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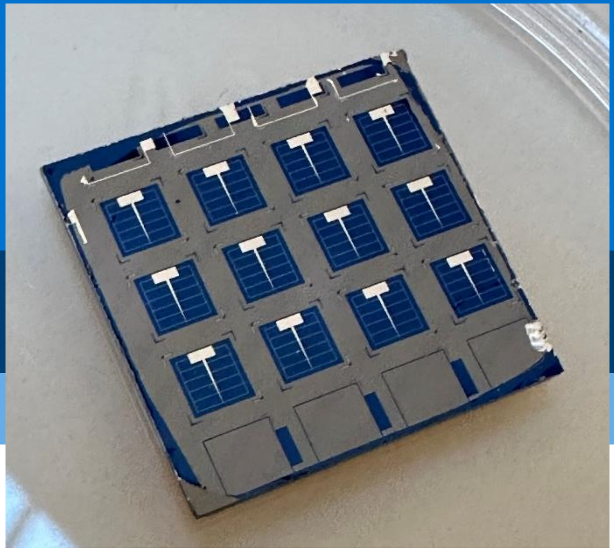
Developing Transition Metal Oxide-Based Carrier-Selective Contacts for Non-Epitaxial InP Solar Cells

Anish Chaluvadi[1], Luksa Kujovic[2], Adam Law[2], John M. Walls[2], Hannah Joyce[3], Louise Hirst[1,4]

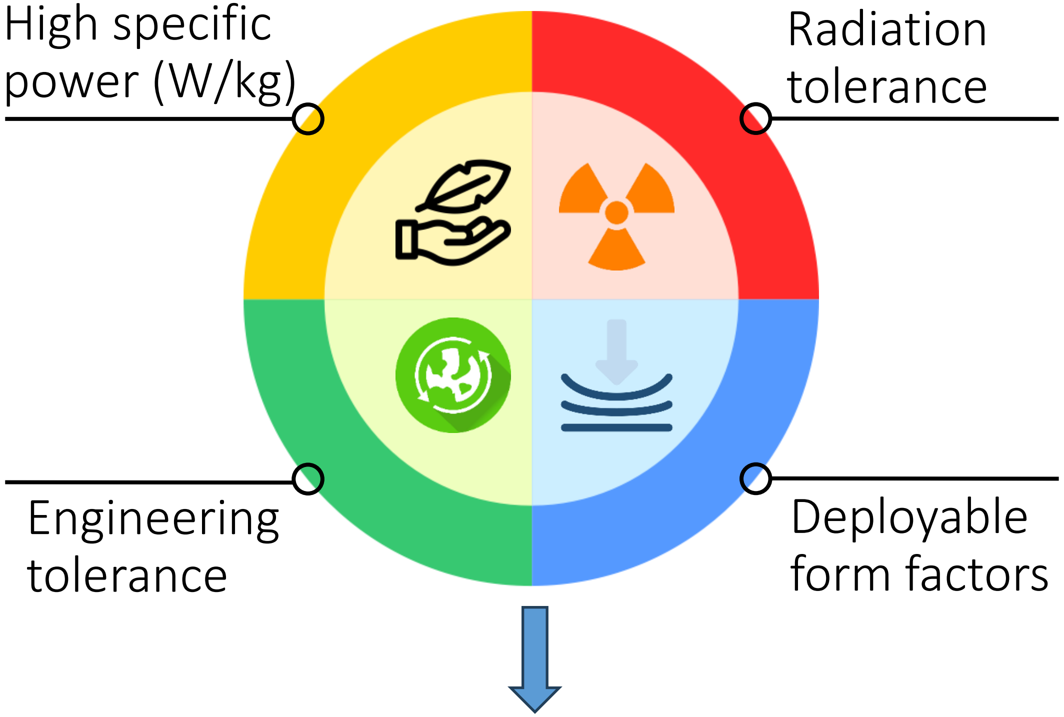
[1]Department of Materials Science and Metallurgy, University of Cambridge
[2]Centre for Renewable Energy Systems Technology, Loughborough University
[3]Department of Engineering, University of Cambridge
[4]Cavendish Laboratory, Department of Physics, University of Cambridge



42nd Space Power Workshop – Advanced Concepts Session, April 30, 2025

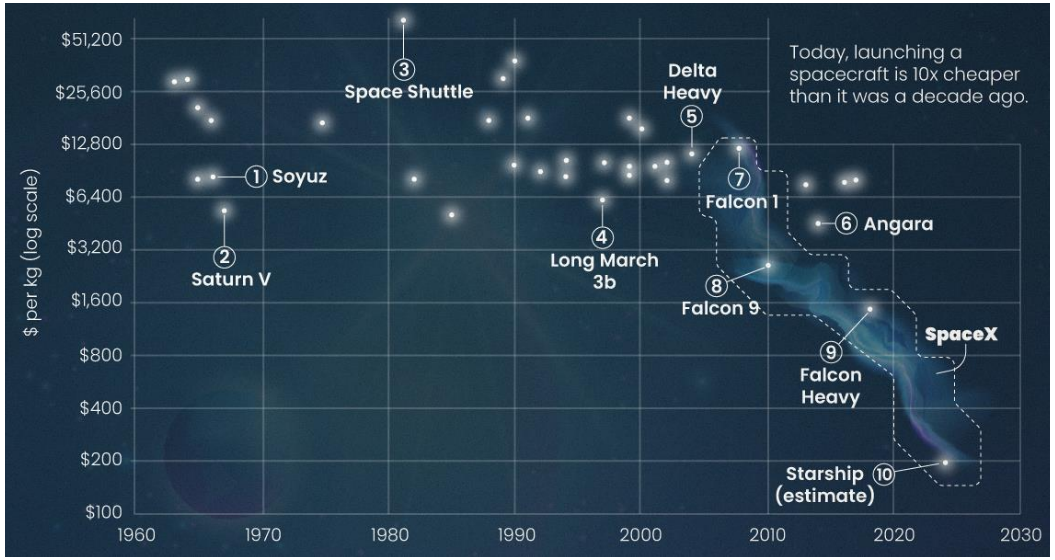
Challenges in Space Solar: Cost, Scalability & Radiation

Unique Requirements of Space



High efficiency, high cost III-V solar cells

Exponentially falling launch costs have led to hardware becoming a significant cost bottleneck [1]



Solar arrays and power subsystems represent **20–40% of satellite hardware costs**, especially for SmallSats and megaconstellations[2]

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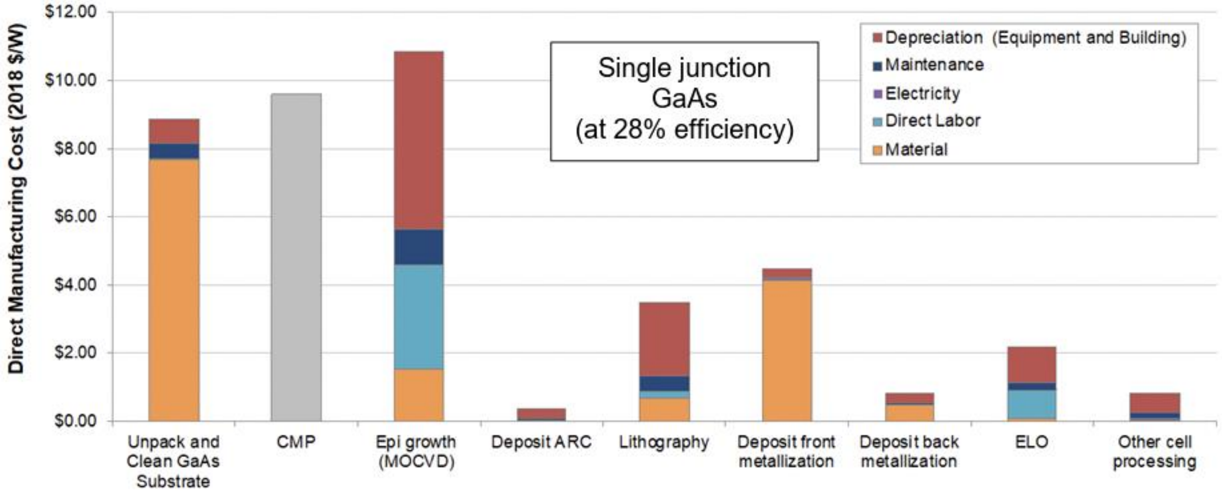
[1] https://www.visualcapitalist.com/the-cost-of-space-flight/
[2] https://www.nasa.gov/smallsat-institute/sst-soa/power-subsystems/#3.2.1

Rethinking III-V Solar Fabrication

Traditional III-V solar cells cost $60-100/W, two orders of magnitude greater than terrestrial Si[3]

💰 High-cost, low-throughput epitaxial growth

🛠 Complex post-processing and materials
- Limited substrate reuse techniques
- Metallization



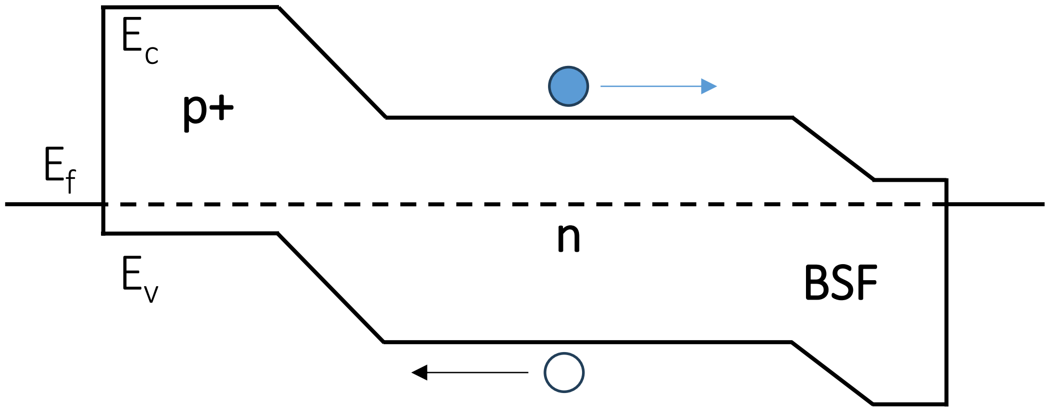
Current epitaxial techniques are intractable for cost-sensitive space applications

[3] K. Horowitz, T. Remo, B. Smith, and A. Ptak, "A techno-economic analysis and cost reduction roadmap for III-V solar cells," National Renewable Energy Lab, no. NREL/TP-6A20-72103, 2018.

Rethinking III-V Solar Fabrication

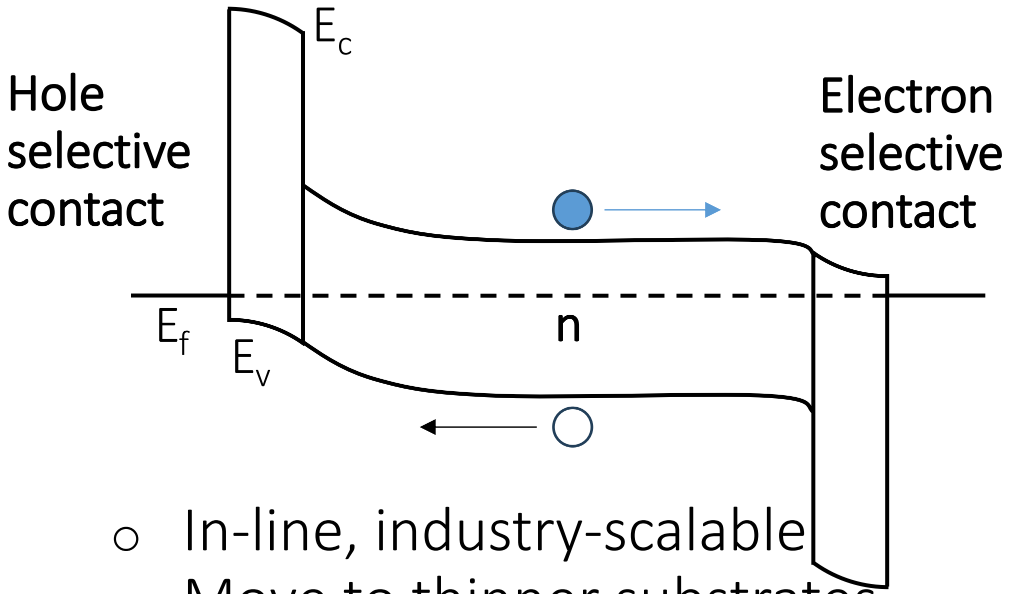
Reframing III-V device fabrication by **prioritizing cost-effective, scalable** processes which are compatible with next-generation, novel architectures

Homojunction formation through epitaxial doping



- Small batch, low-throughput[4]
- Complex growth process
- Variable doping profile

Heterojunction formation through carrier-selective contacts



- In-line, industry-scalable
- Move to thinner substrates

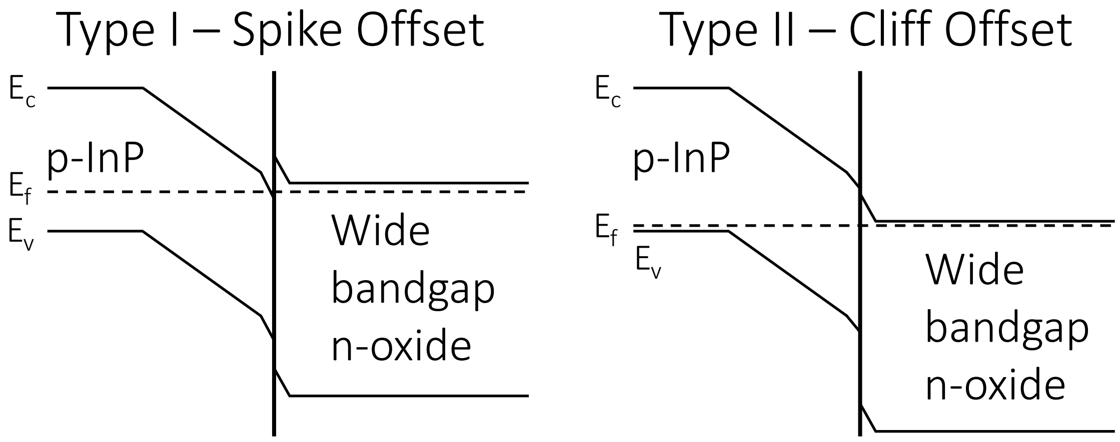
[4] A. Greenway et al., "Low-cost approaches to III-V semiconductor growth for photovoltaic applications," ACS Energy Letters, vol. 2(10), pp.2270-2282, 2017.

Transition Metal Oxides for Heterojunction Solar Cells

Offers efficient carrier selectivity with unique material and process advantages

- Potential for excellent **interface passivation**
- Potential for **low-temperature, high-throughput techniques** like sputtering
- No lattice-matching or heavy diffusion doping
- Usage of **Earth-abundant, low-cost materials**

Demonstrated at industrial scale for Si heterojunction solar cells



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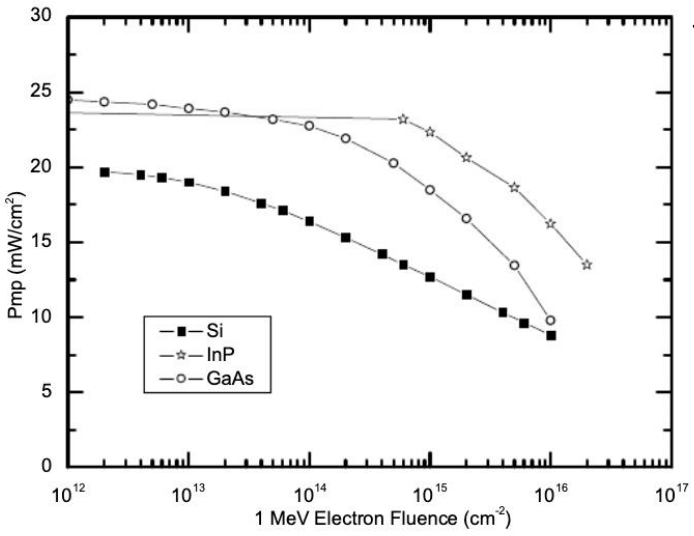
InP Offers High Defect Tolerance

Radiation Tolerance

Growth Tolerance

- Non-ionizing energy loss (NIEL) values for InP (~10^{-2} MeV cm^2/g for 3 MeV protons) are the lowest amongst space solar cell materials[5]
- Lower deep-level defect formation energy[6]
- Higher rate of room-temperature and minority-carrier injection enhanced annealing[6]



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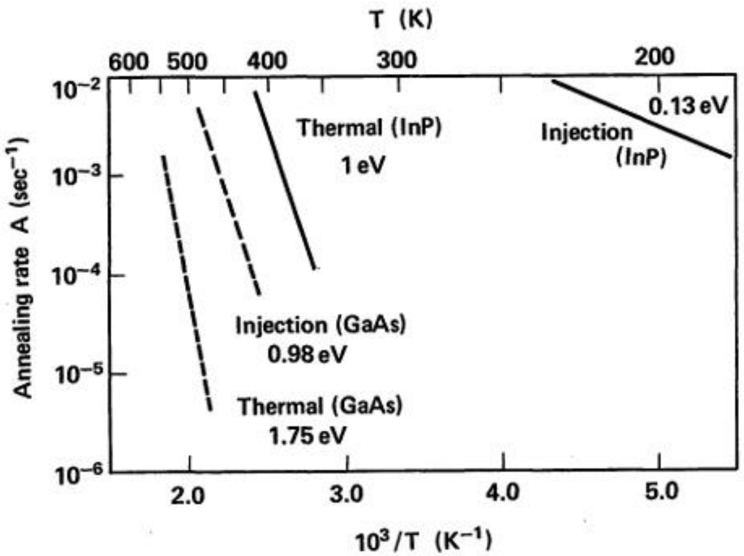

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[5] R. Walters et al., "Space radiation effects in InP solar cells," IEEE Transactions on Nuclear Science, vol. 38(6), pp. 1153-1158, 1991.

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

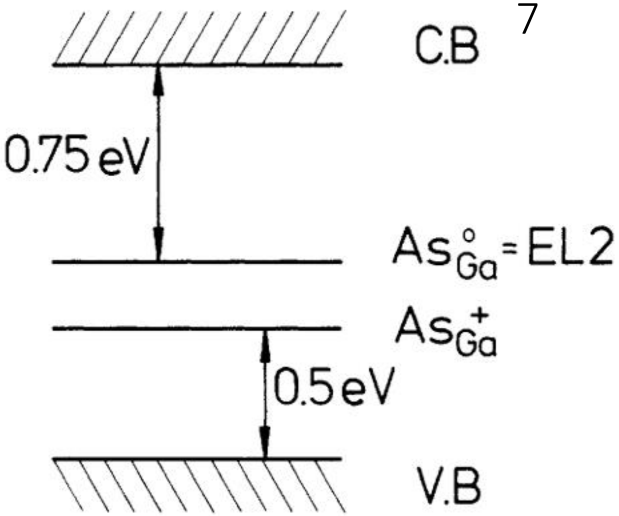
InP Offers High Defect Tolerance

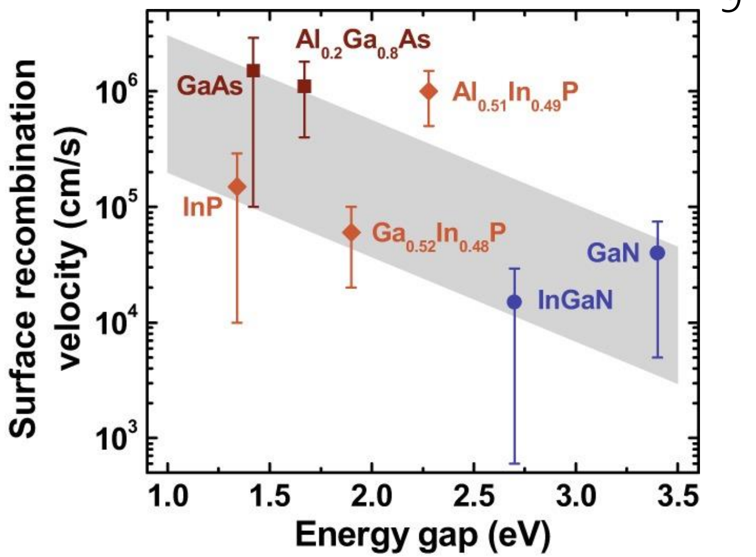
Radiation Tolerance

Growth Tolerance

- Lower thermal expansion coefficient exhibiting better stability during crystal growth, resulting in **fewer defects**[7]
  - No process limiting EL2 defect as compared to GaAs

- Longer minority carrier diffusion lengths and **low surface recombination velocity**[6,8,9]



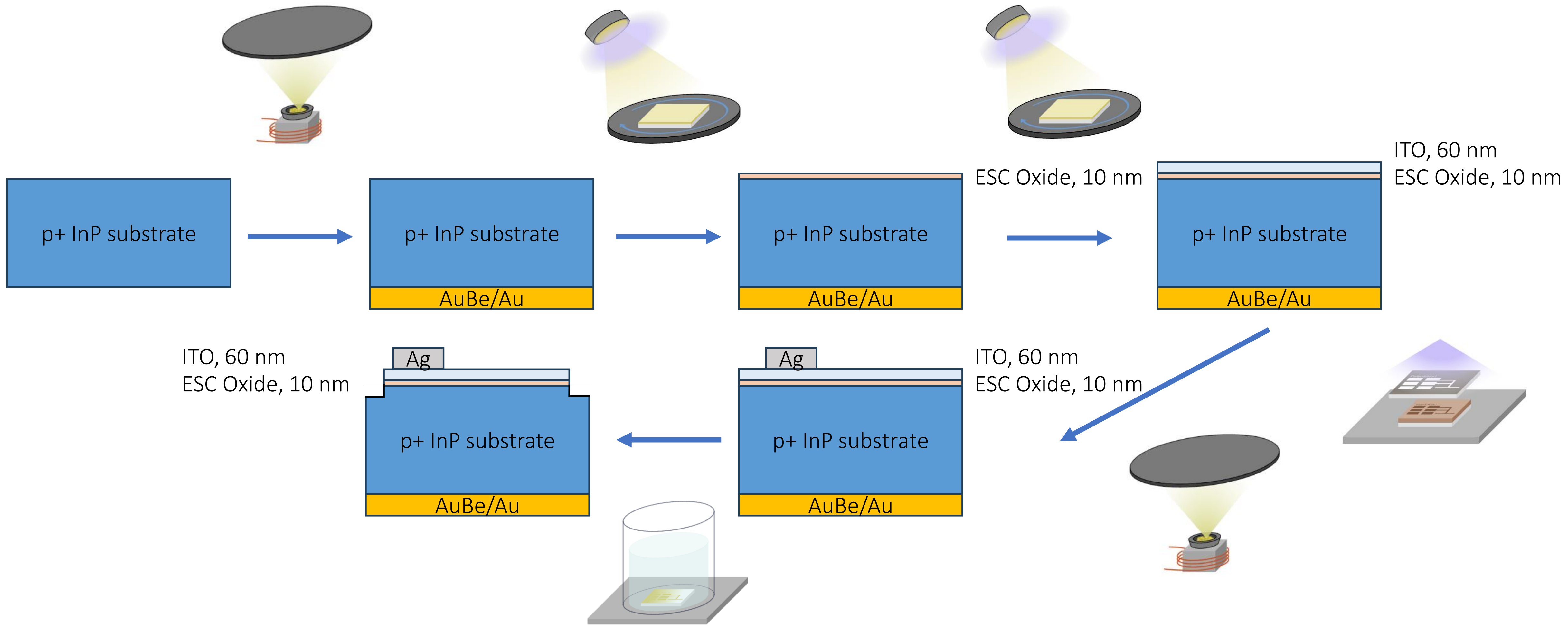


[7] M. Kaminska., "EL2 Defect in GaAs," Phys. Scr. vol. T19B, pp. 551, 1987.

[8] H. Joyce et al., "Electronic properties of GaAs, InAs and InP nanowires studied by terahertz spectroscopy," Nanotechnology, vol. 24(21), pp. 214006, 2013.

[9] K. Bulashevich and S. Y. Karpov, "Impact of surface recombination on efficiency of III-nitride light-emitting diodes," PSS RRL, vol. 10(6), pp. 480-484, 2016.

Device Processing



Cost Analysis

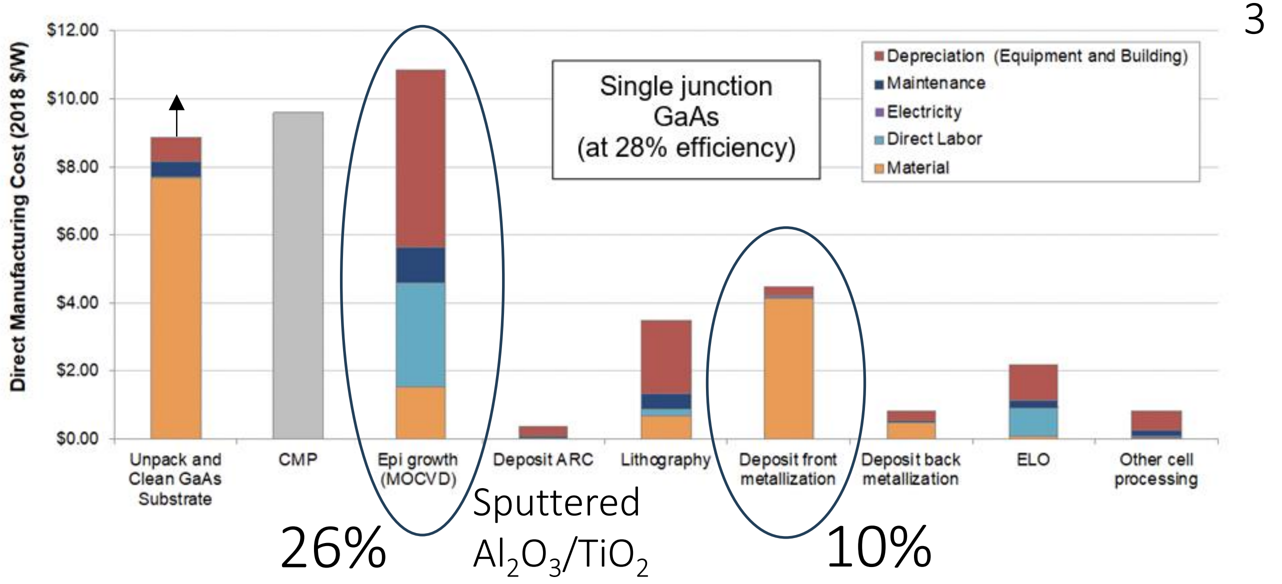
Aim to target **two key, highlighted areas of cost reduction**[3]

- Epitaxial growth costs
- Metallization

Assumptions

- Thinner substrates will have a similar effect on substrate cost as ELO reuse processing
- 20% AM1.5 efficient fully sputtered architecture is achievable

$41/W



Reduced layer growth cost from $11/W to $1.50/W

Reduced per gram cost of front contact material (Ag: $0.55/g vs. Au: $43/g)*

*Further development of Ni/Al front contact for space-grade is necessary

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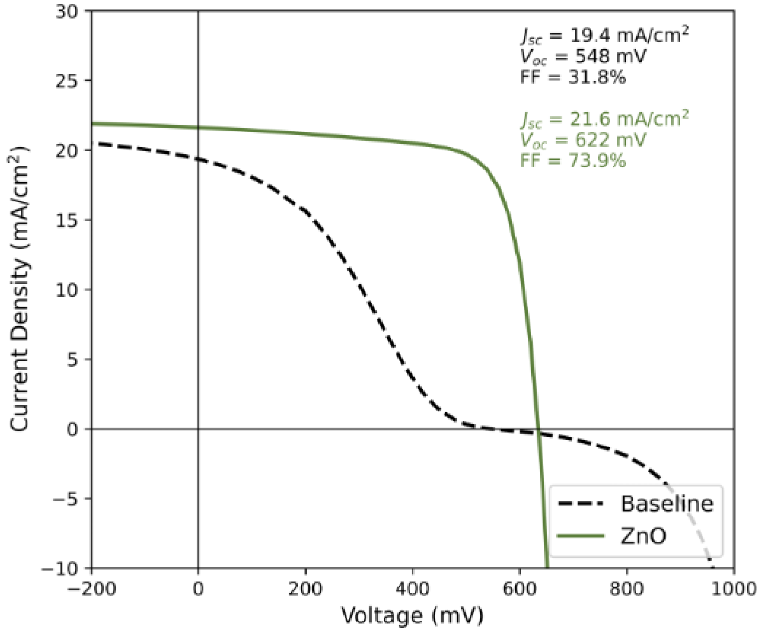
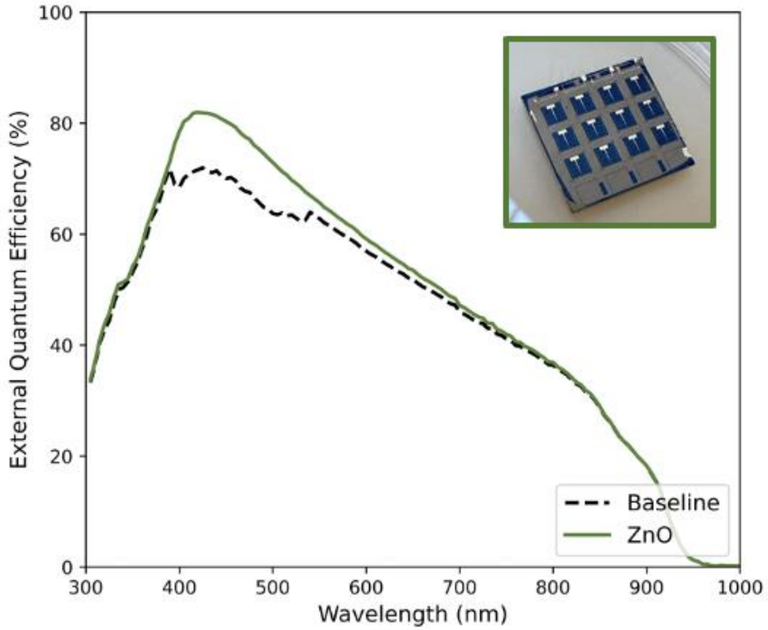
[3] K. Horowitz, T. Remo, B. Smith, and A. Ptak, "A techno-economic analysis and cost reduction roadmap for III-V solar cells," National Renewable Energy Lab, no. NREL/TP-6A20-72103, 2018.

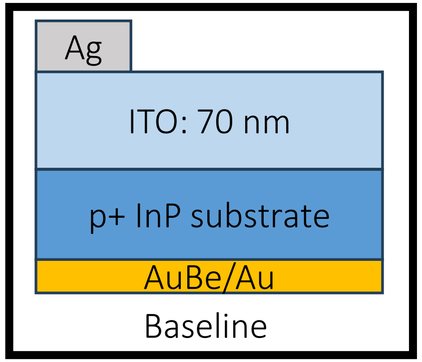
ZnO Electron-Selective Contact for InP

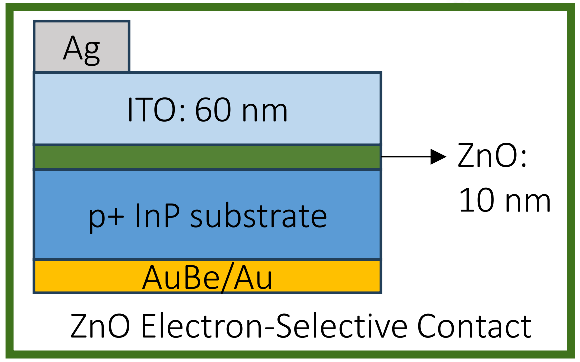
Cell efficiency of 7.27%

- ZnO clearly demonstrates barrier-free carrier extraction
- Without emitter thinning, ARC, or minimizing shading loss (10%)
- Record for fully sputtered InP device architecture (previously 6.02%)[10]



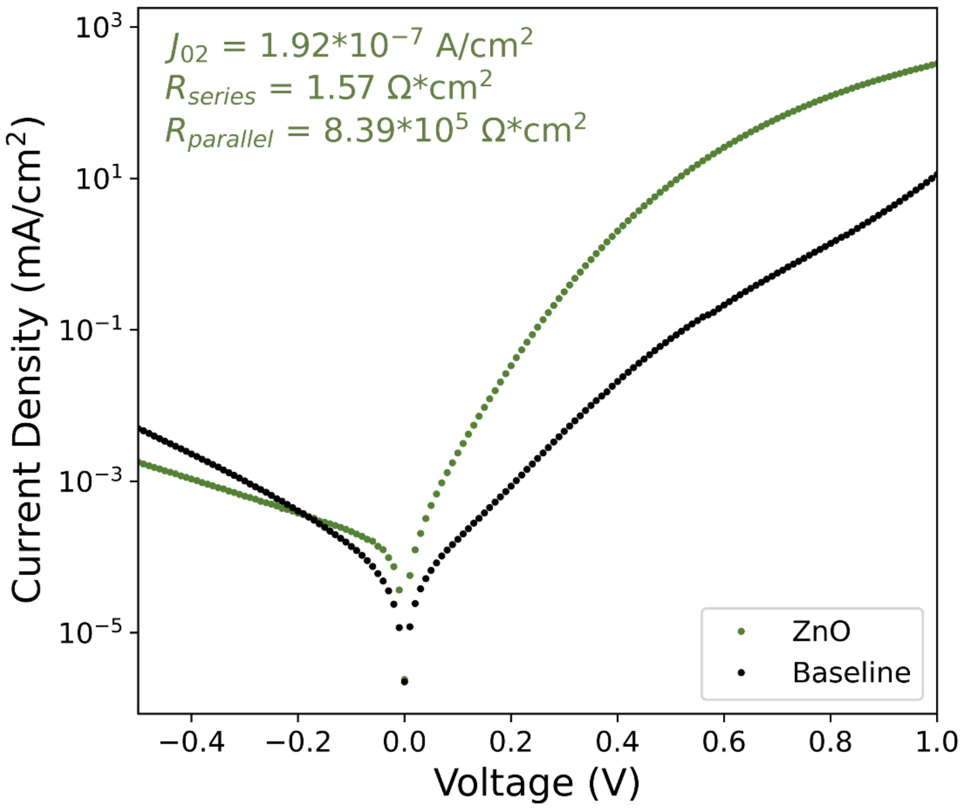




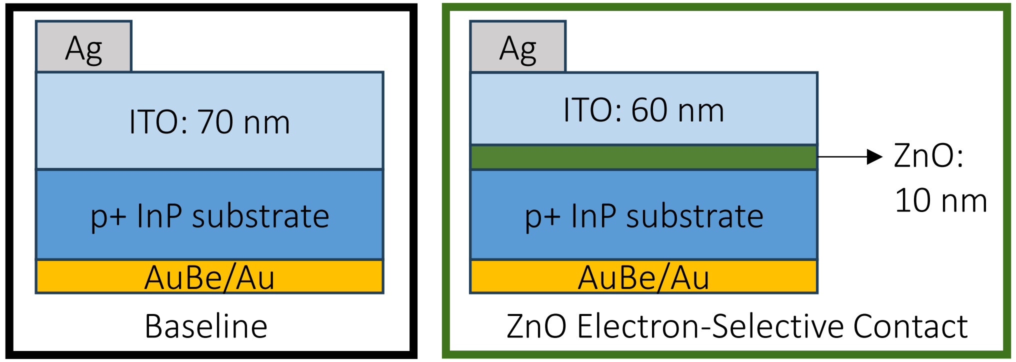


[10] K. Pande and C. Manikopoulos, "ZnO-p-InP heterojunction solar cells," Solar Cells, vol. 4, pp. 147-152, 1981.

ZnO Electron-Selective Contact for InP

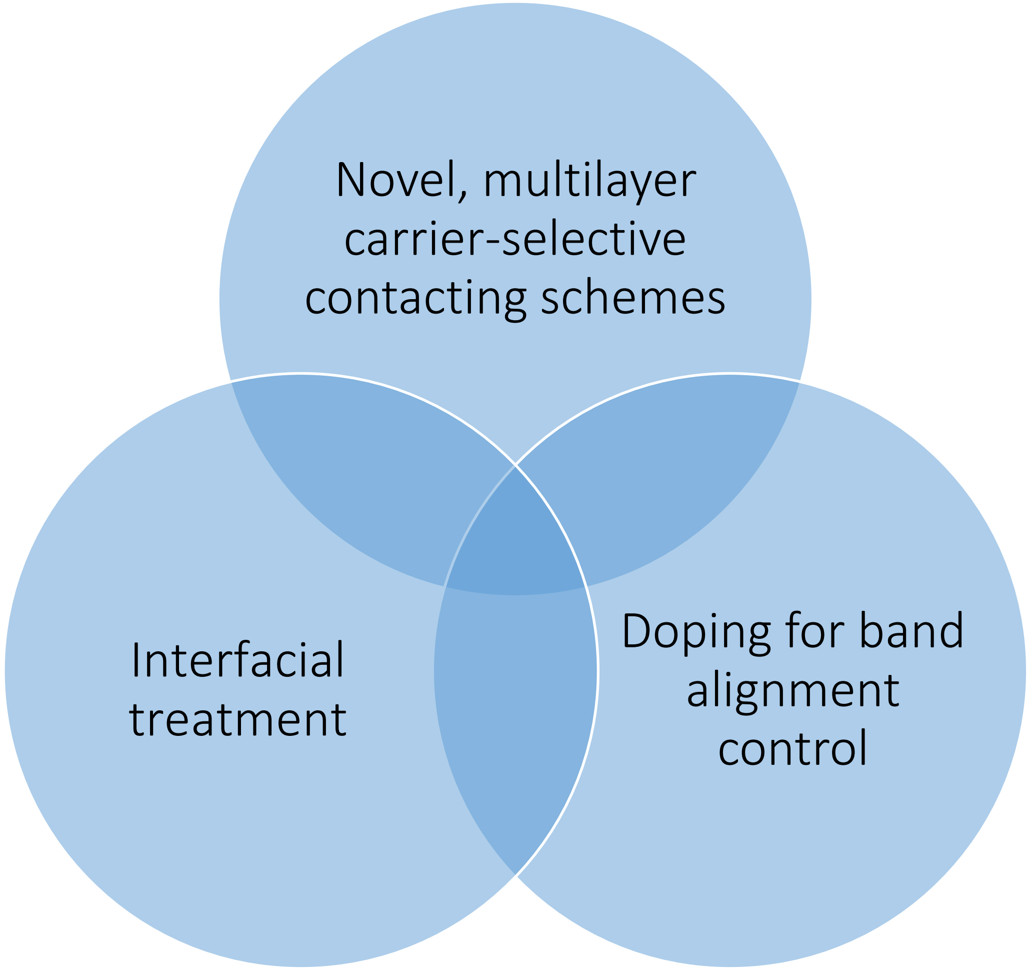


- Consistent sheet resistances of ~67 Ω/sq for ITO
  - ZnO was too resistive to measure
- Maintains smooth surface morphologies, RMS roughness of 0.4 nm
- RF sputtering at low temperatures minimizes interfacial damage with uniform nanocrystalline ZnO coverage[11]



[11] P. Hajara, T. P. Rose, K. J. Saji, “Effect of substrate temperature and RF power on the structural and optical properties of sputtered ZnO thin films,” J. Phys.: Conf. Ser. vol. 2357, pp. 012018, 2022.

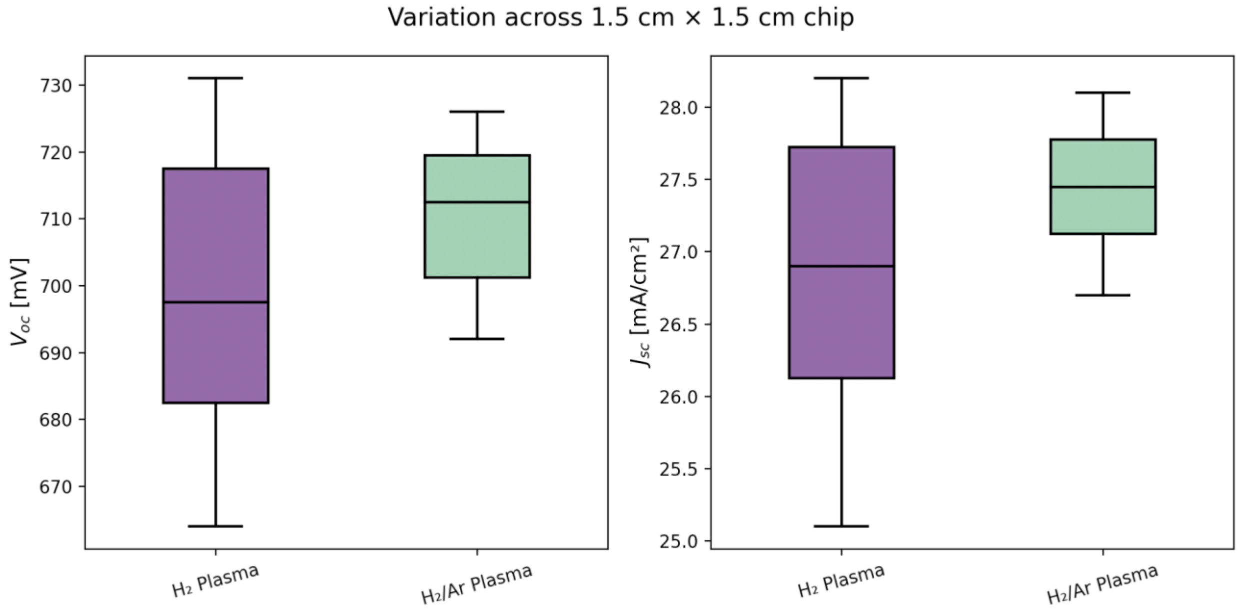
Significant Potential for Advancement



Interfacial Treatment – H_2 Plasma

Hydrogenation has been used to passivate shallow Zn acceptors and form a charge-depleted layer in the bulk[12]

- **Challenges**: Damaging InP surface (due to In-droplet formation) and difficult reproducibility[12]



Introducing Ar to stabilize H_2 plasma, mitigating surface roughening and lowered J_{02} by an order of magnitude

J_{sc}: 27.6 mA/cm^2
V_{oc}: 702 mV
FF: 76.1%
η (AM0): 10.79%

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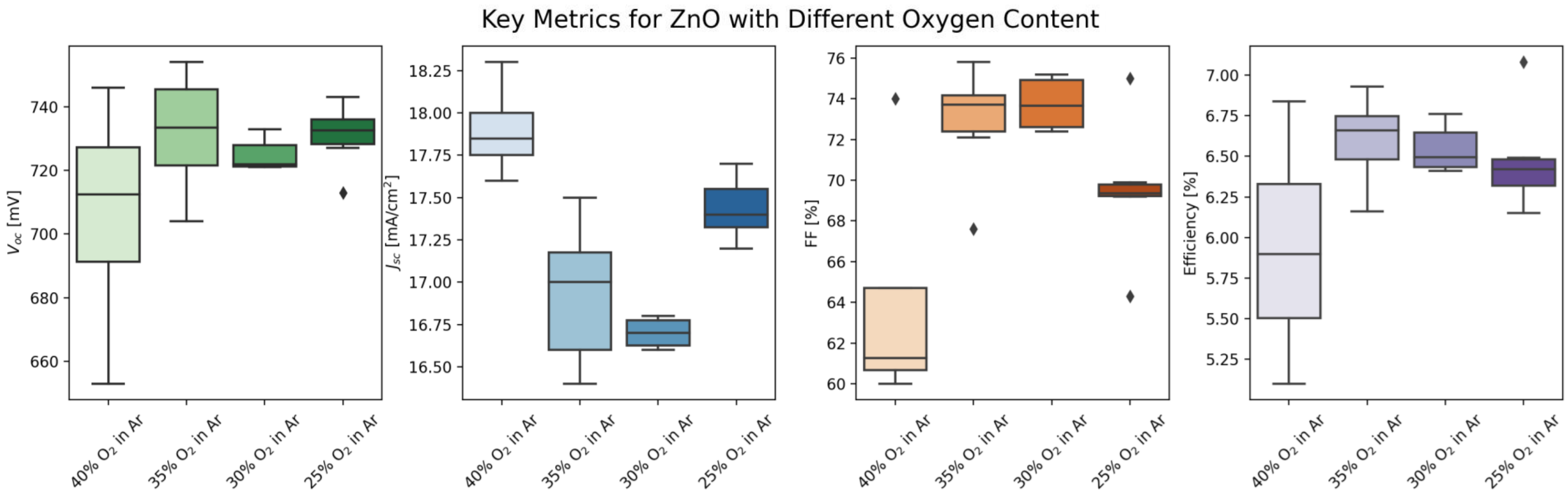
[12] B. Gupta et al., "Unveiling the role of H2 plasma for efficient InP solar cells," Solar RRL, vol. 7(6), pp. 2200868, 2023.

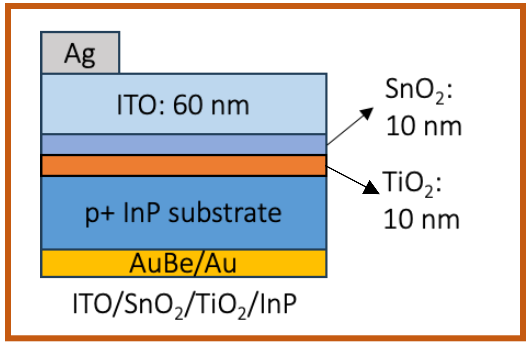
Oxygen Vacancy and Metal Doping

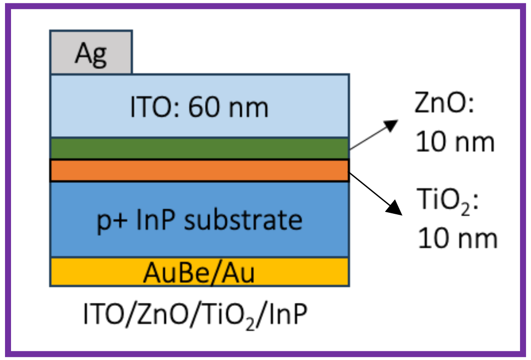
- Optimization of oxygen vacancies presents a **trade-off between n-type conductivity, charge carrier transport, and increased visible light absorption**
- Confirmed **bandgap narrowing** as increased oxygen vacancies using UPS

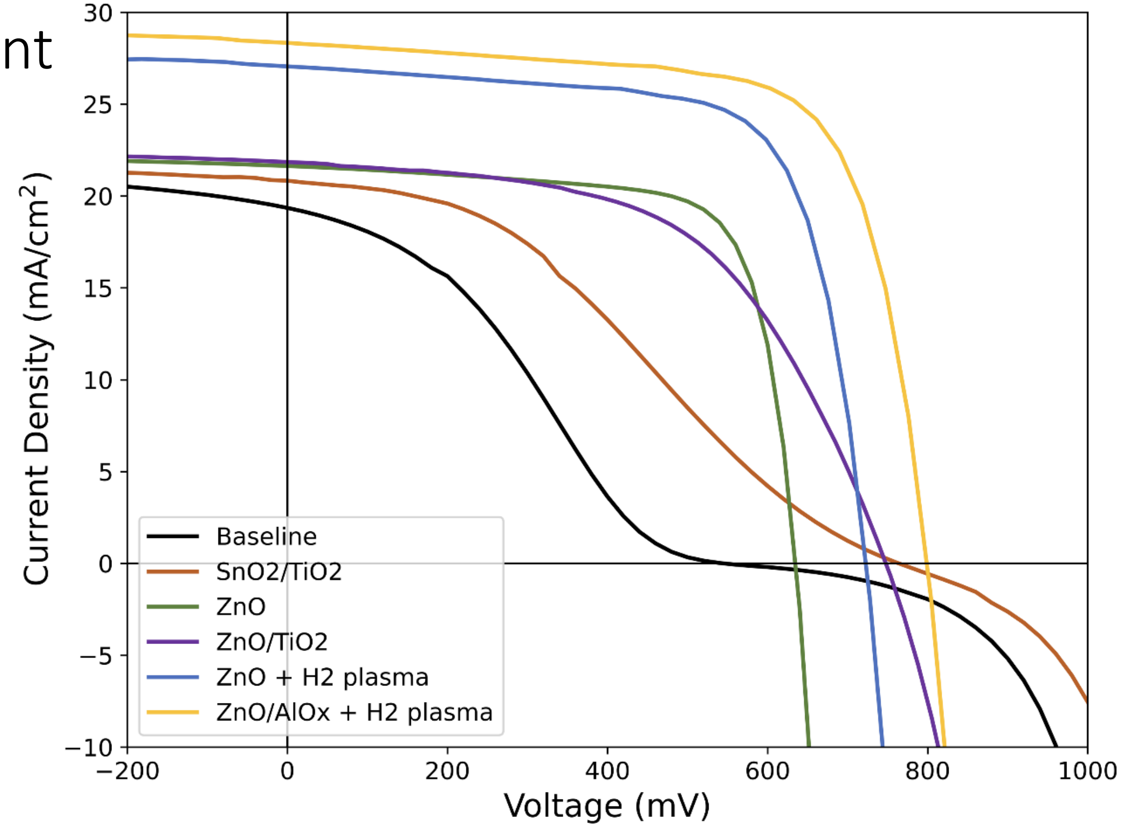


Multilayer Oxide Systems

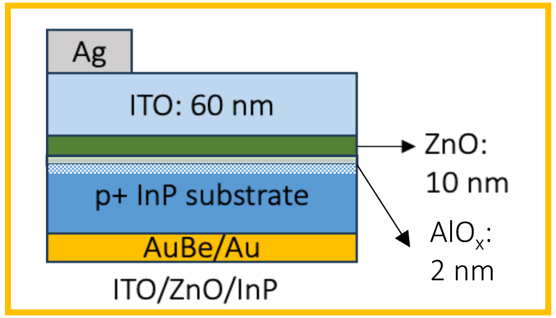
Preliminary demonstration of cascading band alignment for increased V_{oc}







Attempting to decouple passivation and carrier extraction + H_2 plasma



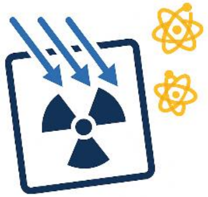
J_{sc}: 28.8 mA/cm^2
V_{OC}: 809 mV
FF: 76.1%
η (AM0): 12.91%

Future Work

- Optimization of electron-selective contact
  - Going to **thinner ESC**
  - Optimizing **oxygen vacancy doping**

- **Improved passivation** of space charge region either through interfacial treatment or multilayer system

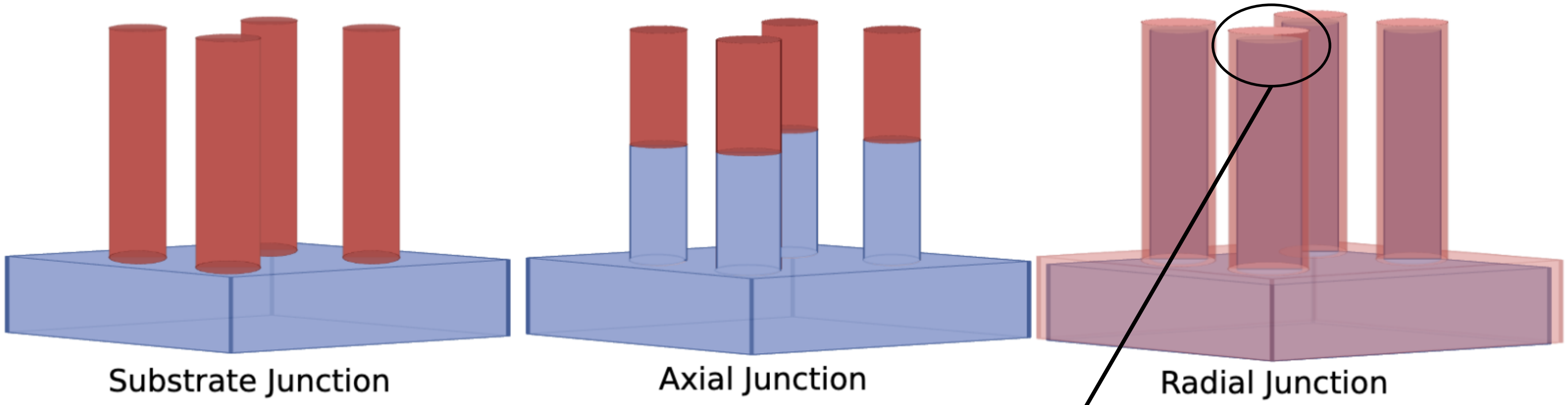
- **Radiation testing** for electronic stability of non-epitaxial device



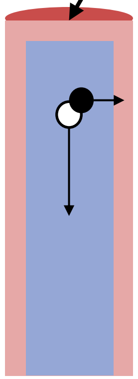
- Immediate **pathway to 15% AM0 efficiency**:
  - Reduced front contact coverage
  - Addition of lower index ARC

Application to Next-Generation Approaches

Radiation Tolerant Nanowire Solar Cells



- Effectively **decoupling light absorption and charge carrier extraction vectors**
- Demonstrated **intrinsic radiation tolerance** due to reduced dimensionality and diffusion lengths[13]



Thinner Substrates/Spalled InP

Fundamental Challenges

1. Reduced dimensionality results in limited light absorption
2. High surface-to-volume ratio results in higher rates of non-radiative recombination (defects)
3. Epitaxial dopant incorporation to form radial junctions is quite complicated and variable

Non-epitaxial carrier-selective contacts enable radial junction nanowires without dopant incorporation

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[13] P. Espinet-Gonzalez et al., "Nanowire solar cells: a new radiation hard PV technology for space applications," IEEE J. Photovolt., vol. 10(2), pp. 502–507, 2020.

Application to Next-Generation Approaches

Radiation Tolerant Nanowire Solar Cells

15

Thinner Substrates/Spalled InP

Integrating transition metal oxide-based carrier-selective contacts with spalled InP spalled thin films

- **Reduced material cost**
- **Improved radiation tolerance** from thinner substrates

Preliminary results, using TiO_2 ALD, demonstrate 8.9% efficiency (under AM1.5) on 15 µm spalled InP thin film[14]

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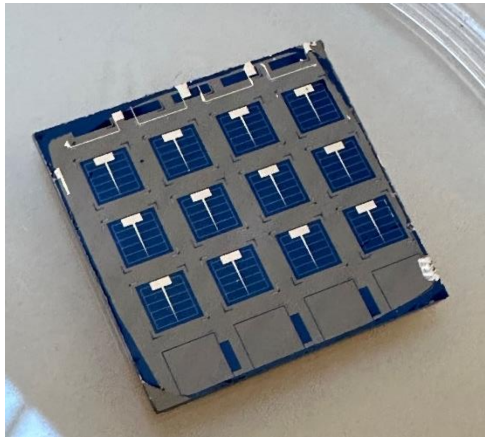
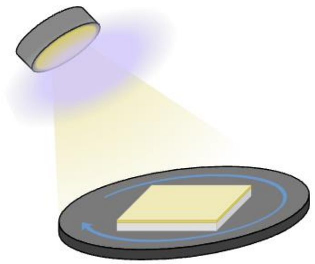
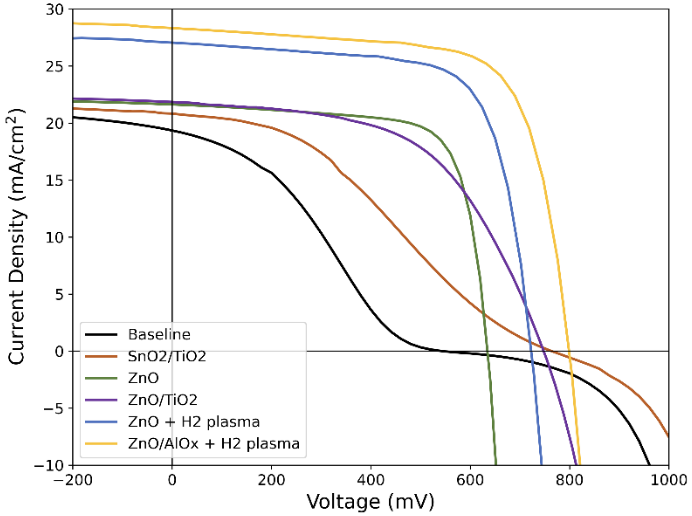
[14] B. Gupta et al., "Mechanically Exfoliated InP Thin Films for Solar Energy Conversion Devices," Small Science, vol. 4(12), 2024.

Conclusions

1. Present **7.27%** efficient (under AM0) fully sputtered InP solar cell using ZnO as an electron-selective contact
2. Demonstrate significant potential in cost-efficiency using less complex and industry scalable techniques
3. Highlight large parameter space and multiple pathways to enhanced device performance, with preliminary results achieving an efficiency of **12.91%**







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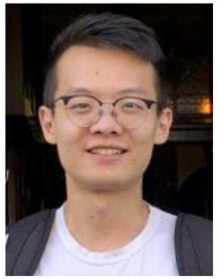
Jiayi Li


Stefan Diesing


Luksa Kujovic


Adam Law


John M. Walls


Hannah Joyce


Louise Hirst

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vsac2@cam.ac.uk

InP as a Scalable Solution

- Indium processed as zinc concentrate byproduct**, diffused in occurrence**.
- **Potential for distributed refining** but low market demand currently.
  - Gallium for comparison: significant export controls from China, which accounts for 99% of worldwide primary low-purity gallium production
- Lower toxicity and import regulation

Indium

World Refinery Production and Capacity:

	Refinery production 2023	Refinery production 2024[e]	Refinery capacity 2024[e]
United States	—	—	—
Belgium	19	10	50
Canada	40	35	70
China	690	760	1,100
France	21	21	70
Japan	65	60	70
Korea, Republic of	180	180	310
Peru	—	—	50
Russia	5	10	15
Uzbekistan	1	1	1
World total (rounded)	1,020	1,080	1,800

Gallium

World Low-Purity Production and Production Capacity:

	Primary production 2023	Primary production 2024[e]	Production capacity 2024
United States	—	—	—
China	[4]621,000	[4]750,000	1,000,000
Japan[e]	3,000	3,000	10,000
Korea, Republic of[e]	3,000	3,000	16,000
Russia[e]	6,000	6,000	10,000
Other countries[5]	—	—	[e]88,000
World total (rounded)	633,000	760,000	[e]1,100,000

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[1] USGS

Designing Non-Epitaxial Carrier-Selective Contacts

Literature

Oxides	Device Type	J_{sc} [mA/cm^2]	V_{oc} [mV]	FF [%]	Efficiency [%]
[1]TiO_2/InP	Planar	30.5	785	80.5	19.2
*[2]Ta_2O_5/InP	Planar	30.1	822	77	19.1
*[3]ZnO/InP	Planar	29.4	819	75.23	18.1
*[4]ZnO/GaAs	Planar	26.2	890	79.2	18.5
*[5]Ferri-hydrite/InP	Planar	28.6	761	76.2	16.6
[6]ZnO/InP	Nanowire	31.3	736	74.6	17.1

[1] Yin *et al.*, ACS Photonics. ***1****(12)*, 1245-1250 (2014).
[2] Narangari *et al.*, Nanoscale. ***11***, 7497-1505 (2019).
[3] Raj *et al.*, J. Phys. D: Appl. Phys. *51(39)*, (2014).
[4] Raj *et al.*, ACS Appl. Energy Mat. ***4****(2)*, 1356-1364 (2021).
[5] Gupta *et al.*, ACS Appl. Mat. & Inter. ***15****(38)*, 44912-44920 (2023).
[6] Raj *et al.*, ACS Nano. ***13(10)***, 12015-12023 (2019).

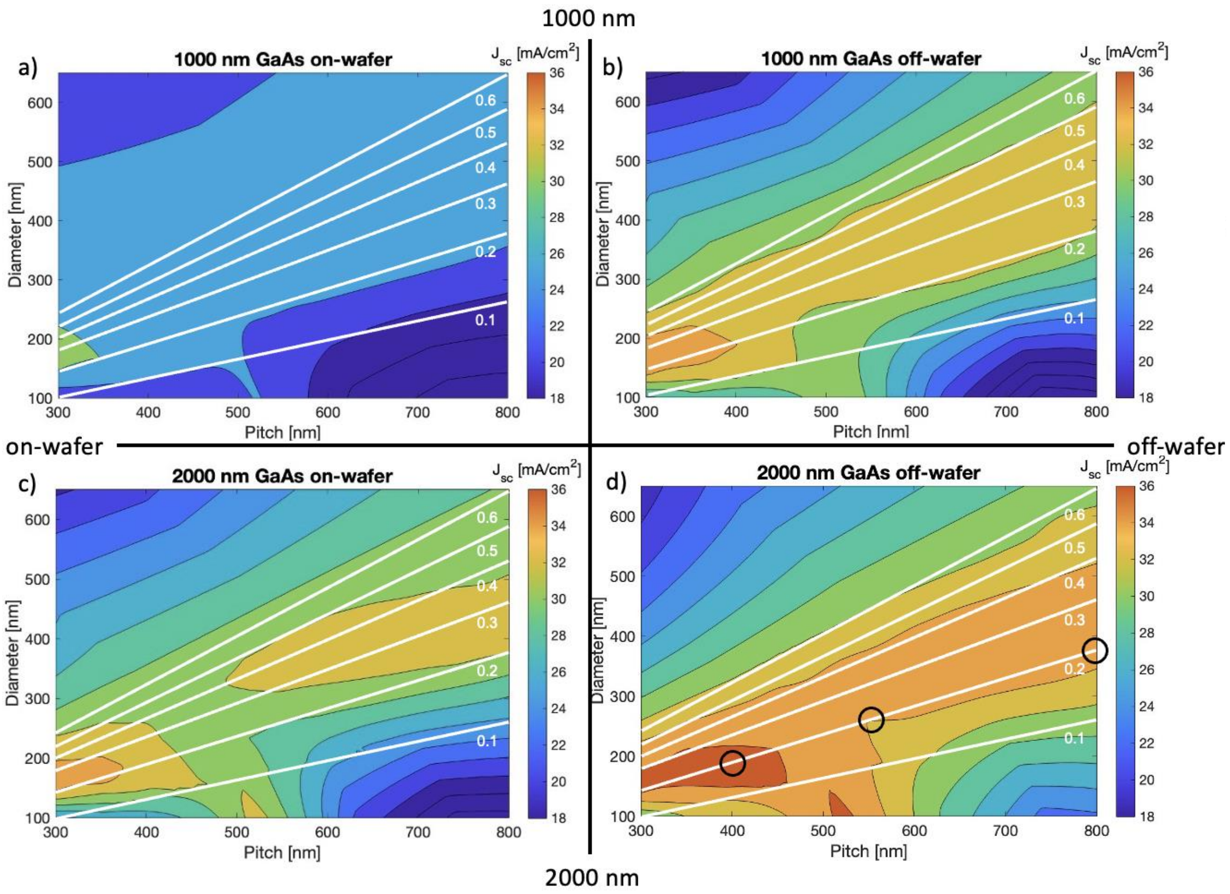
Loughborough Oxide Thicknesses – Ellipsometry + AFM

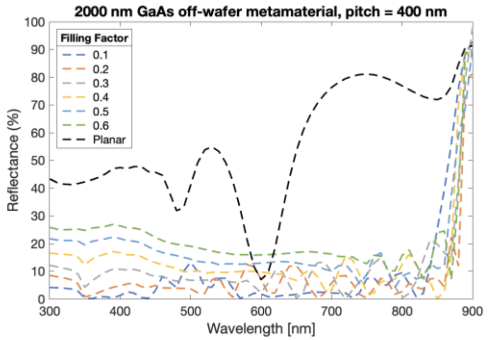
Oxide	Nominal Thickness (nm)	Fitted Thickness (nm)	Oxide Regrowth	Roughness (nm)	RMSE
ITO	60	66	Yes – 7.3nm	2.6	10.7
ITO	300				
ZnO	10	7.8	Hard to Distinguish	1.2	8.3

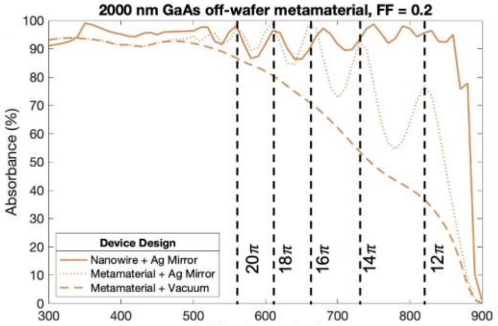
Surface	Substrate Temp. (°C)	O_2 Content (% in Ar)	Nominal Thickness (nm)	RMS Roughness
Bare InP	-	-	-	1.03
ZnO	100	1	10	0.41
ITO	300	0.56	70	2.37

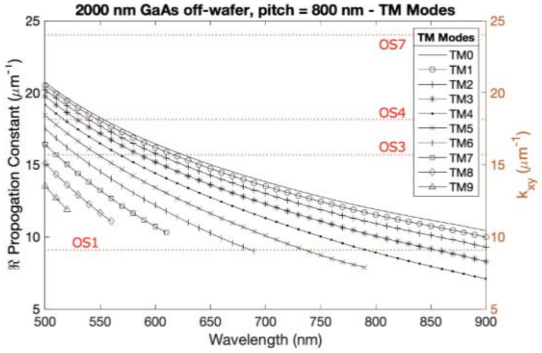
Field Enhancement through Engineered Light-Trapping

Design Space Screening using Full-Field Simulation



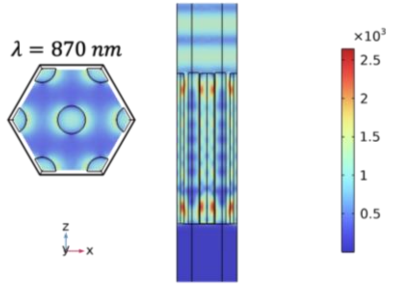






Deconvolution of light absorption by understanding individual mechanisms:

1. Reduced reflection at front surface
2. Fabry-Perot modes due to constructive interference of specular reflected waves
3. Identify individual waveguide modes from scattering



d = 188nm, pitch = 400nm – HE_{11} mode