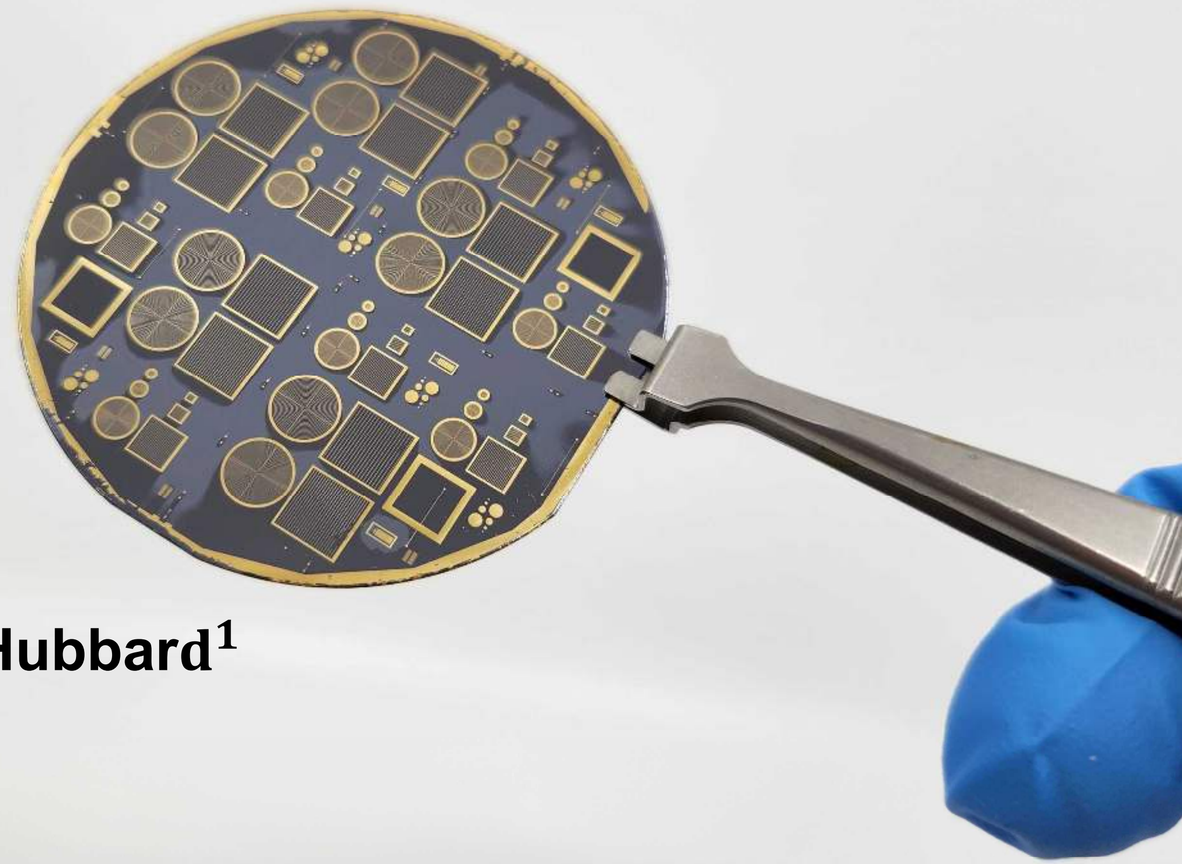
wer beaming at 1064 nm, From Cells to stems



ynn Fleming[1], Steve Polly[1], Seth Hubbard[1]
ester Institute of Technology
Power Research Laboratories

20, 2026

Golisano Institute for Sustainability
NanoPower Research Laboratories

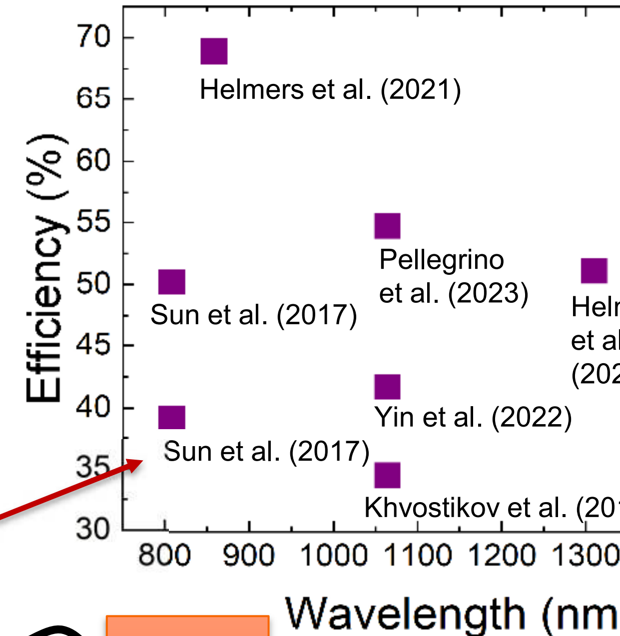
SPACE POWER WORKS

ser Power Beaming

Abundant Energy Location

transmission

Energy Use Location



ver ion

laser

Photovoltaic laser power converter

load

wer on mand

reless ical ivery

Image: NASA Goddard

Image: Powerlight and U.S. Naval Research Laboratory

Image: Cory Price, WorldAtla

olisano Institute for Sustainability
lanoPower Research Laboratories

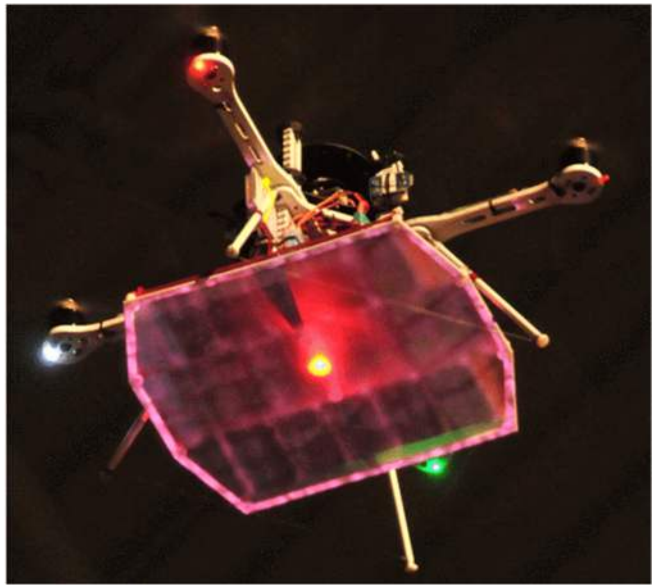
Laser Power Beaming

Rochester Institute of Techn

tellite-to-satellite

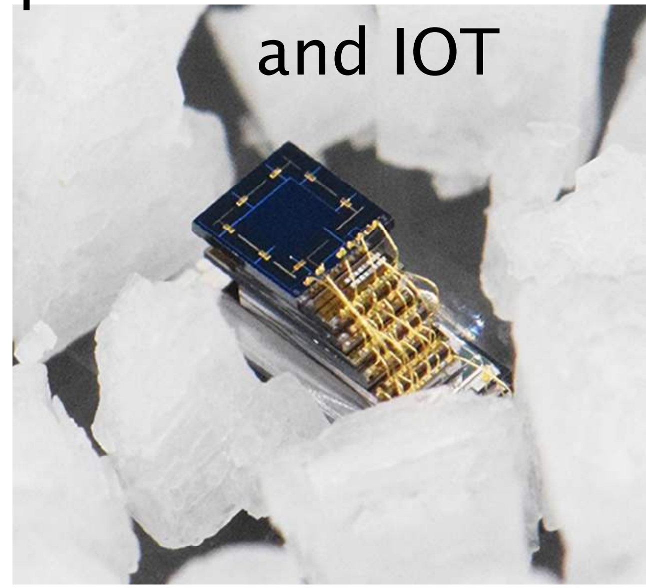
hys.org/news/2022-01-revolutionizing-
ower-laser.html

UAV Charging



M. C. Achtelik et al. 2011

Implantable medical de
and IOT

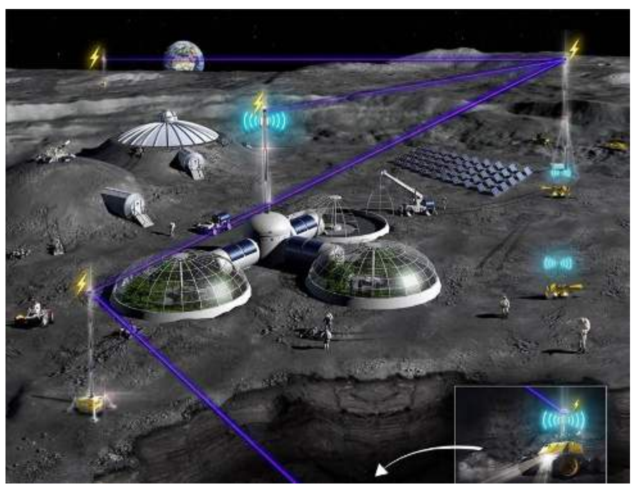


E. Moon, et al. 2019

pace Solar Power

val Research Laboratory

Lunar colony and rover



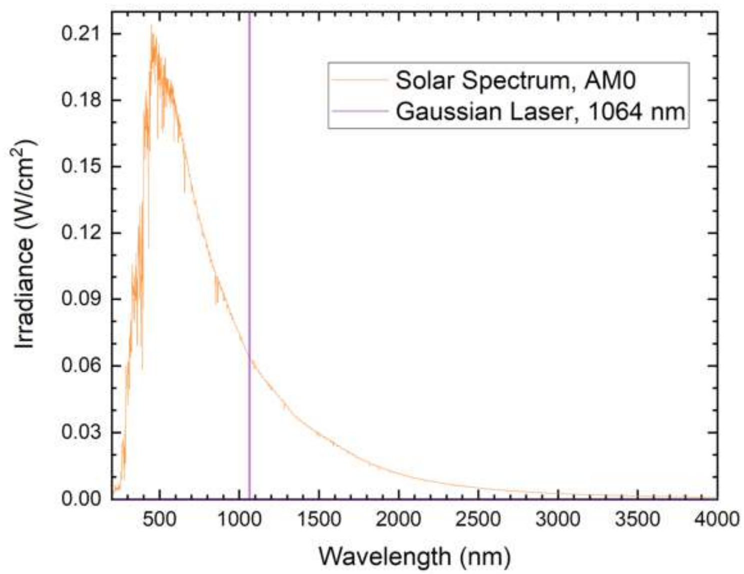
Powerlight Technologies

G. A. Landis, 2020

ser

ng Distance,
w Loss

- igh power
- igh coherence
- igh efficiency
- 064 nm
  - Already widely used for high power applications
  - Higher beam quality than GaAs lasers
  - Our laser: $M^2 < 1.5$
  - Others can reach $M^2 < 1.01$



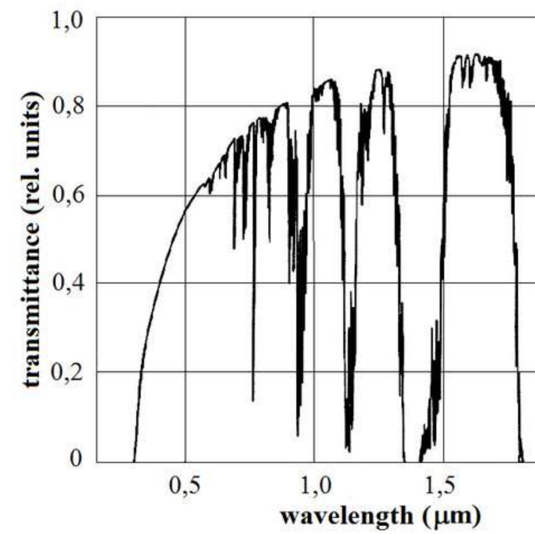
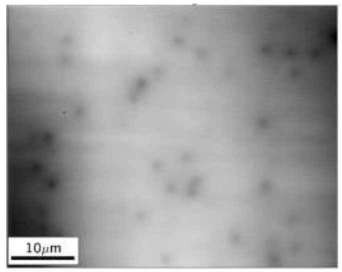


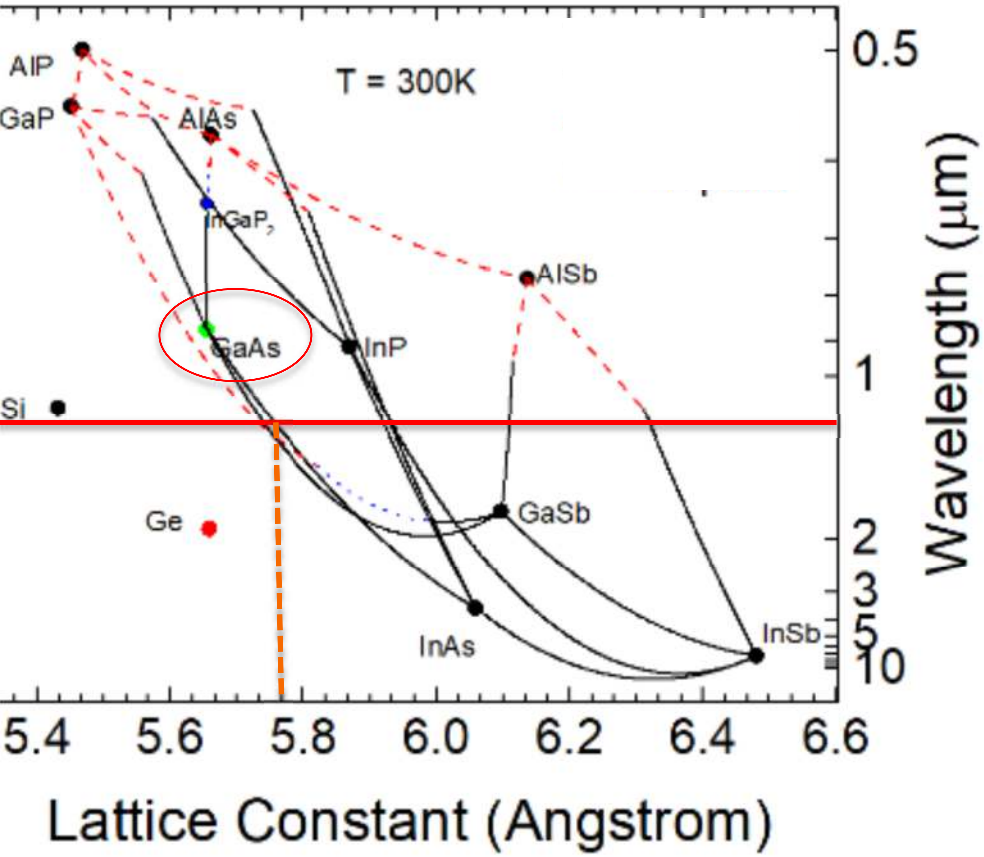
Image: Michael Belov et al.

Image: IPG Photonics, 50 W Ytterbium Fiber Laser, 20+% WPE

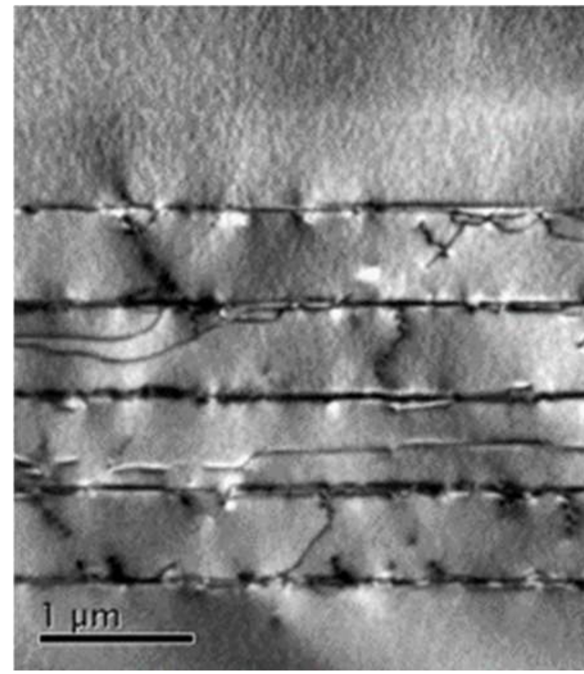
VPE Growth



- Target 1064 nm, ~1.1 eV bandgap
- Metamorphic 5x600 nm step grade
- Growth Temps: 550-750°C. Precursors: T TMIn, DEZn, CCl_4, AsH_3, DETe2, PH_3, Si_2



$In_{0.20}$GaAs:Zn
$In_{0.24}$GaAs:Zn
$In_{0.20}$GaAs:Zn
$In_{0.16}$GaAs:Zn
$In_{0.12}$GaAs:Zn
$In_{0.08}$GaAs:Zn
$In_{0.04}$GaAs:Zn
GaAs:Zn
p-GaAs substrate

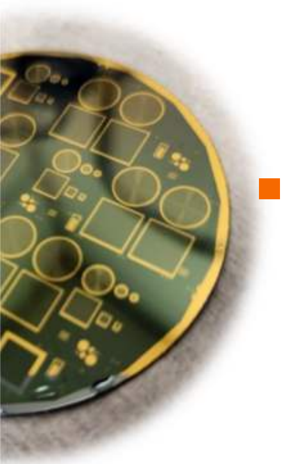


TEM shows TDD upper lin
$4 * 10^6\ \mathrm{cm}^{-2}$
Plan View CL TDD:
$1.6 * 10^6\ \mathrm{cm}^{-2}$

ingle Junction LPC Design

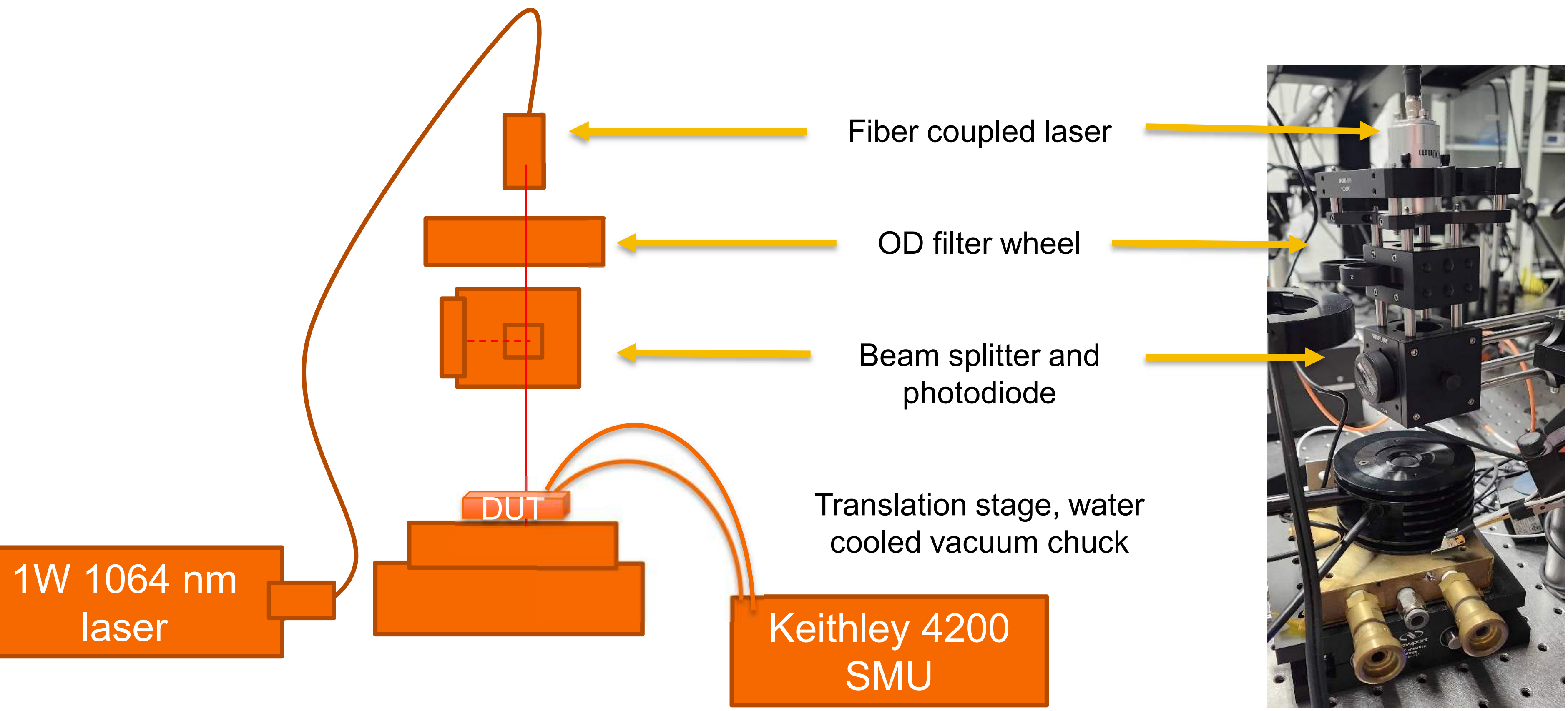
- 1064 nm = 1.17 eV laser
- 1.1 eV absorber (70 meV above band edge)
- $In_{0.20}Ga_{0.80}As$
  - Calculated absorption coefficient for 1064 nm: $\alpha = 0.926 * 10^6\ \mathrm{m}^{-1}$
  - 1/e Absorption Depth: 1118 nm
- Absorber thickness for 95% absorption: 3.5 micron

Au		
In20GaAs:Si	Contact	100 nm
In68GaP:Si	FSF	30 nm
In20GaAs:Si	Emitter	100 nm
In20GaAs	UID	10 nm
In20GaAs:Zn	Base	3000 nm
In68GaP:Zn	BSF	30 nm
InGaAs:Zn	MMG	5x600nm
GaAs:Zn	Buffer	100 nm
p-GaAs	Substrate	
Au/Zn/Au		



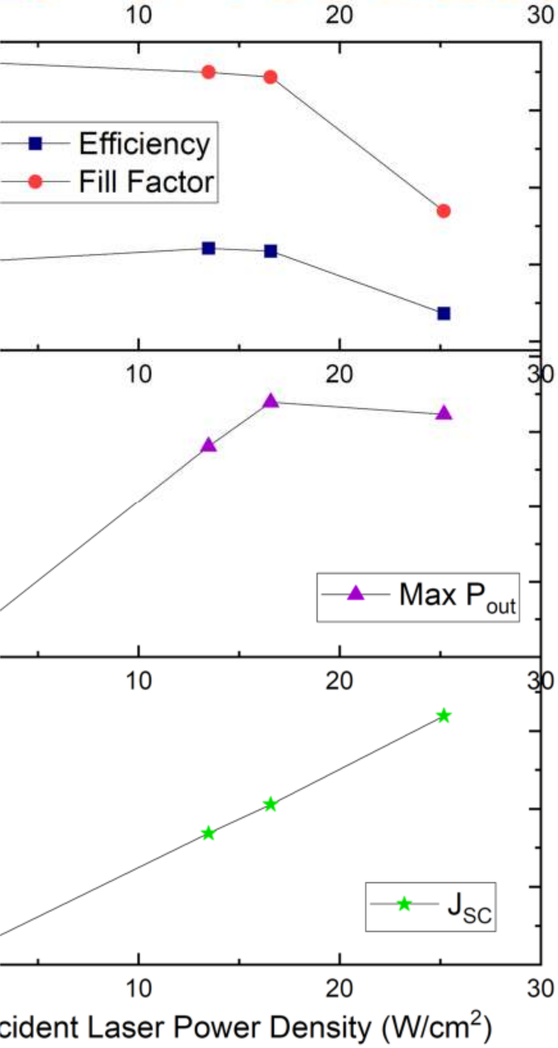
esting

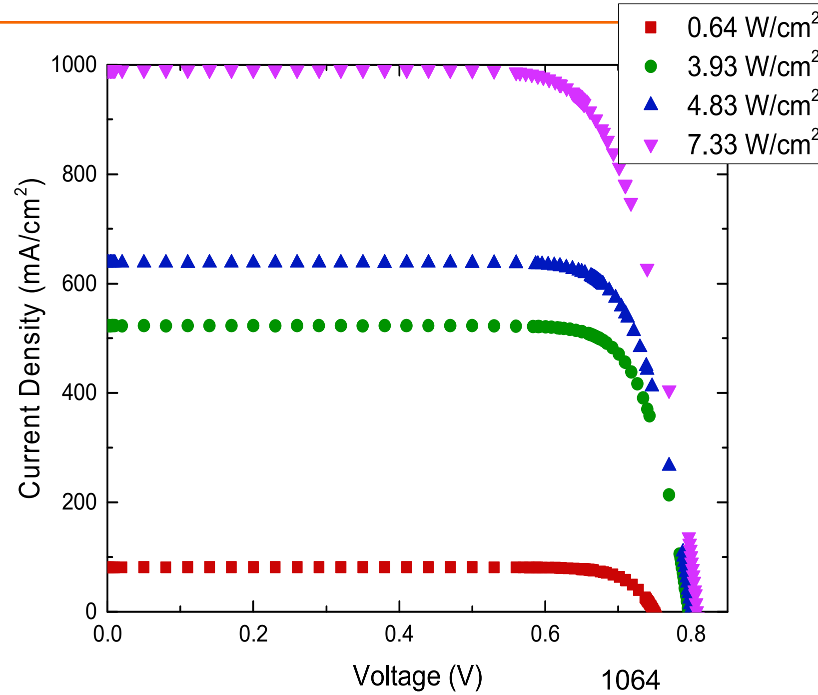
Variable Power Laser Illuminated I-V

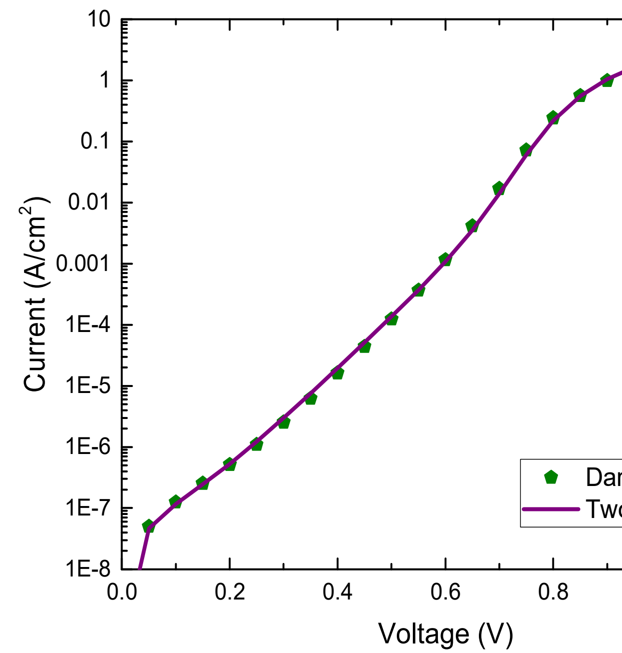


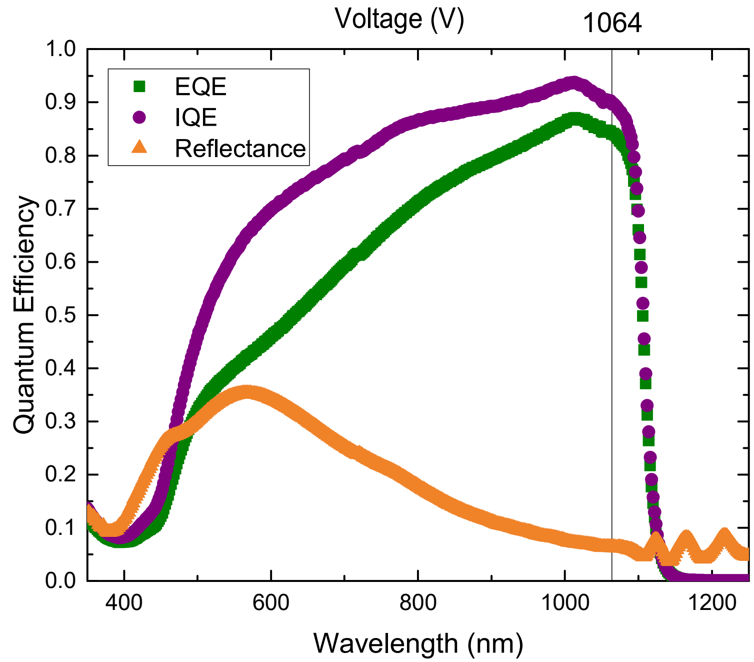
Gaussian beam, diameter 1.16 mm, some tenability of output power

LPC Results









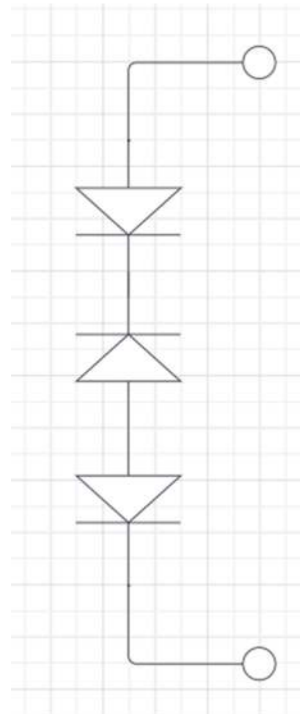
J_{01}	$1.5 * 10^{-14}$
J_{02}	$8.5 * 10^{-9}$
R_{series}	0.077
R_{shunt}	$1.5 * 10^{6}$

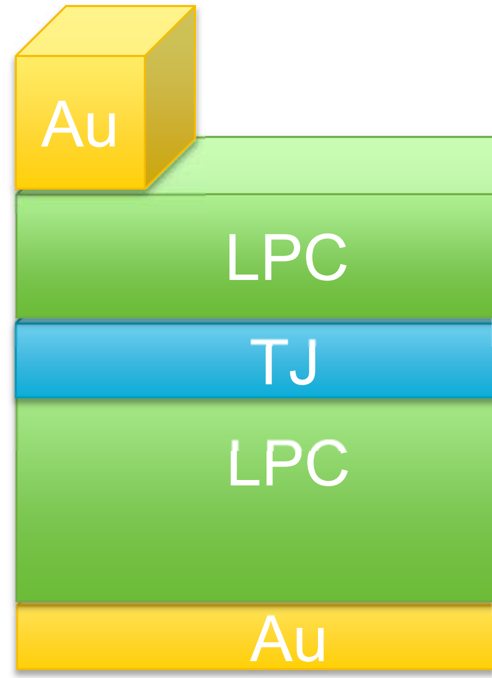
- Max efficiency 39.8% with A
- J_{SC} at 4 W/cm^2 roughly 620
- V_{OC} exceeds 0.8 V, W_{OC} = 0
- EQE 80% at 1064 nm

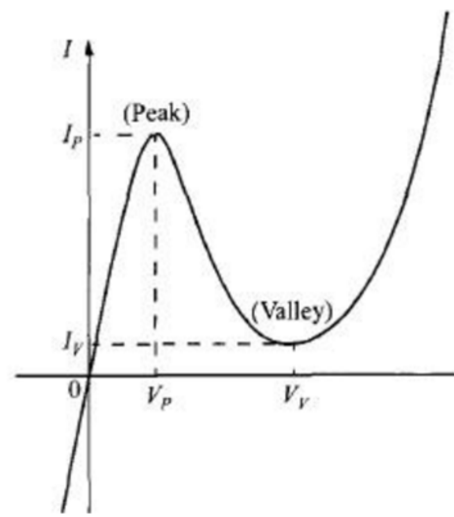
lultijunction Approach

crease Voltage, Lower Current

- Vertically stack subcells
- Appliance compatible-voltage
- Decreasing Joule heating losses
- Requires tunnel junctions
- Higher power output







Tunnel diode characteristic I-V
From: S.M. Sze and K. K. Ng. *Physics of Semiconductor Devices,* 2006.

PC Design

1064 nm = 1.17 eV laser

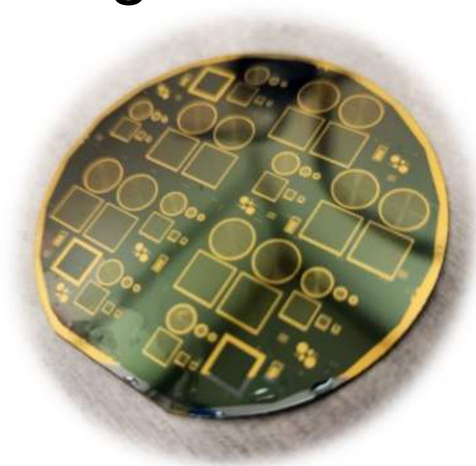
1.1 eV band edge (70 meV laser)

$In_{0.20}Ga_{0.80}As$

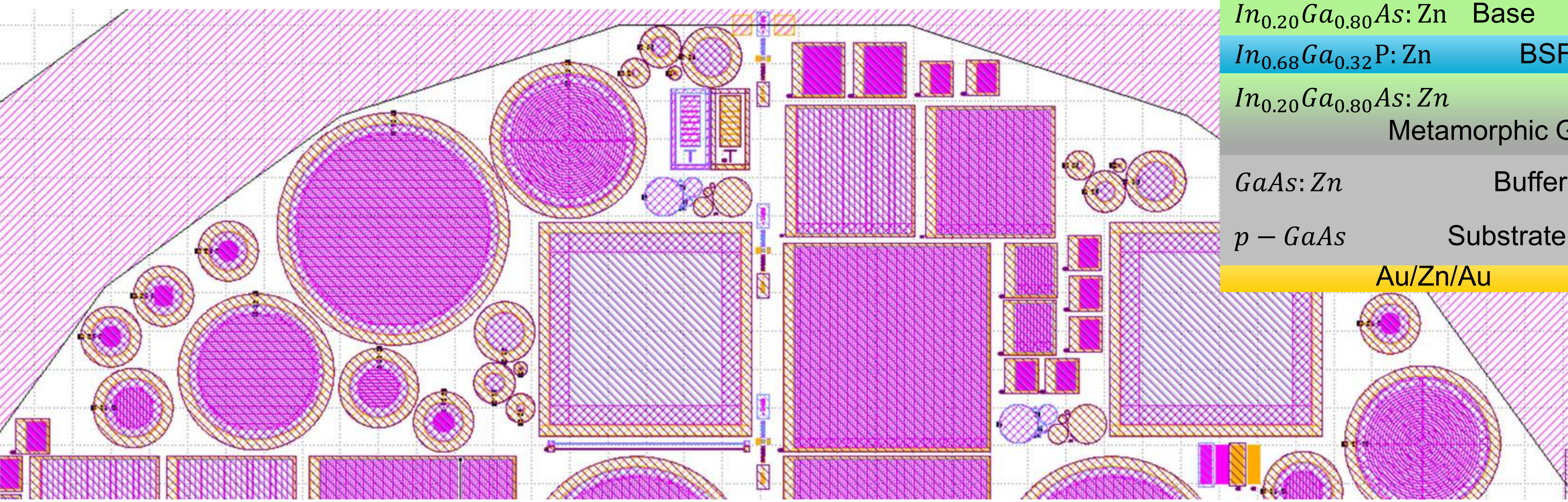
Absorber thickness: 3.7 um, 95% light absorbed

Standard III-V processing

- 3.5 um front metal

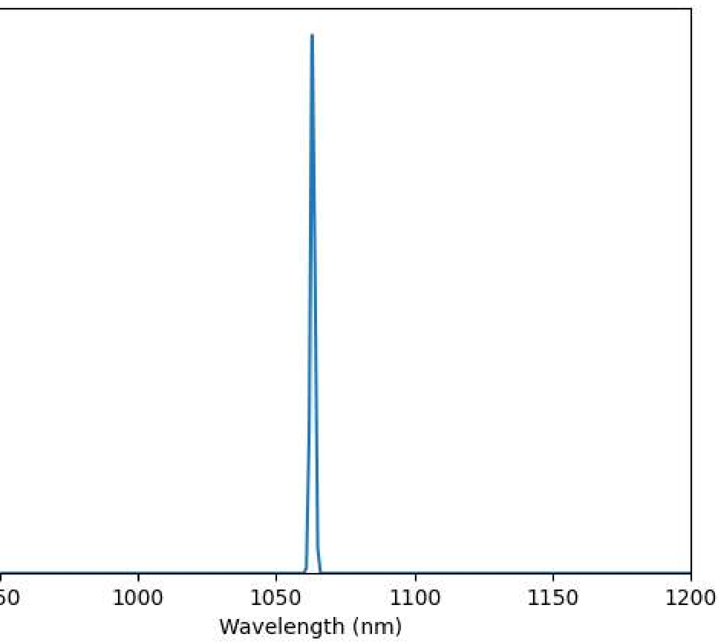


LPC Integration



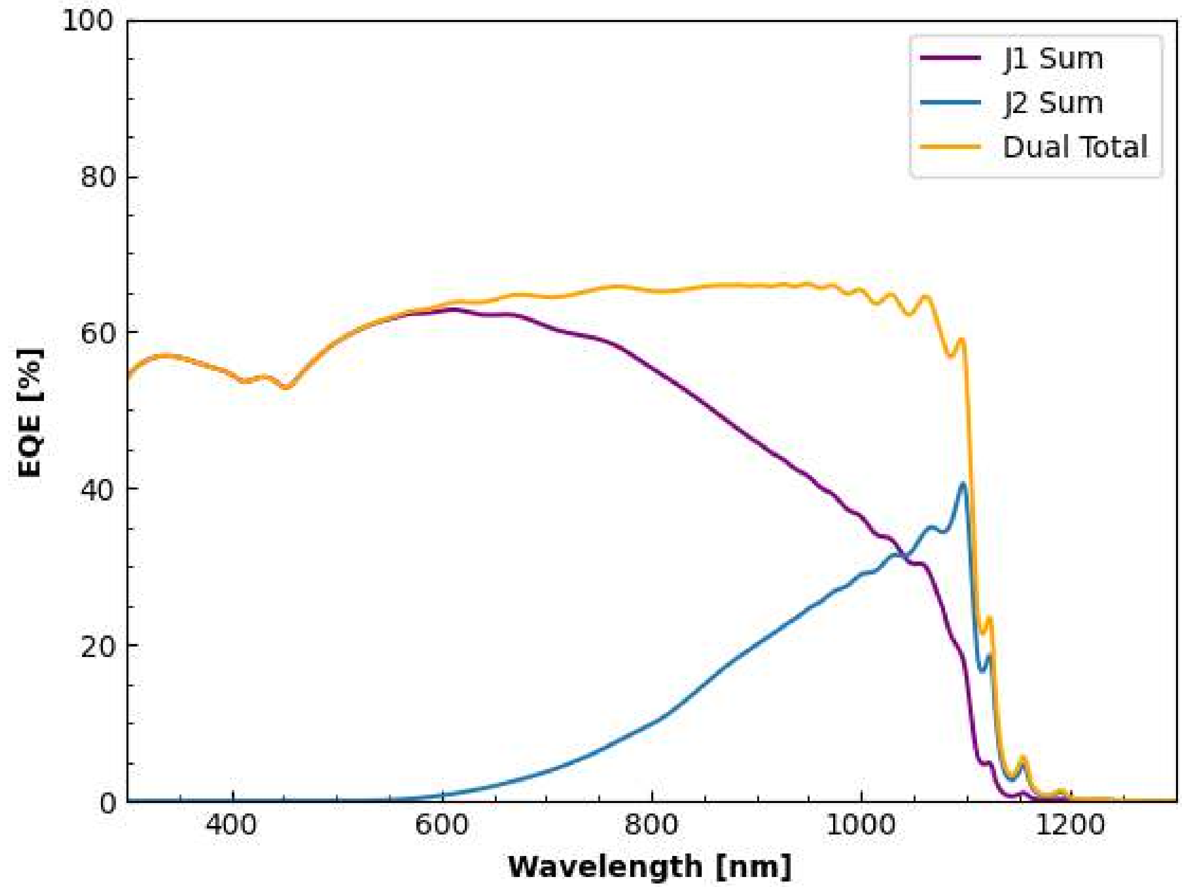
Design

t-Diffusion Modeling

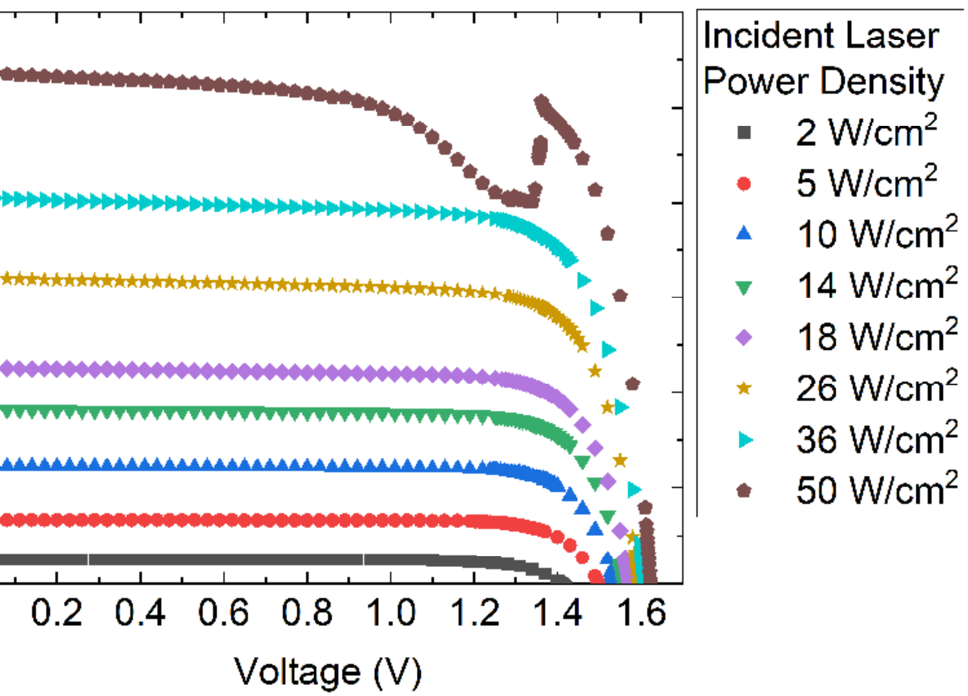


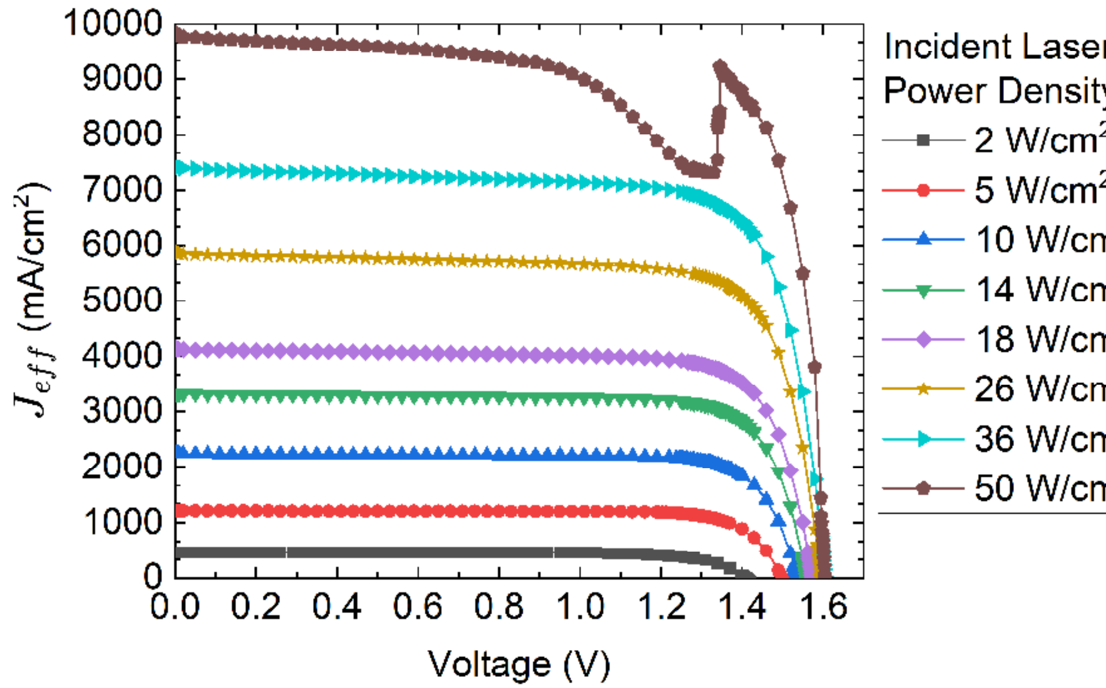
deled laser source:
- 063.2 nm center
- nm FWHM
- ntegrated power 4 W/cm^2

- Assumed material parameters equal to the fitted parameters the 1J device
- Accounted for parasitic optical absorption from the tunnel jur
- Predicted Efficiency: 35% without, 45% with ARC



Results **No ARC**



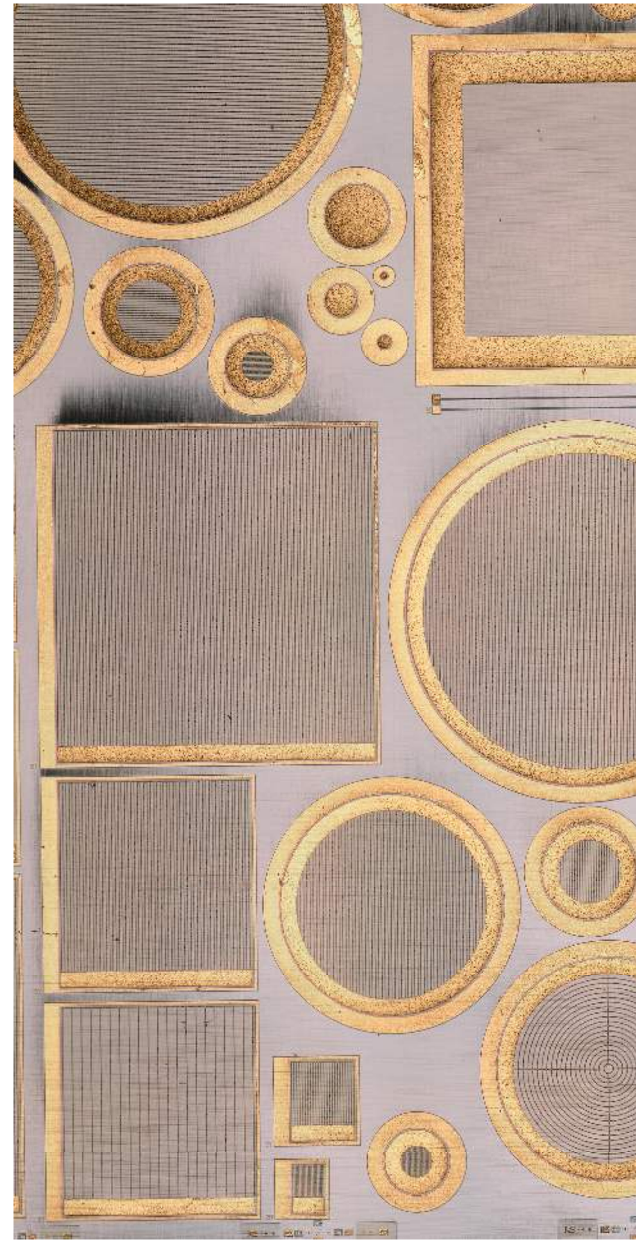


- ue to Gaussian beam, at center of beam current ensities are >20X a uniform illumination of the ame power over the full cell area
- mproved current match and tunnel junction needed

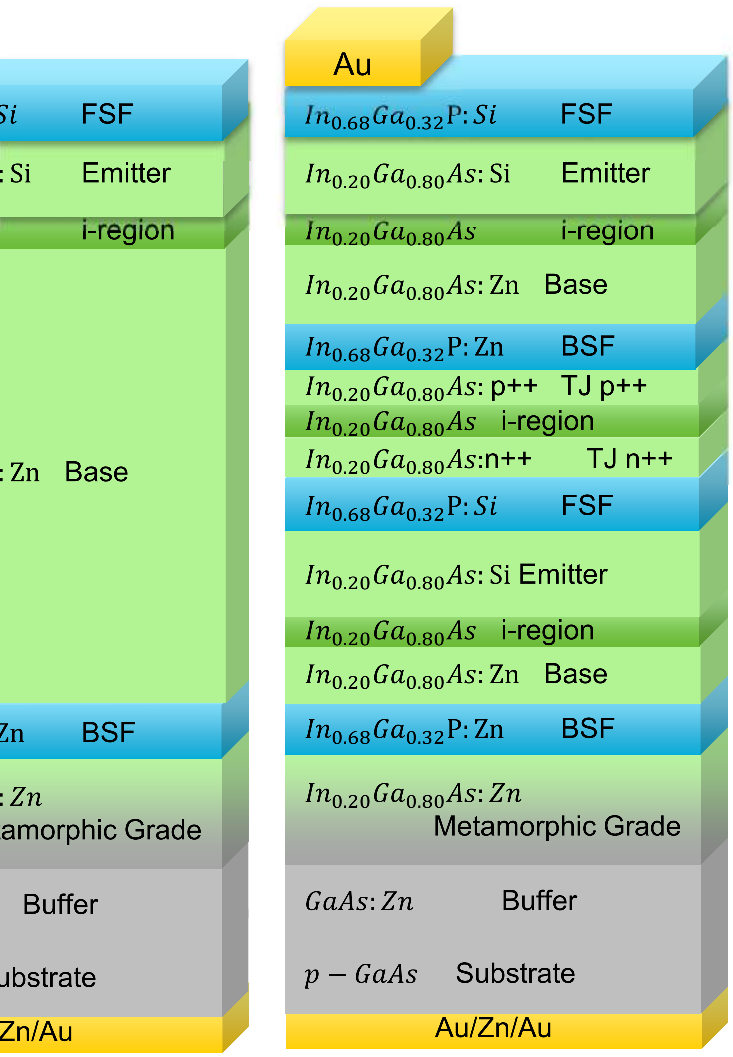
- $V_{OC-2J} = 1.95\ V_{OC-1J}$
- 28% efficient at 3.6 W/cm^2
- Comparable J_{SC} and V_{OC}

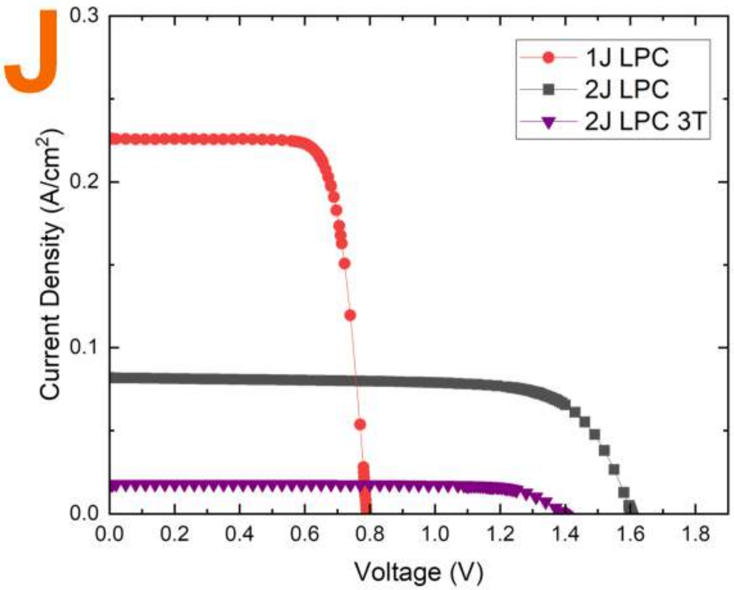
Mask Design

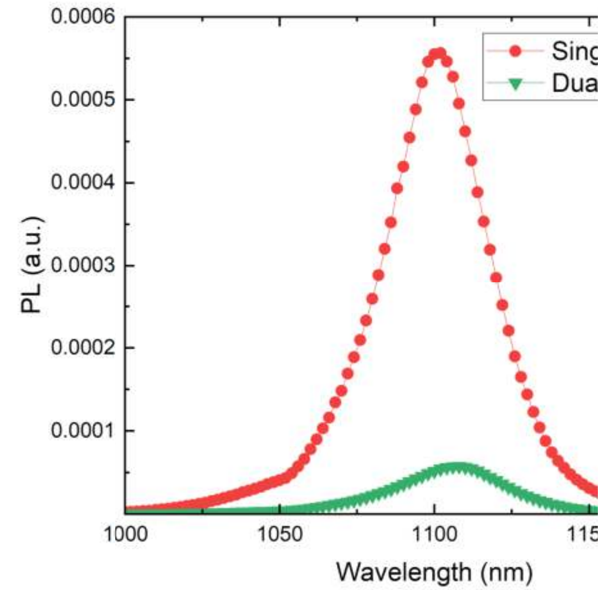
- Physically isolate performance of each junction by creating a third terminal
- Create diagnostic test structures
  - QE pads
  - Dark diode pads
  - TLM pads
  - Metal resistance bars
  - Metal height and etch depth bars
- Re-optimize grid for high current density

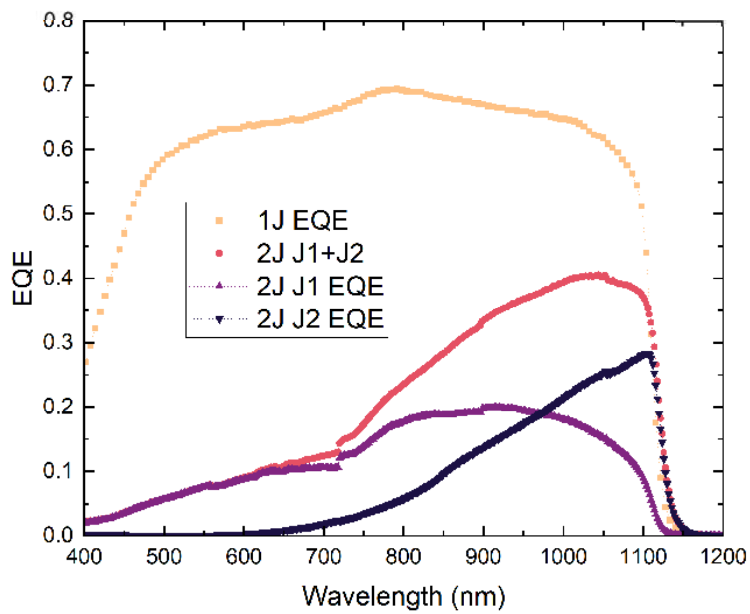


omparison to 1J









- Photoluminescenc
  532 nm
- Optical thickness
  - 1J and 2J identica
    this depth
  - 2J top junction is
    luminescing equa

onclusions

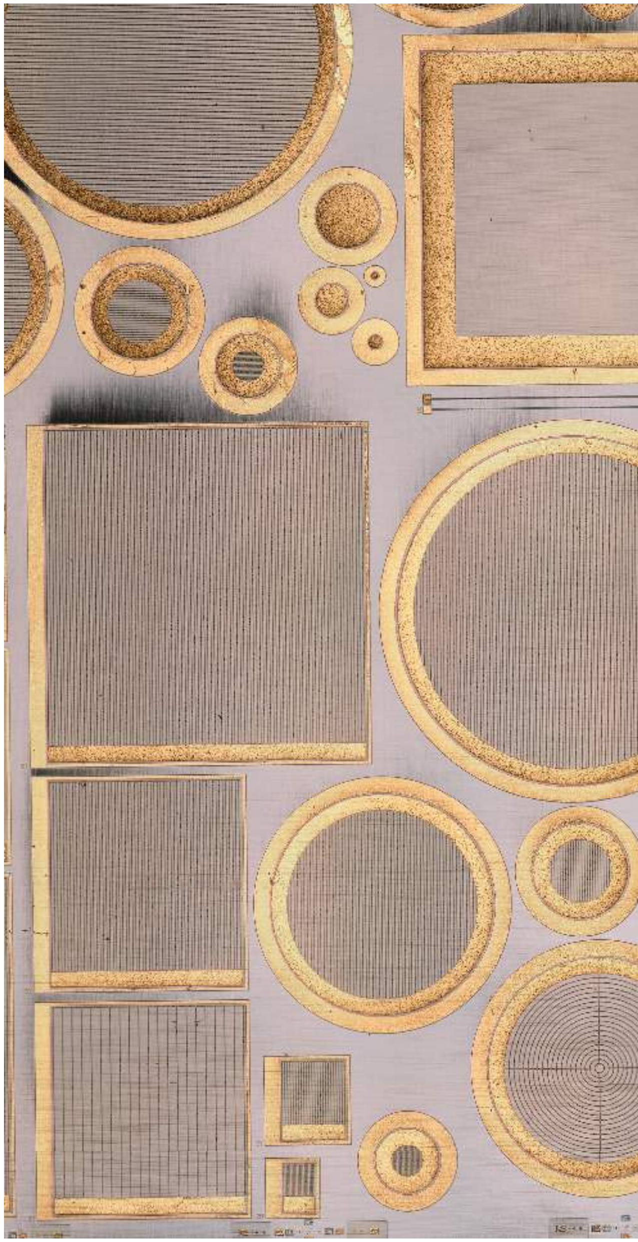
1J LPCs reached 40% efficiency at 4 W/cm^2

Temperature testing showed junction temperatures up to 80^{o}C over ambient

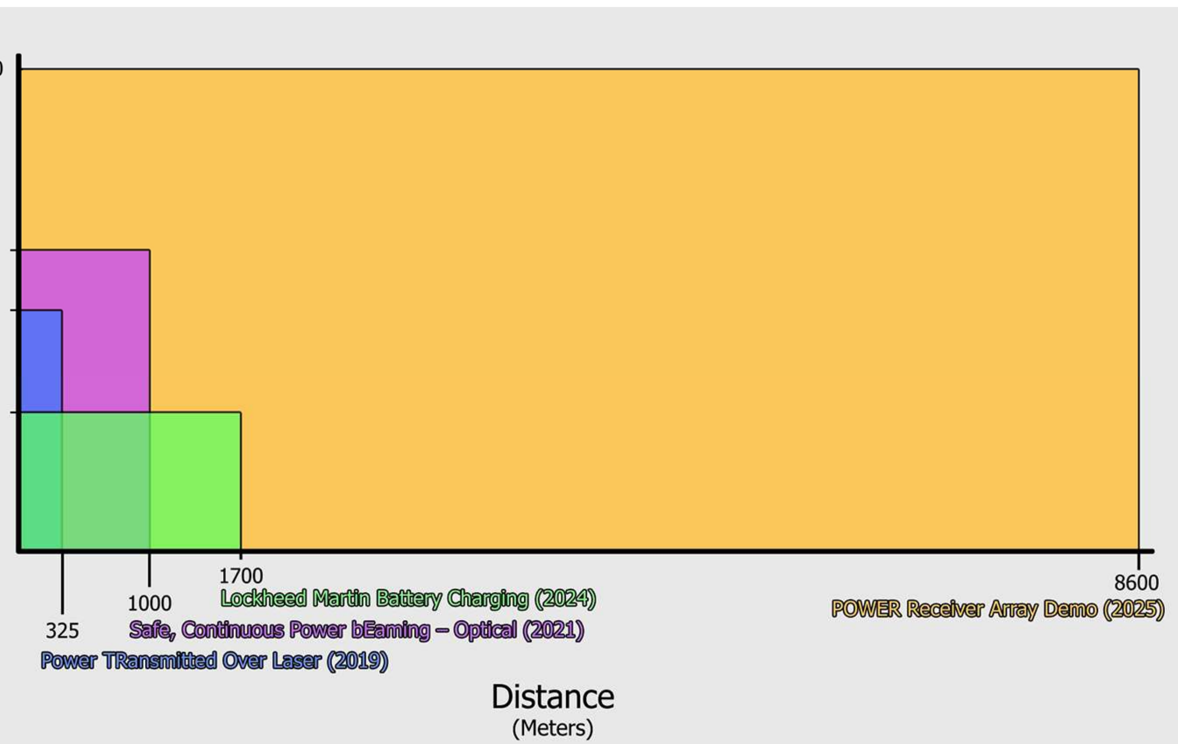
2J LPCs were designed with a 3T mask to help deconvolve variables

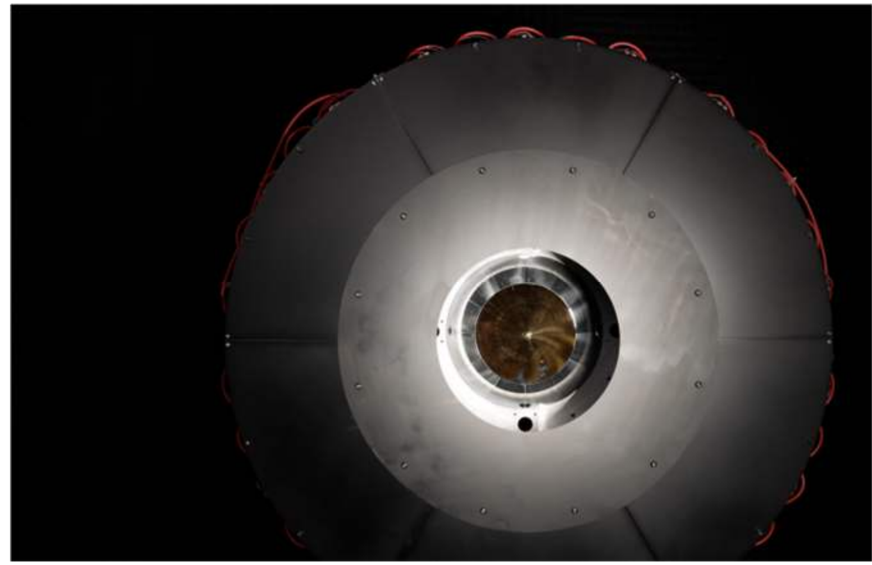
3T testing shows significant series resistance and material quality concerns in the top cell

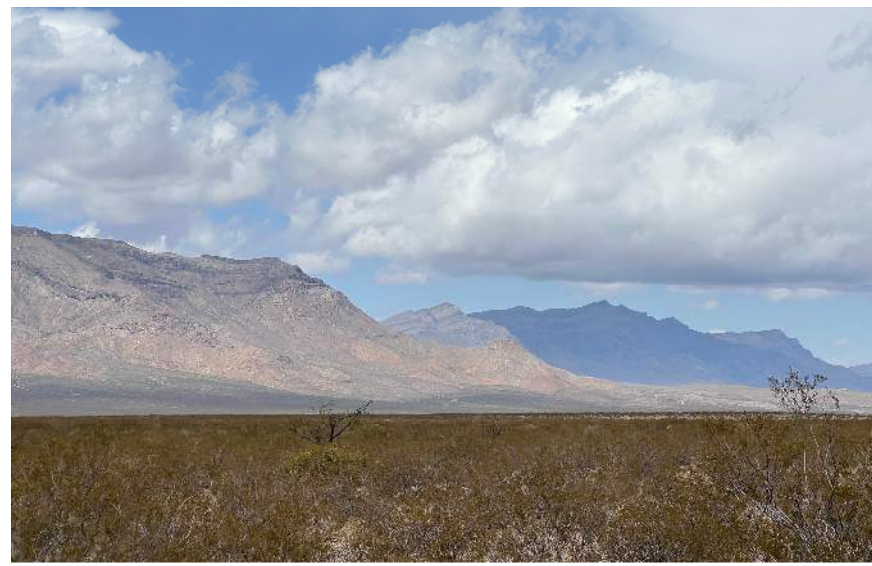
Future testing will further identify the source of the issue.



eld Testing







ps://www.darpa.mil/news/2025/darpa-program-distance-record-power-beam

U.S. NAVAL RESEARCH LABORATORY

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NanoPov
Research
Laborato

DARP

Acknowledgements

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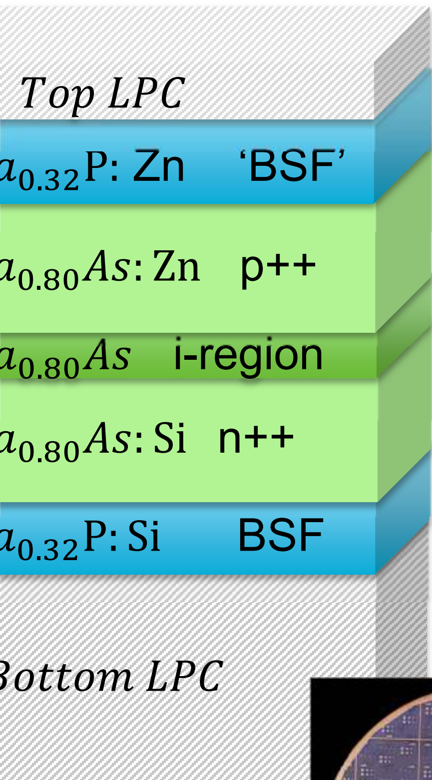
- Geoffrey Landis (NASA GRC)
- Alex Grede (US NRL)
- Ken Schmeider (US NRL)
- Thank you for listening!

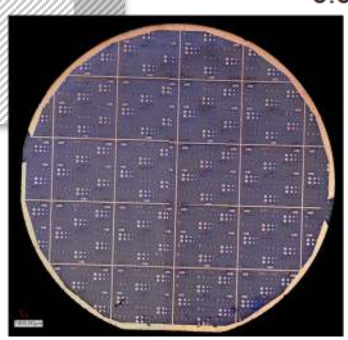
This work is supported by a NASA Space Technology Graduate Research Opportuni

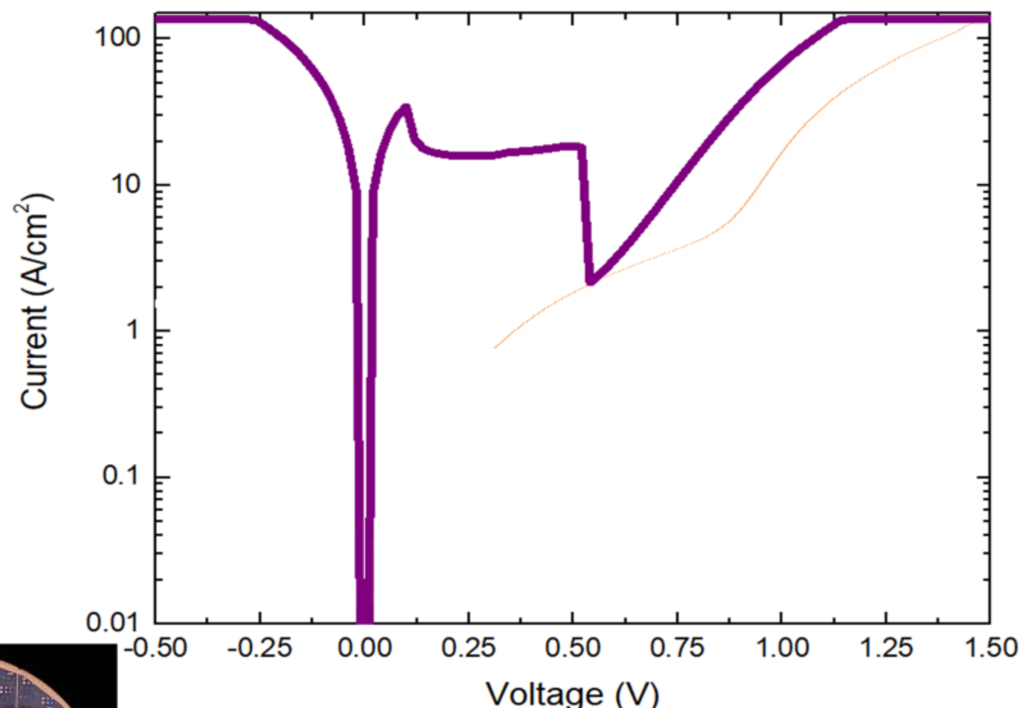
Thank you!

nneling Junction Development

pants, pre-flows, diffusion barriers





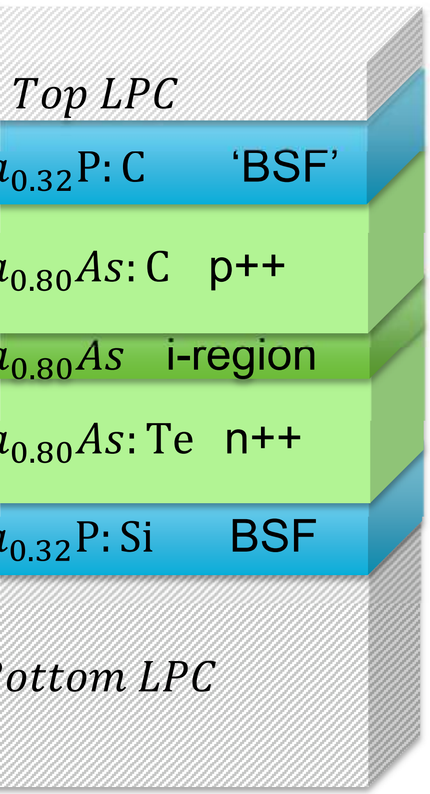


Original Zn/Si devices

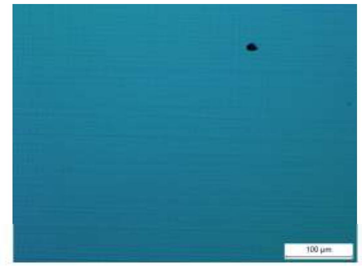
- Initial tunneling curr A/cm^2 at 0.1 V
  - Up to ~ 100 W/cm² irradiance for 2J
- Resistive after top L growth-> low efficier LPCs
- Failure at <<100 W/
- Ideally, order of magnitude higher pe current

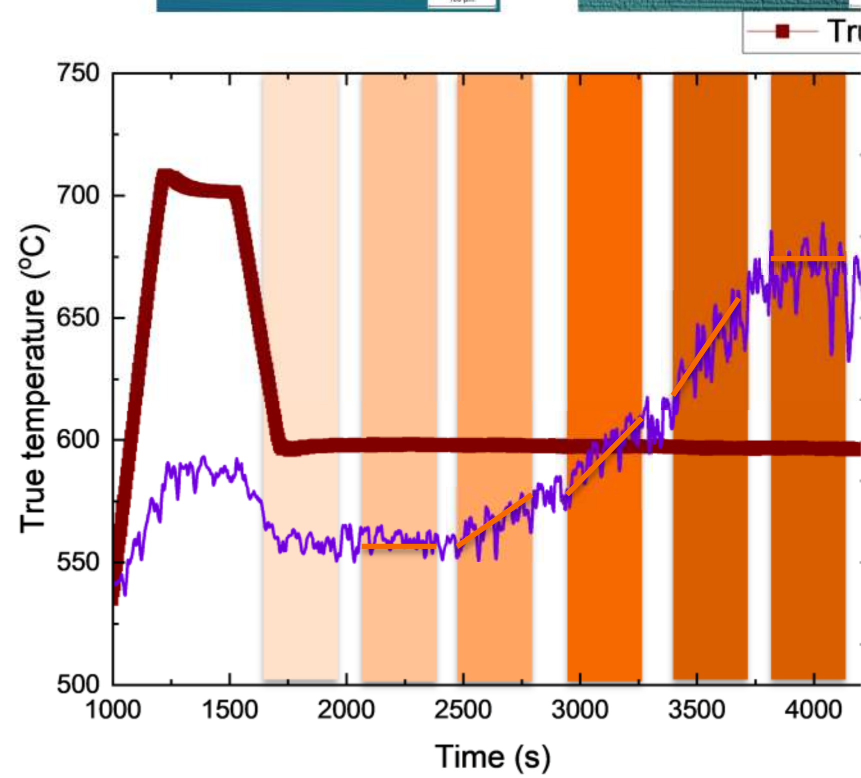
/C Tunnel Junction

Memory Effect Accommodations



- Te reaches higher doping than Si in InGaAs
- Challenges:
  - Surfactant memory effect
  - Surface quality
  - Indium incorporation alteration
- Approach
  - 40 sec DETe pre-flow
  - 5 min DETe post-bake
  - Surface quality DOE
  - kIn variation
- Final doping ≥ 3.4 e19 cm^{-3}





DETe flow (sccm)	0	0.5	1.5	2	4	4
TMIn/III ratio	0.9186	0.9186	0.9186	0.9186	0.9186	0
Est doping (cm^{-3})	---	1e17	1e18	9e18	3.7e19	3

Te/C Tunnel Junction

J2 Growth

e Preflow – 40 sec under arsine

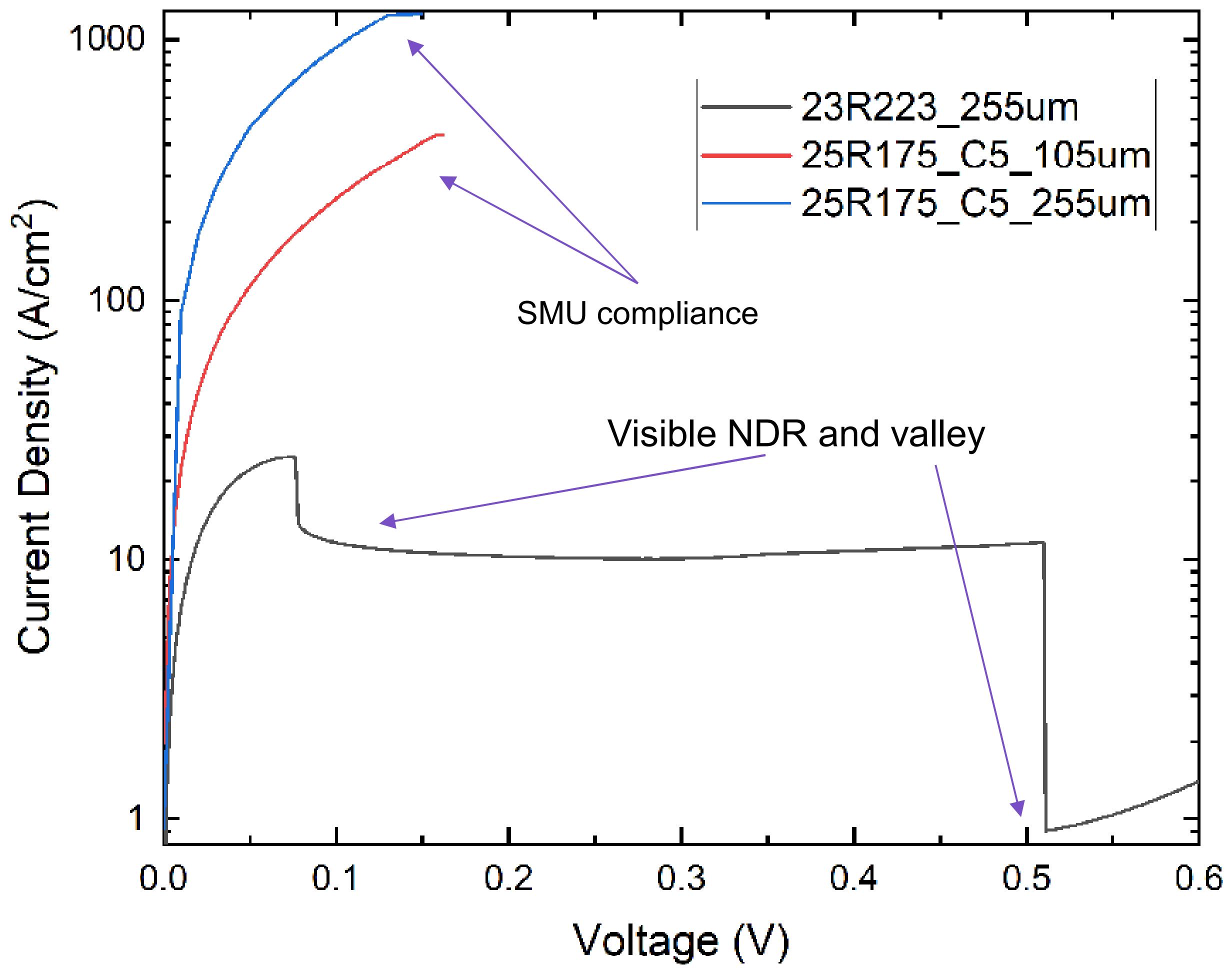
nGaAs:Te Growth

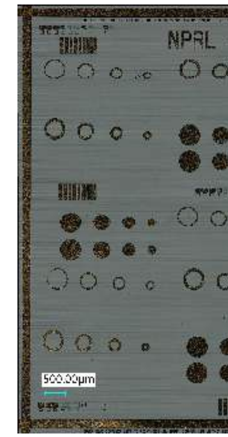
ost-Te bake 5 min at 650C

nGaAs:C Growth – 575C

Ramp back to 650C

J1 Growth

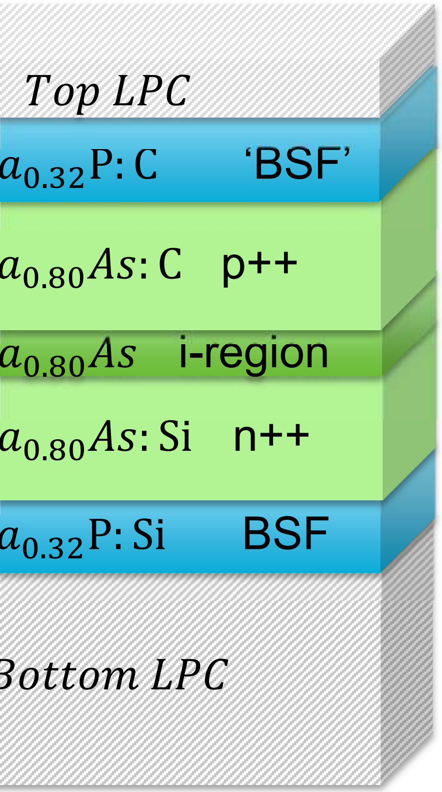


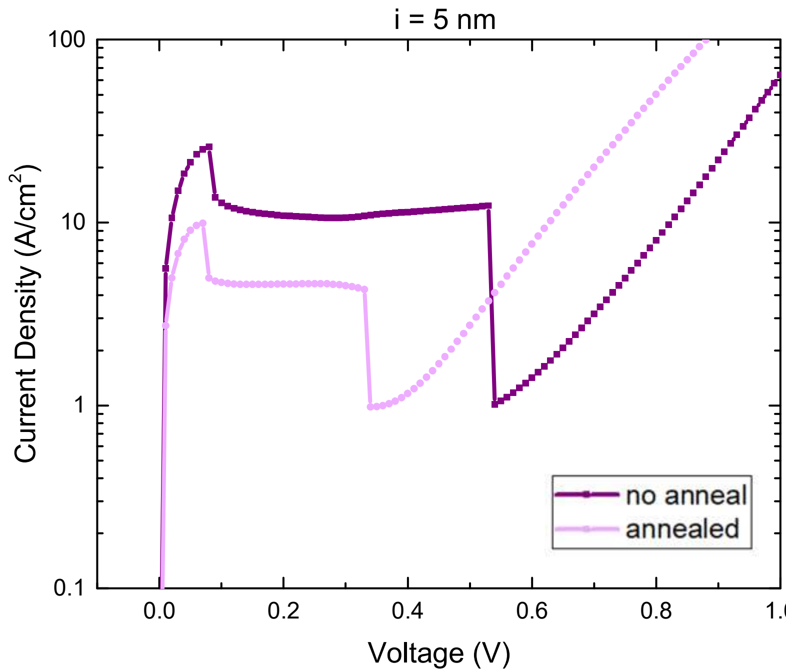


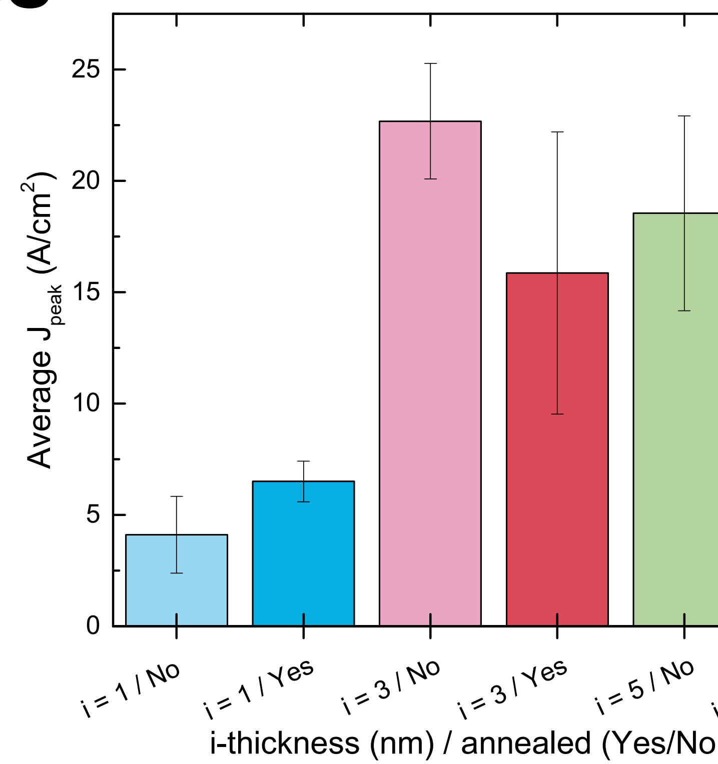
- J_{peak} > 500 A/cm^2
- Voltage loss at 15 A/cm^2: 10 mV

nealing Effects

owing an LPC changes TJ properties







- Varied parameters:
  - i-region thickness = 1, 3, 5
  - annealed? = no, yes
- ΔJ_{peak} of 6.8 to 10.7 A/cm

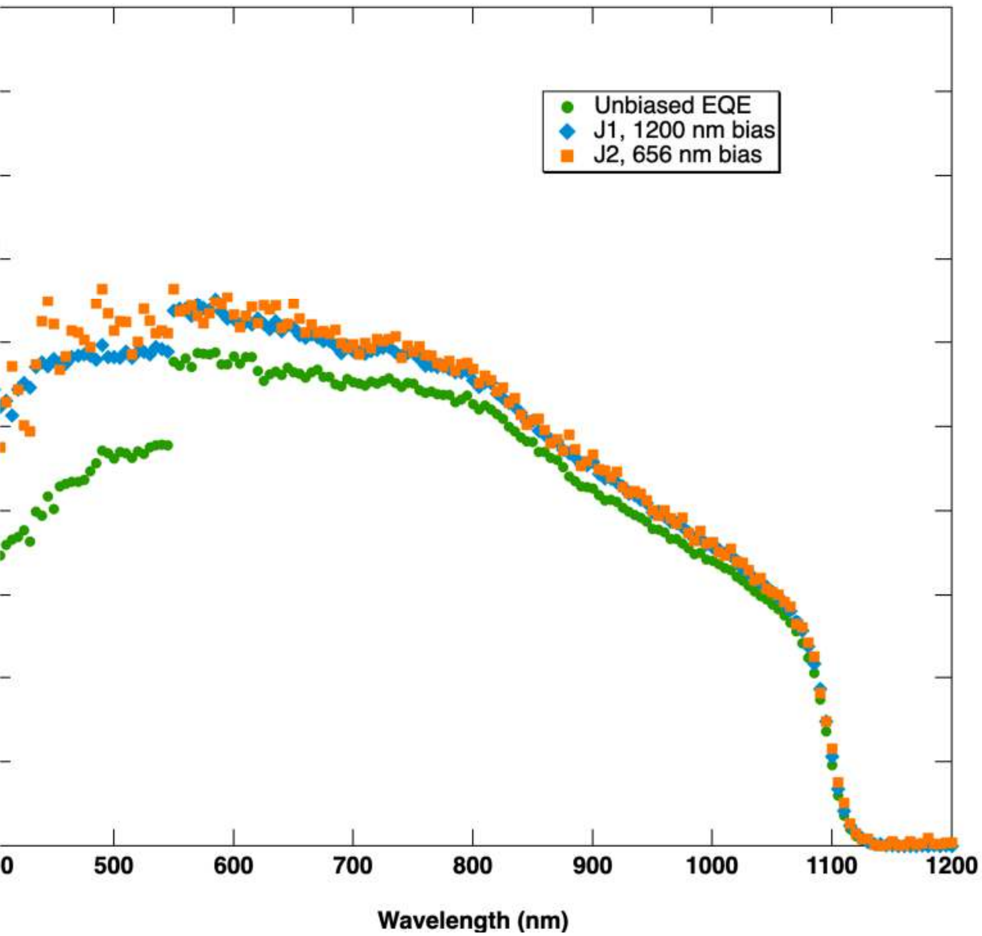
egion prevents compensation of dopants at interface

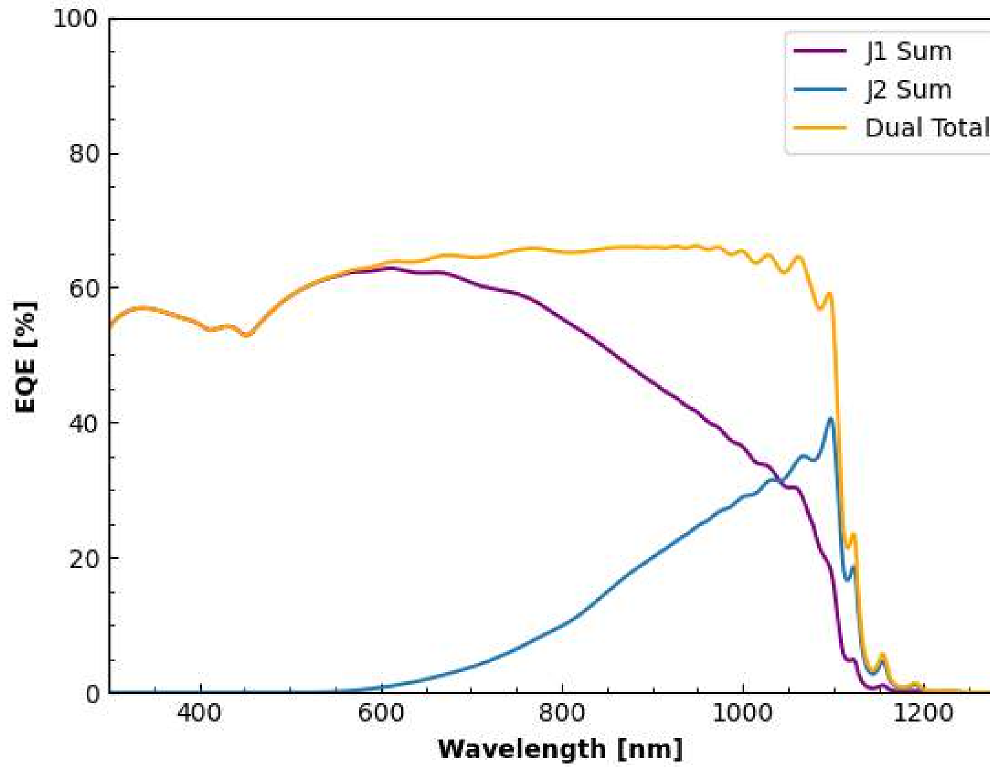
ickness of diffusion barrier impacts current

doping still never surmounted 1e19/cm^2

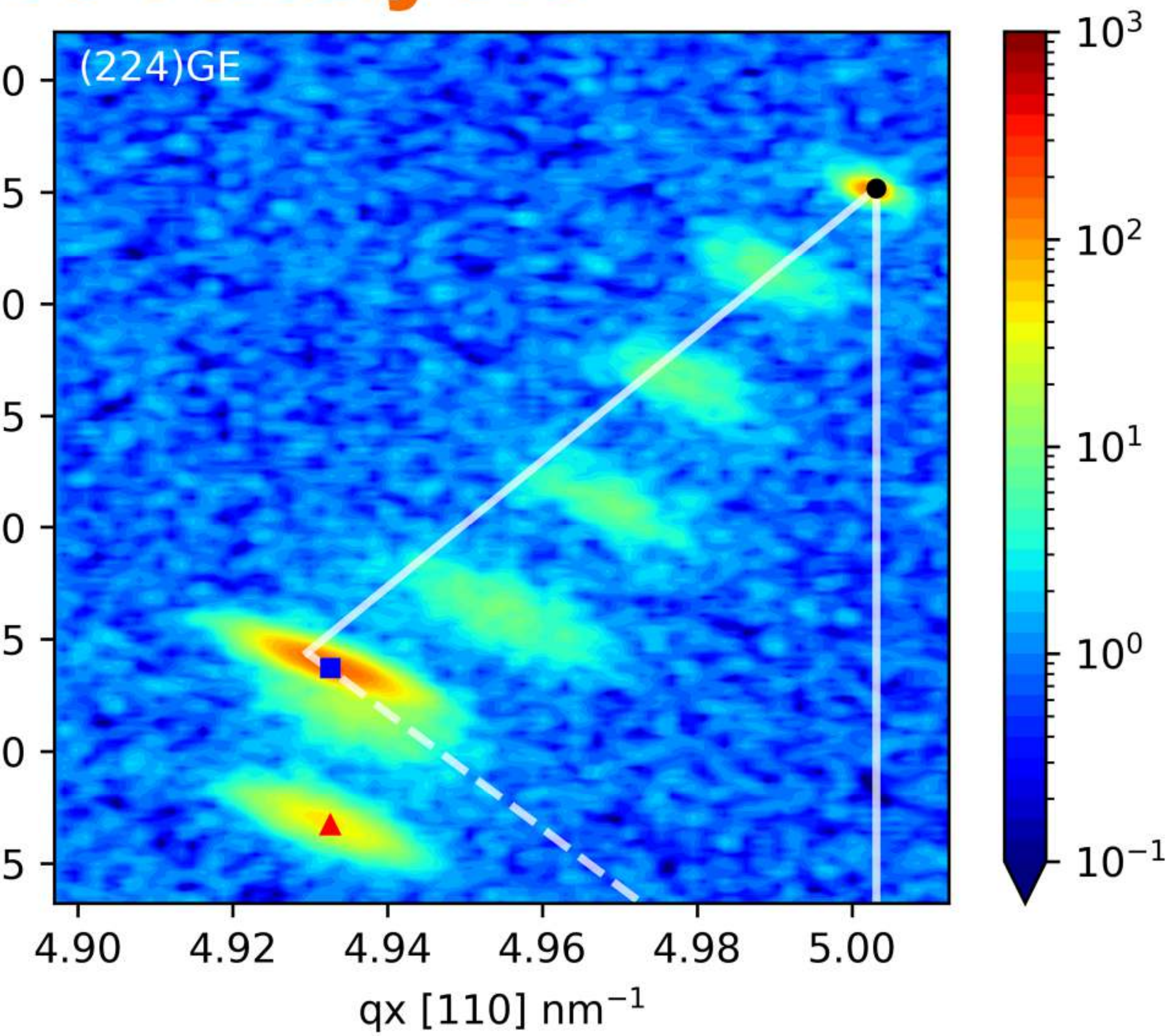
2J LB QE

- Regardless of bias, seeing J1 limiting QE
- In models, too many variables to deconvolve, not enough data





MG Analysis



- RSM: 97% relaxed