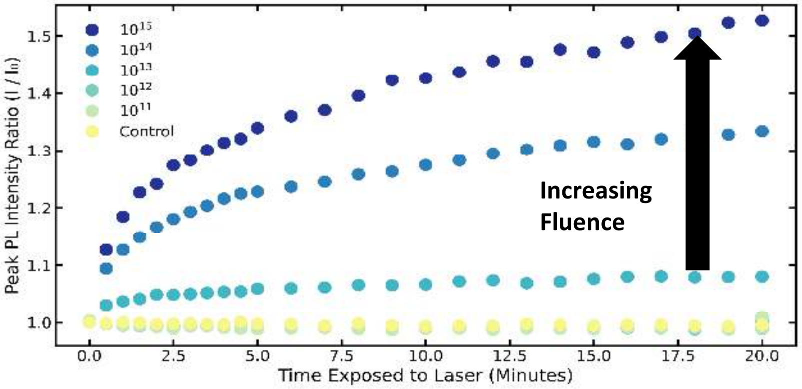
Annealing: Laser-Induced Minority-Carrier Injection

100nm: 2MeV p+ 10^{15} cm^{-2}





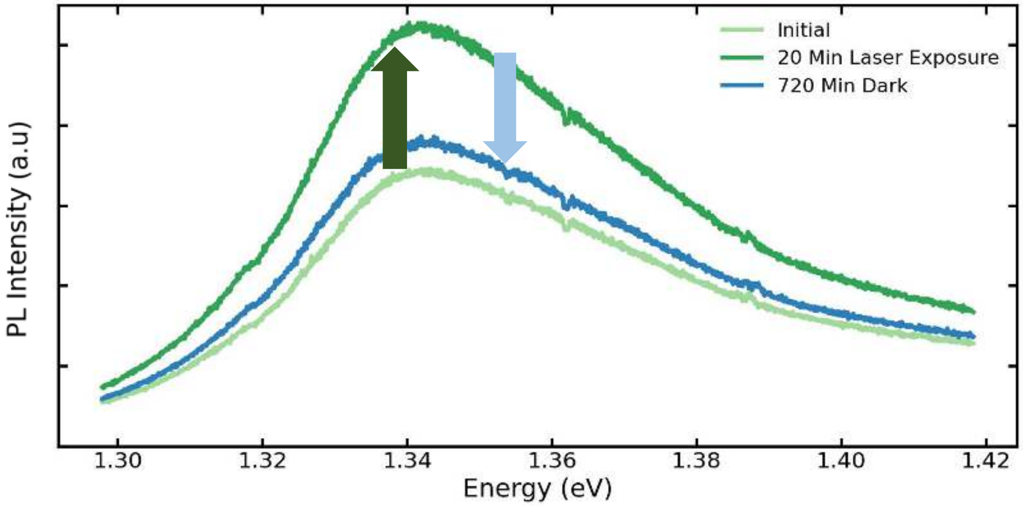
100nm



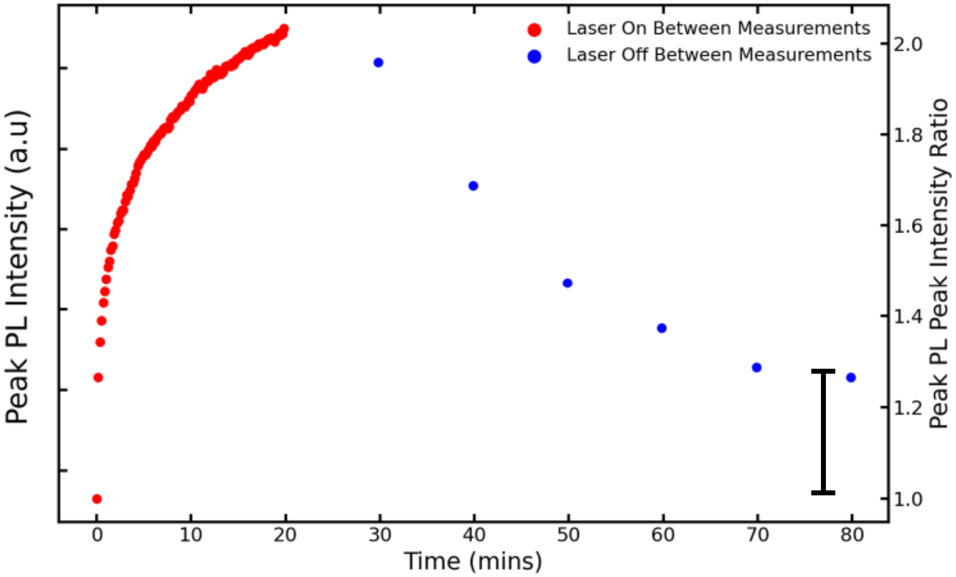
Annealing: Laser-Induced Minority-Carrier Injection

Semi-permanent Nature

300nm: 2MeV p+ 10^{15} cm^{-2}



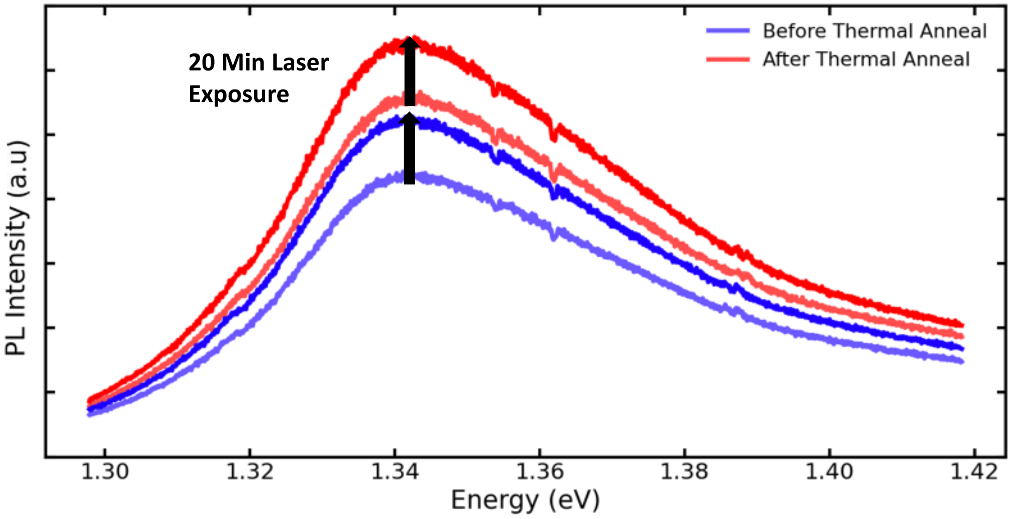
100nm: 2MeV p+ 10^{15} cm^{-2}

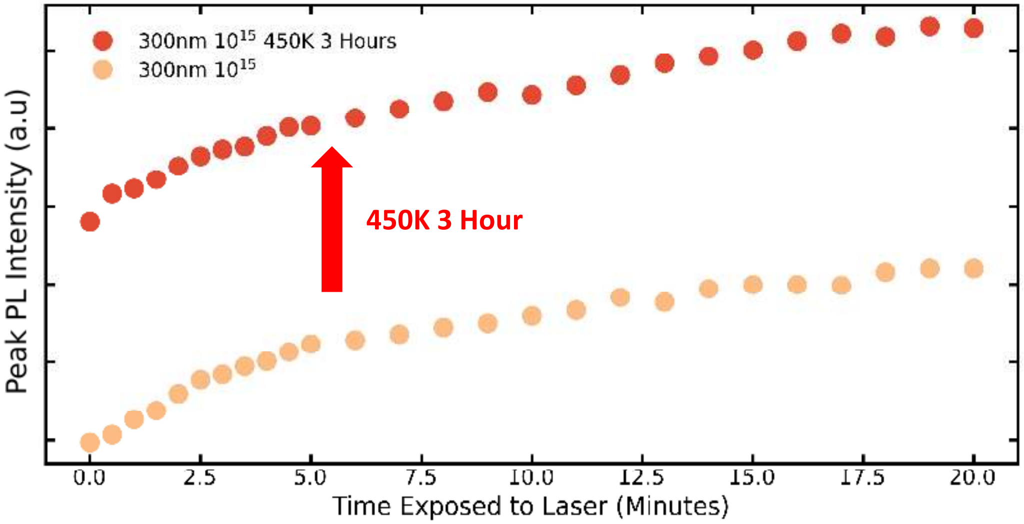


Annealing: Thermal Annealing

450K 3 Hour Anneal + 20 Min Laser Exposure

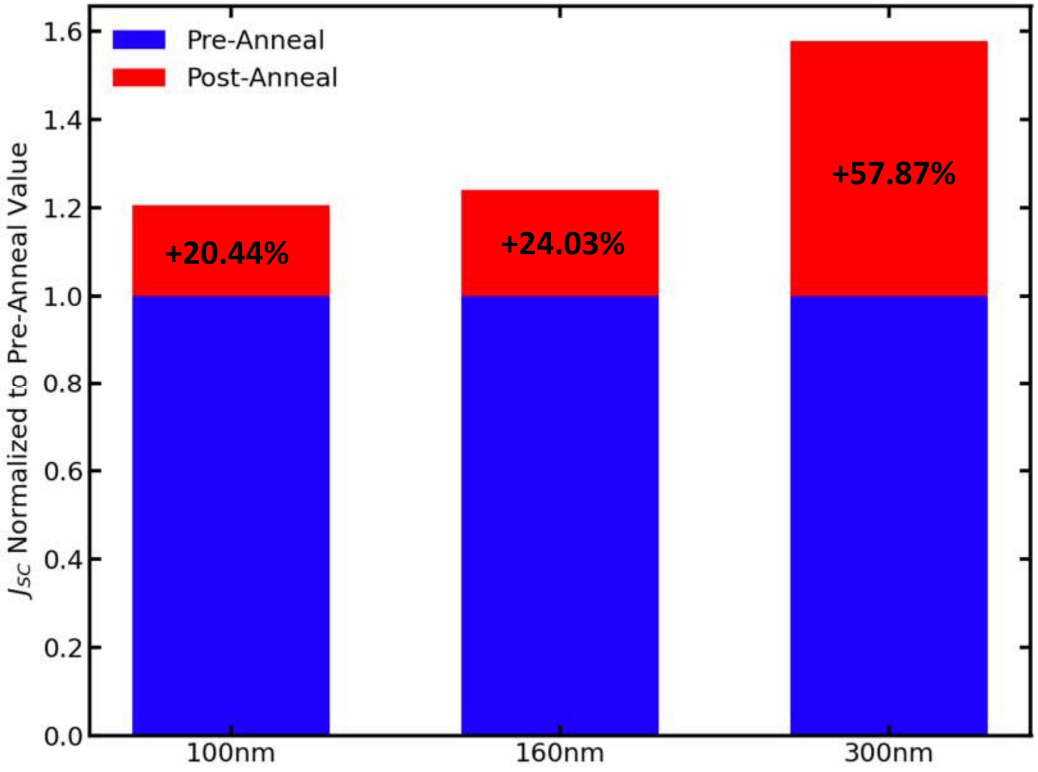
300nm: 2MeV p+ 10^{15} cm^{-2}


20 Min Laser Exposure


450K 3 Hour

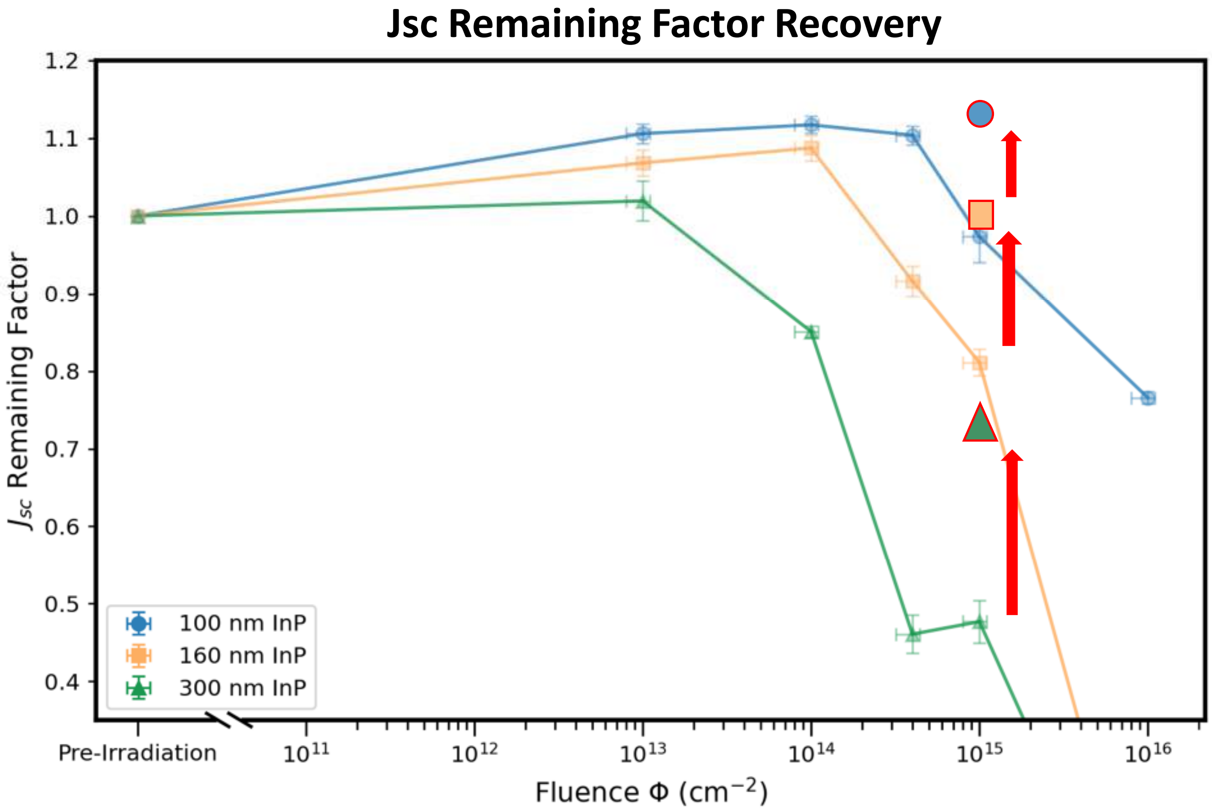
Annealing: Thermal Annealing – Preliminary Device Results

Devices Pre-Anneal Exposed to 10^{15} Fluence



450K 3 Hour Anneal

Annealing: Thermal Annealing – Preliminary Device Results



450K 3 Hour Anneal

Conclusion

- **Ultra-thin Indium Phosphide Demonstrates Elevated Jsc RF Across Fluence**
  - 100nm InP outperforms 80nm GaAs in this metric across all tested fluences

- **Ultra-thin Indium Phosphide Exhibits Thermal and Minority-carrier injection Annealing**
  - semi-permanent minority-carrier injection annealing under high power laser illumination
  - thermal annealing improves PL intensity and device performance

- **Future Work:**
  - harnessing deep level transient spectroscopy to characterize defect states during annealing
  - additional characterization of how measured PL improvements propagate to device performance
  - incorporate light management systems

Ultra-thin InP Presents a Promising Avenue for Radiation Resilient Power Generation in Space Applications

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