Radiation testing of Multi-Junction Solar Cells Employing Quantum Wells and Light Management

Seth M. Hubbard, Stephen J. Polly, Brandon Bogner, Julia D'Rozario

Rochester Institute of Technology, Rochester, New York

Space Power Workshop
April 25, 2023

RIT | NanoPower Research Laboratories

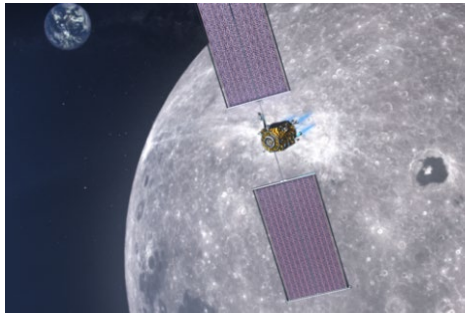
RIT
NanoPower Research Laboratories

Space and Mobile Power

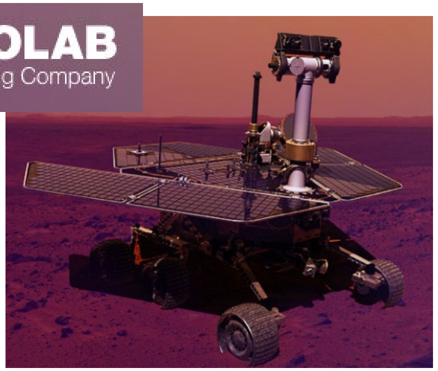
SPW
APRIL 25, 2023

- III-V photovoltaics (PV) are leading power sources for satellites and area/mass constricted systems
- **Constant need for improved efficiency, lower weight, cost and radiation resilience!**

SolAero TECHNOLOGIES

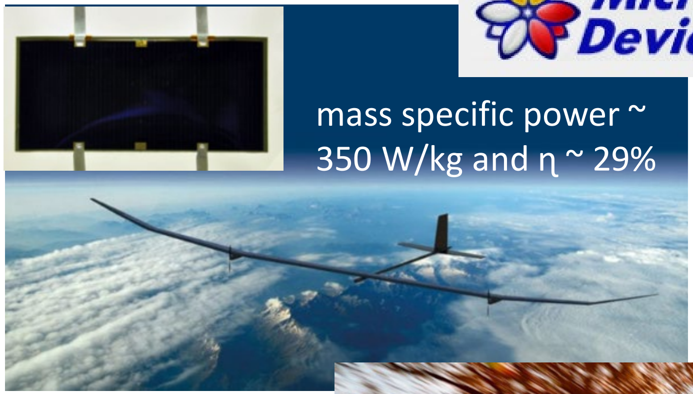


SPECTROLAB
A Boeing Company



Missions operating in low and high Earth orbits as well as on Mars and lunar surfaces

MicroLink Devices, Inc.



High Altitude, Long Endurance (HALE) Unmanned Aerial Vehicle (UAV)

RIT NanoPower Research Laboratories

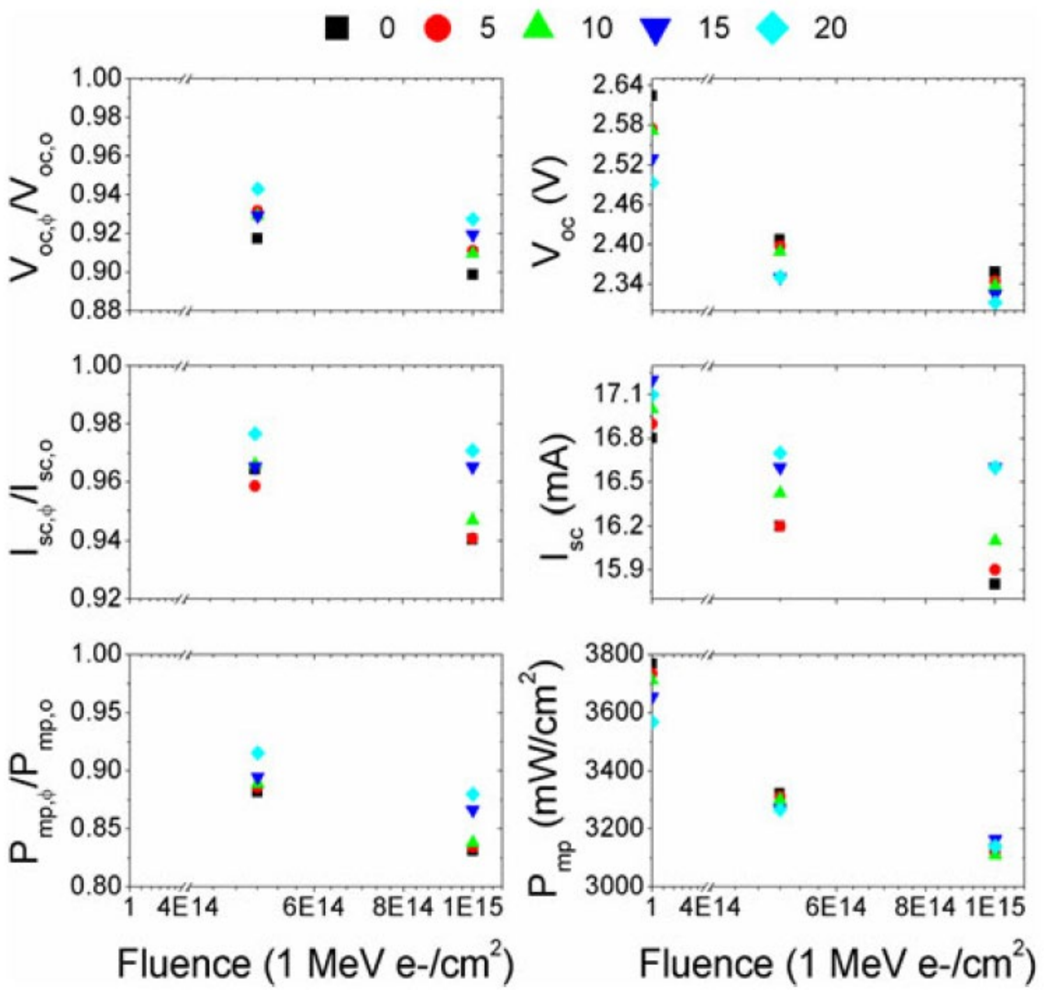
Strategies to increase EOL performance

1. Conventional optimization
- Doping gradients, disordered InGaP, EoL current matching

2. Use radiation Hard Materials
- InP was seen as candidate
- Difficult to integrate into 3J

3. Use strained materials to increase PKO E_A, current matching with QWs or QDs

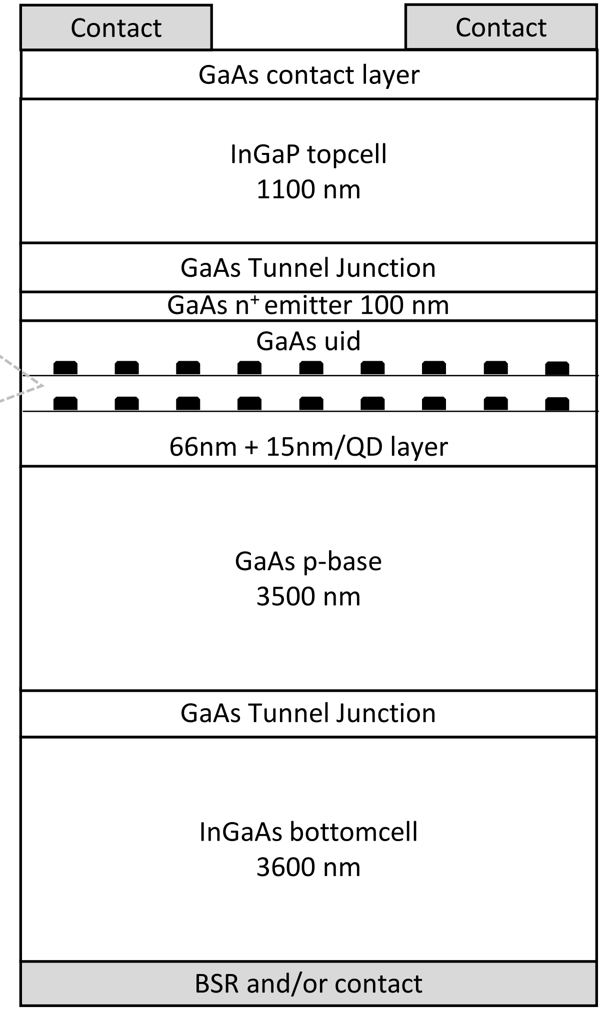
4. Thinning subcells and current matching using light management and trapping

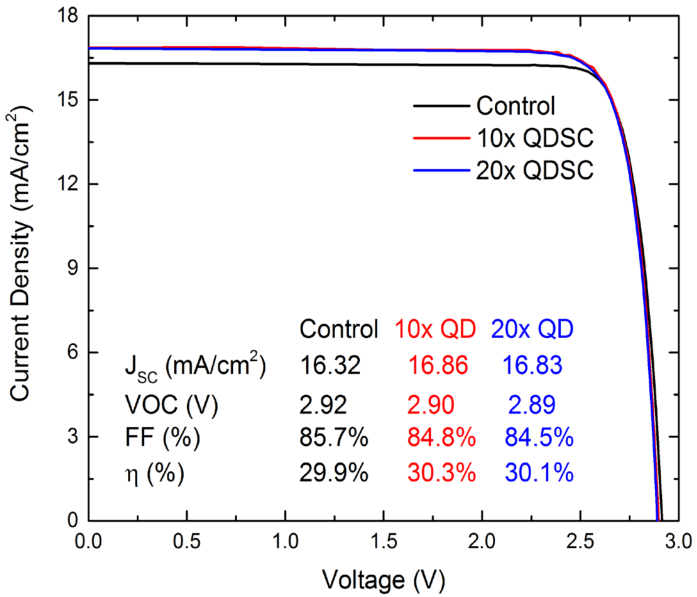


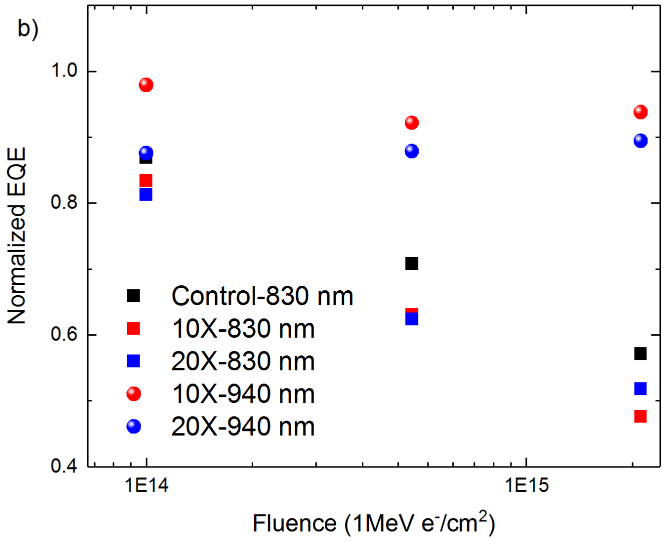
RIT NanoPower Research Laboratories

Initial Work on Nanostrucutred PV

QD provided limited ΔJ_{SC} per layer!
Difficult to stain balance!



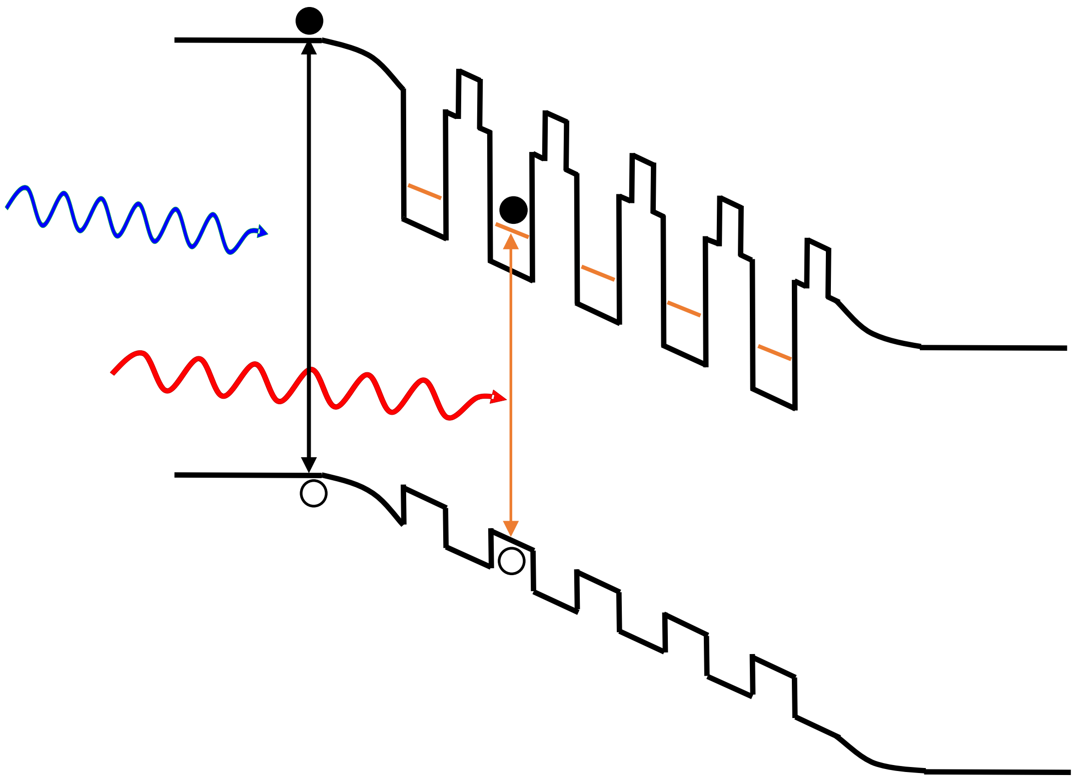


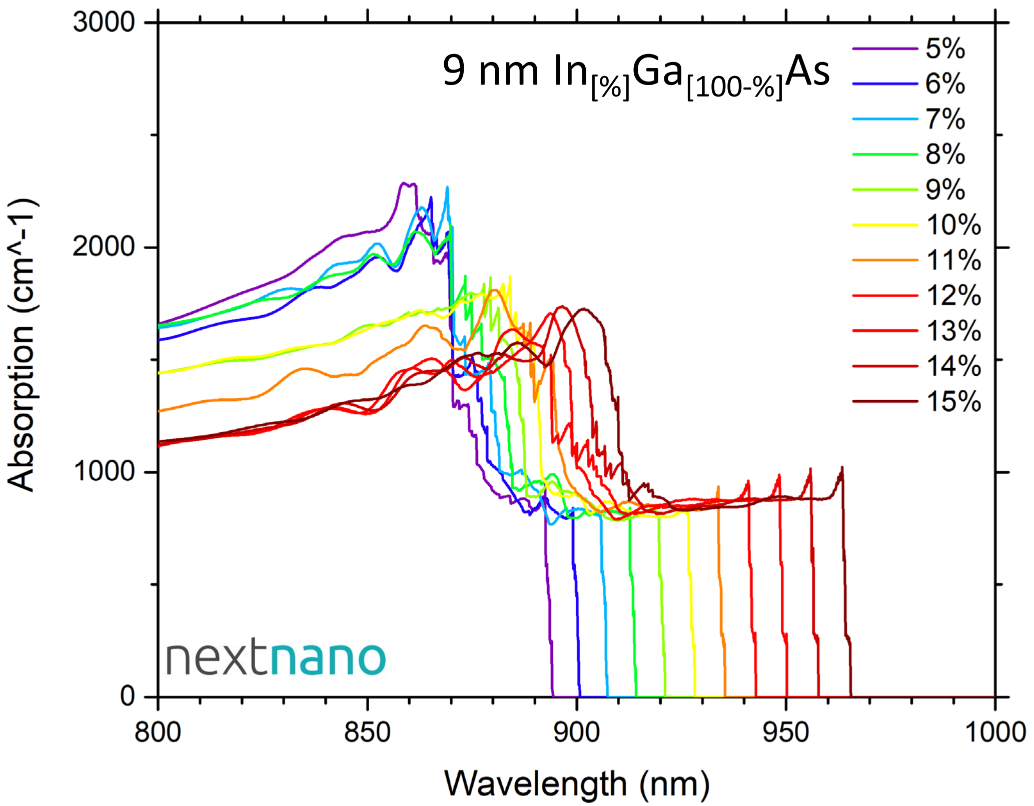


S. R. Tatavarti, Z. S. Bittner, S. M. Hubbard, *Solar Energy Materials and Solar Cells*, vol. 185, pp. 153-157, 2018.

RIT
NanoPower Research Laboratories

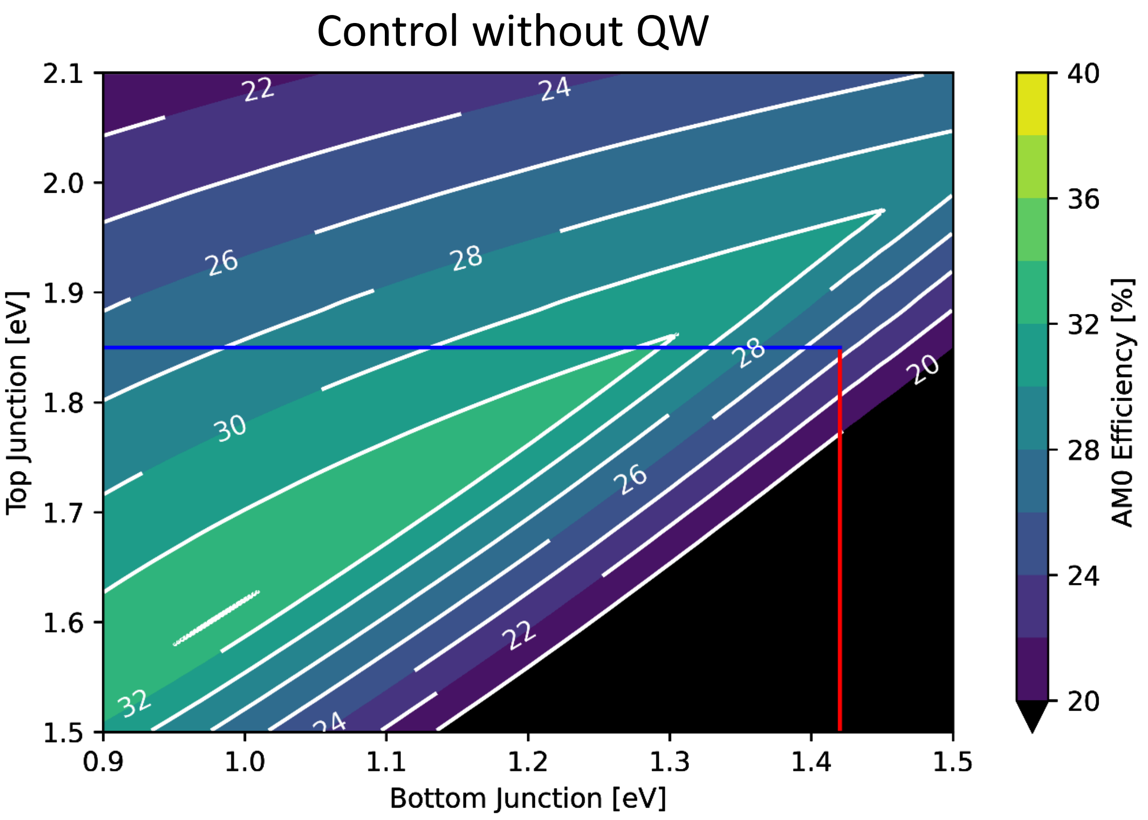
Quantum Wells

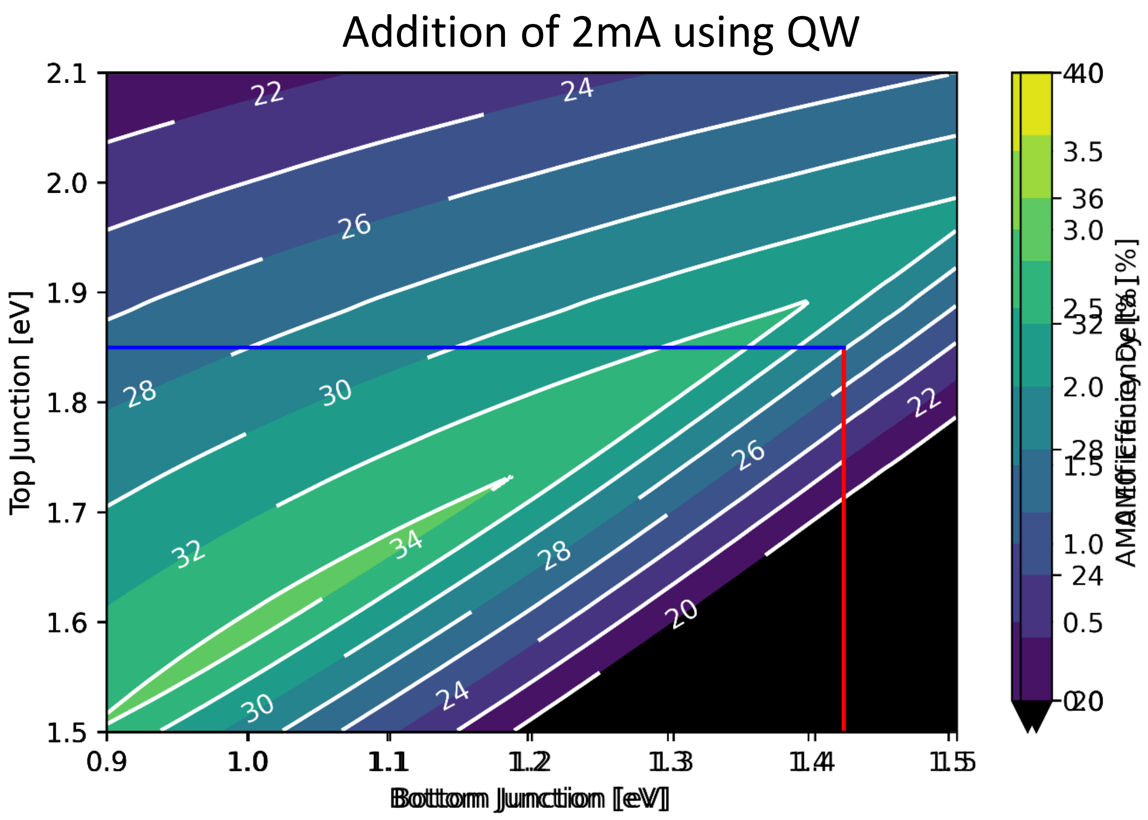




RIT NanoPower Research Laboratories

Dual Junction Model





Initial Model pointed to over 28% AM0 using QW in 2J Configuration

RIT

NanoPower Research Laboratories

RIT III-V EPICenter

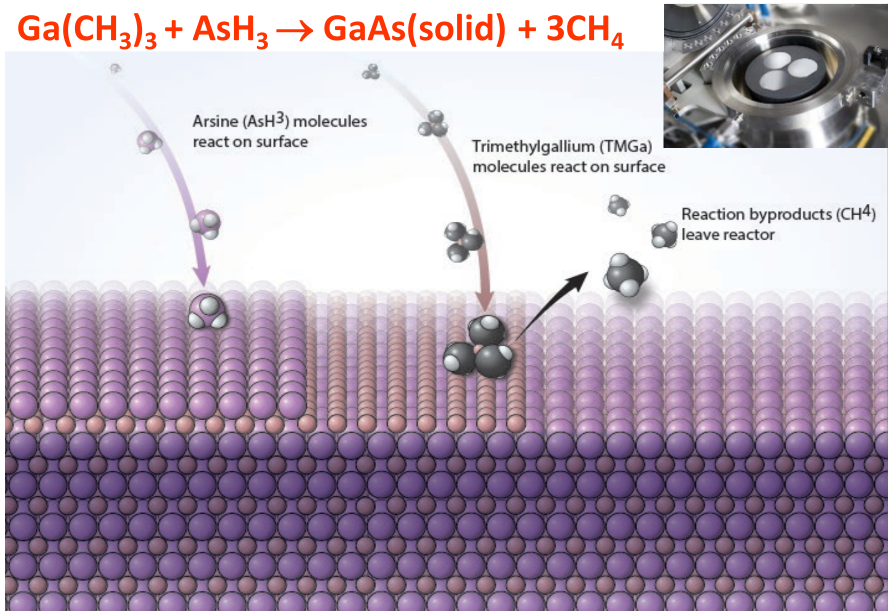
https://www.rit.edu/research/rit-epicenter

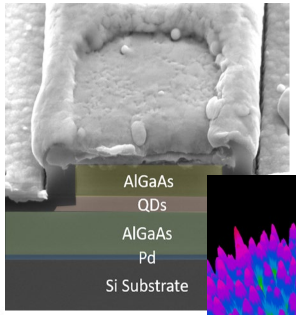
SPW

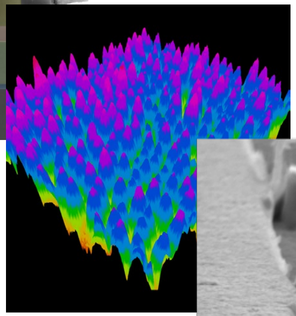
APRIL 25, 2023

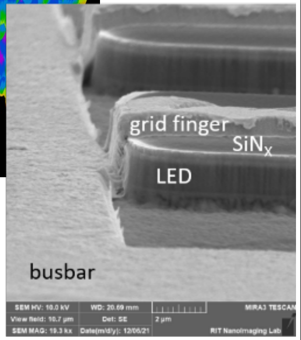
- Rapid prototyping of compound semiconductors Epitaxy of III-V compounds of As, P and Sb
  - Close Coupled Showerhead (CCS) MOCVD
    - 3x2", 1x3" and 1x4" capability
  - In-situ diagnostics: temperature, stress, strain and surface roughness
  - Full complement of ex-situ characterization tools and device fabrication

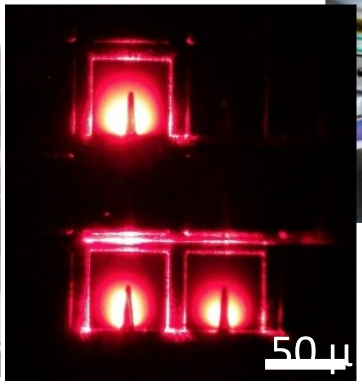
$Ga(CH_3)_3 + AsH_3 \rightarrow GaAs(solid) + 3CH_4$











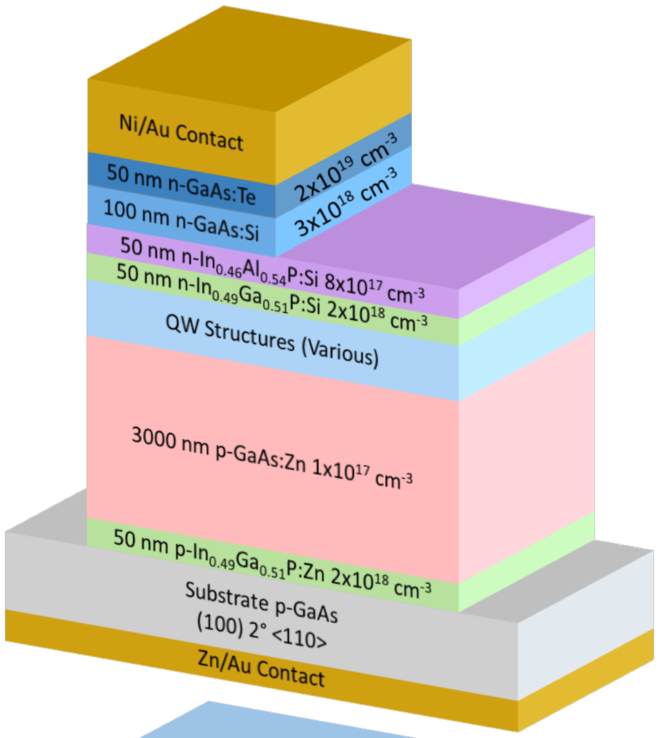
RIT

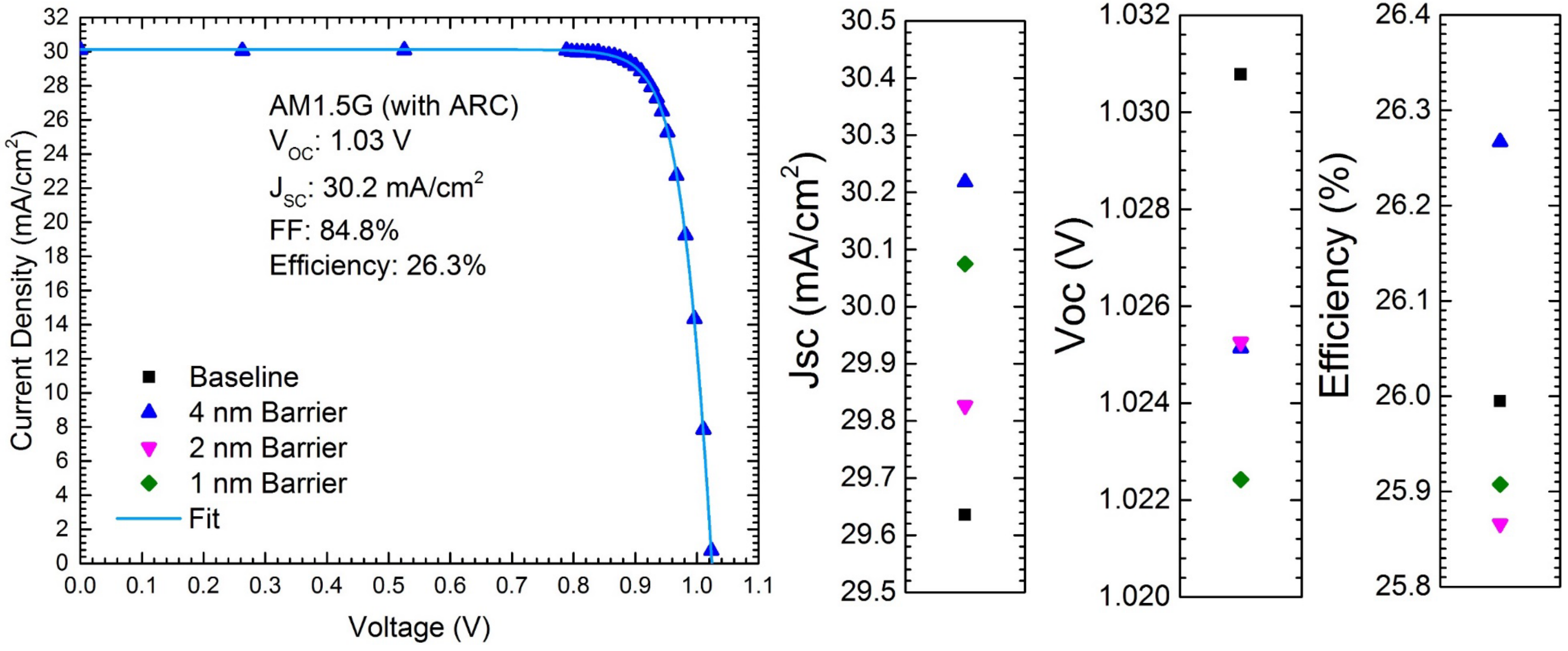
NanoPower Research Laboratories

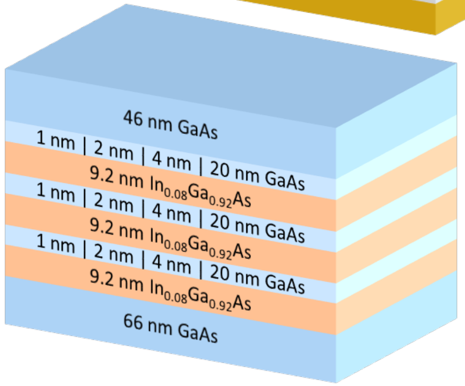
Strained Quantum Wells

SPW

APRIL 25, 2023



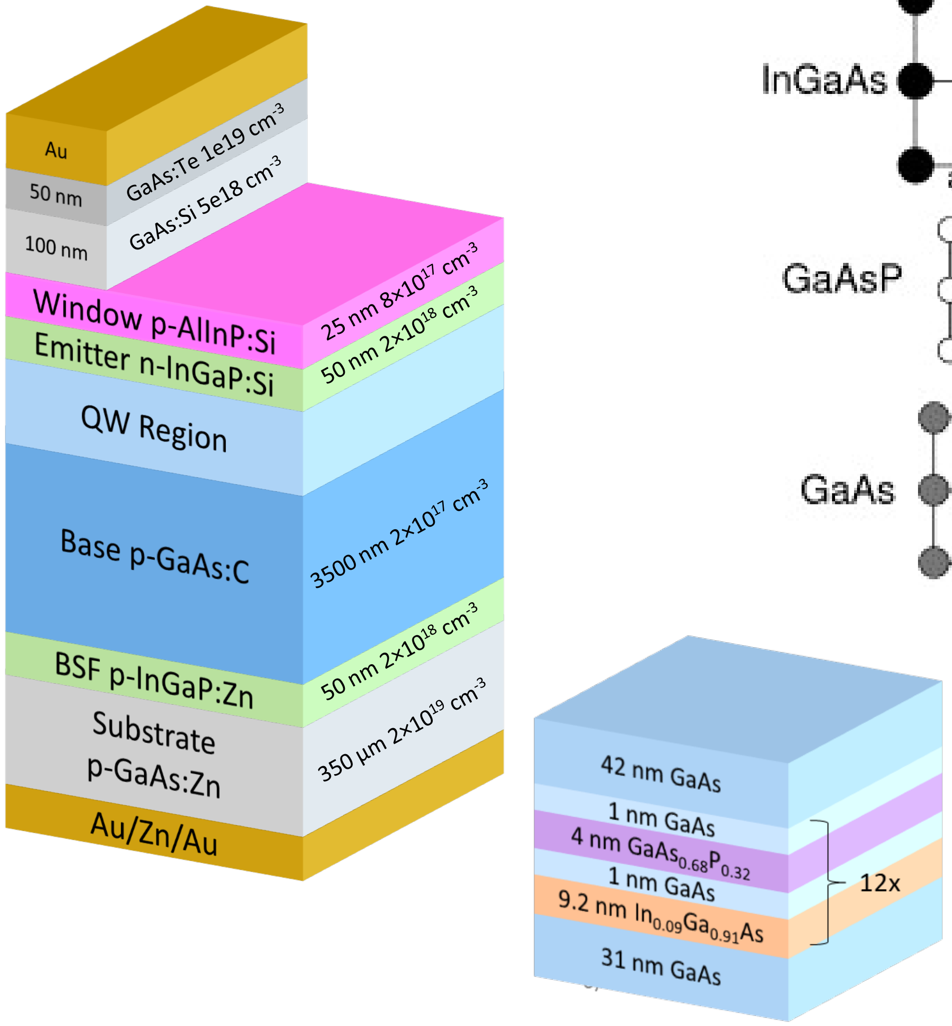


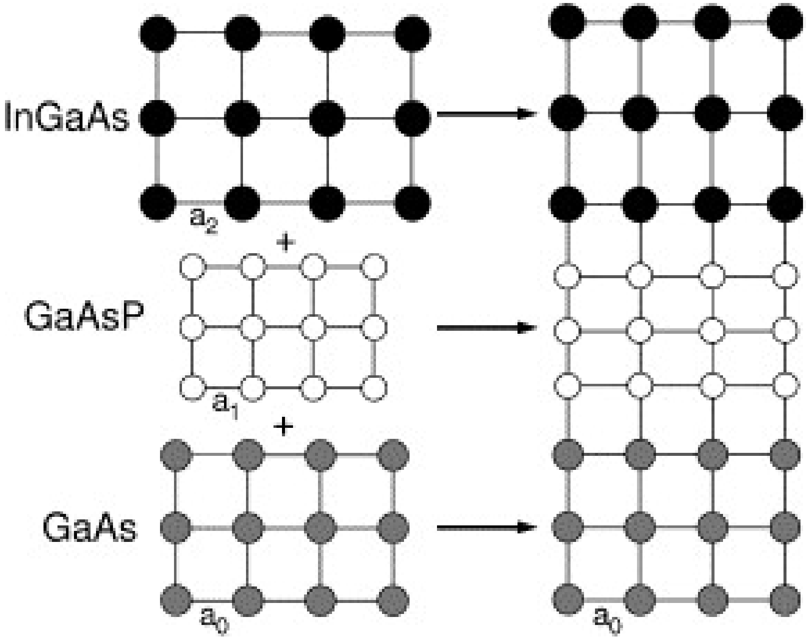


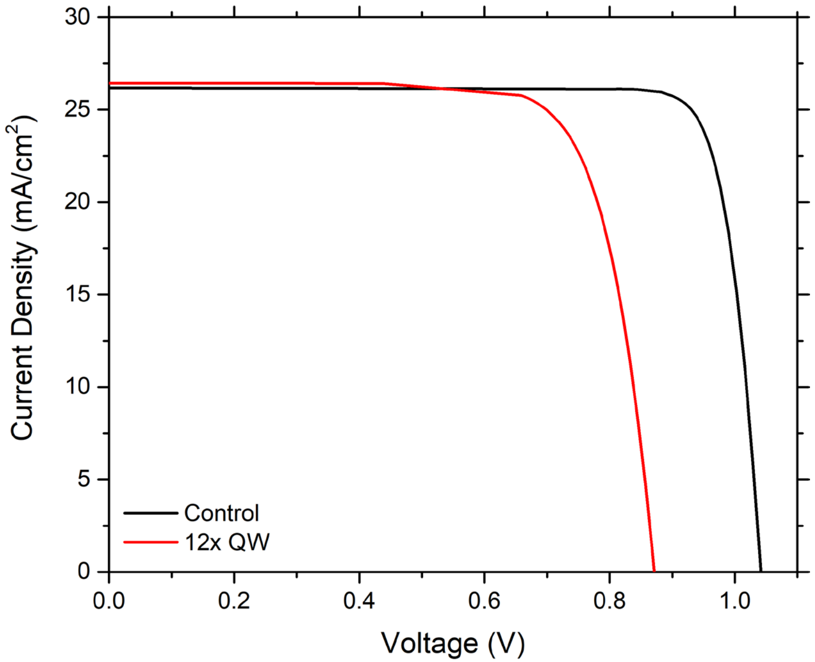
Improved efficiency over control by adding QWs, improving Jsc with minimal loss in Voc

R. E. Welser, S. J. Polly, et al., S. M. Hubbard, *Scientific Reports*, 2019

Adding Strain Compensation





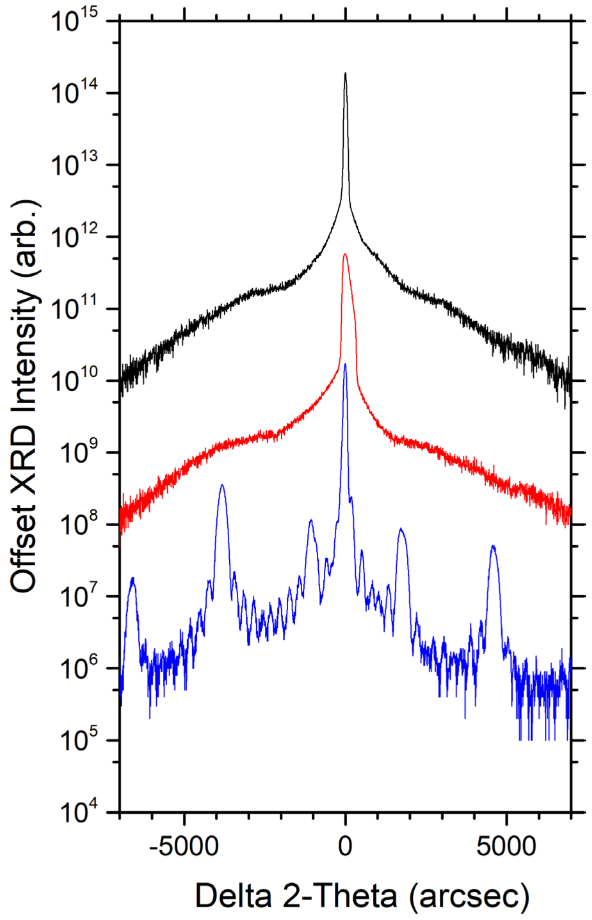


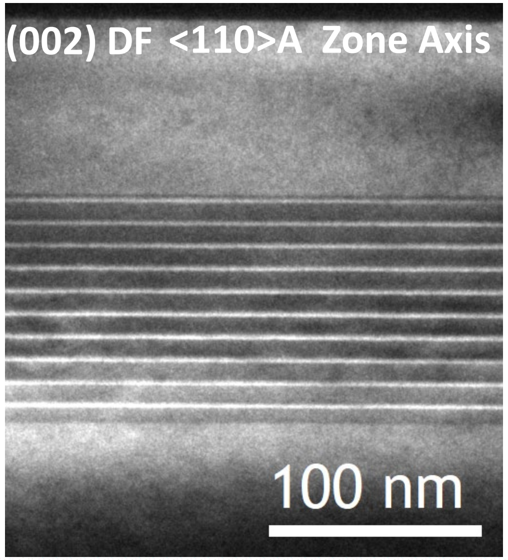
Significant drop in Voc by adding strain compensated QWs

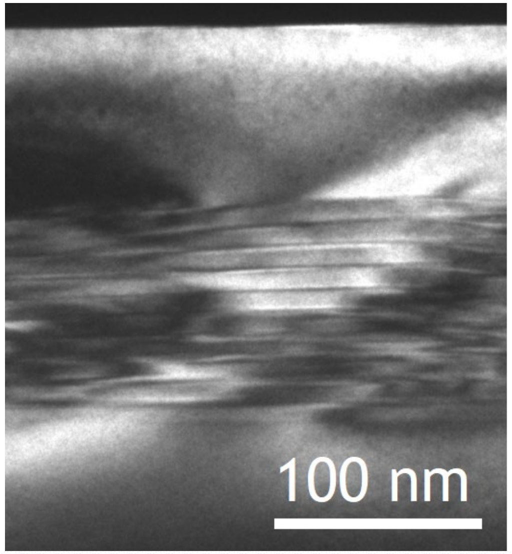
S. J. Polly, et al., *J. Crystal Growth,* 2016

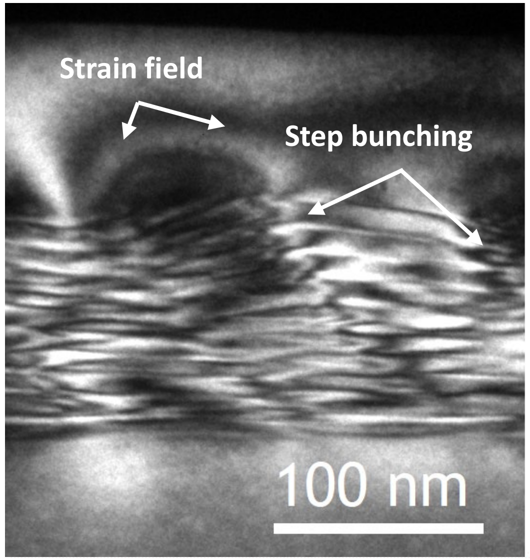
Offcut Effects on QW Growth

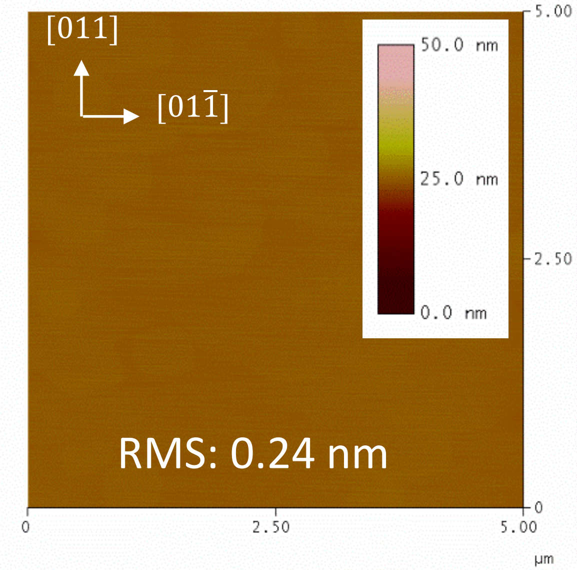
(100) on-axis | (100) 2° <110> | (100) 6° <110>

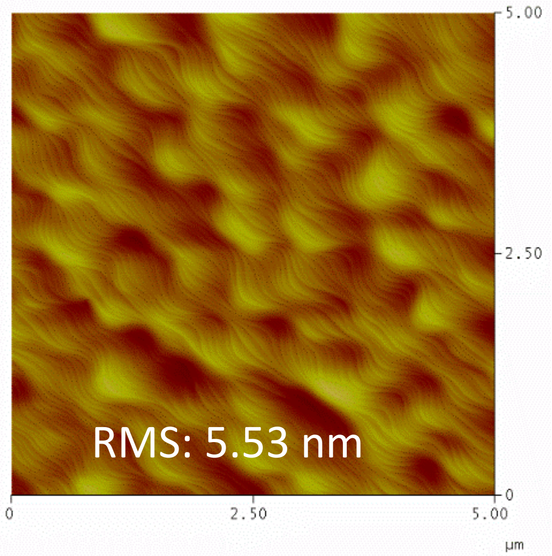


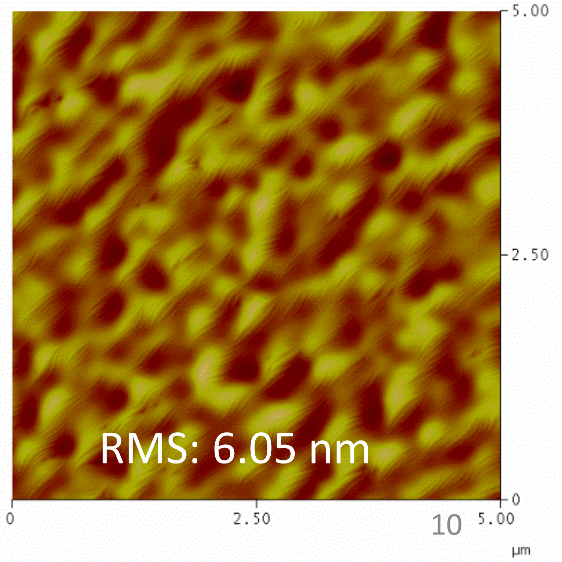




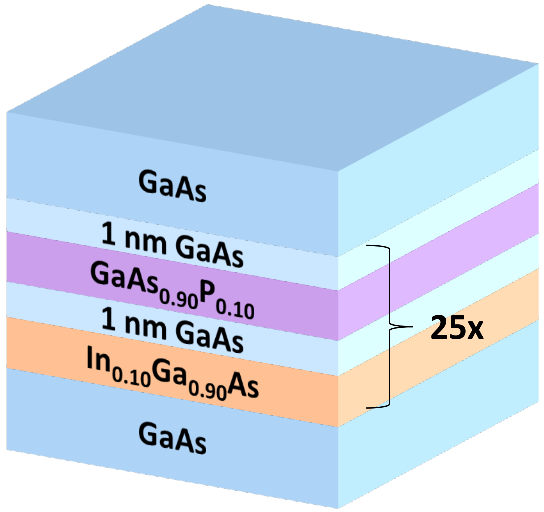








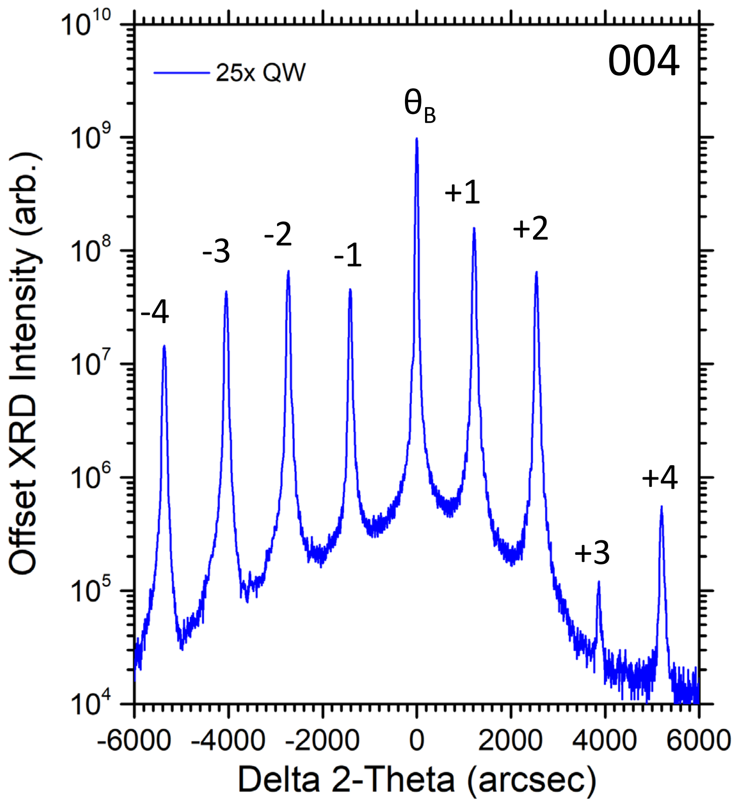
$In_{0.10}Ga_{0.90}As$ / $GaAs_{0.9}P_{0.10}$ Design

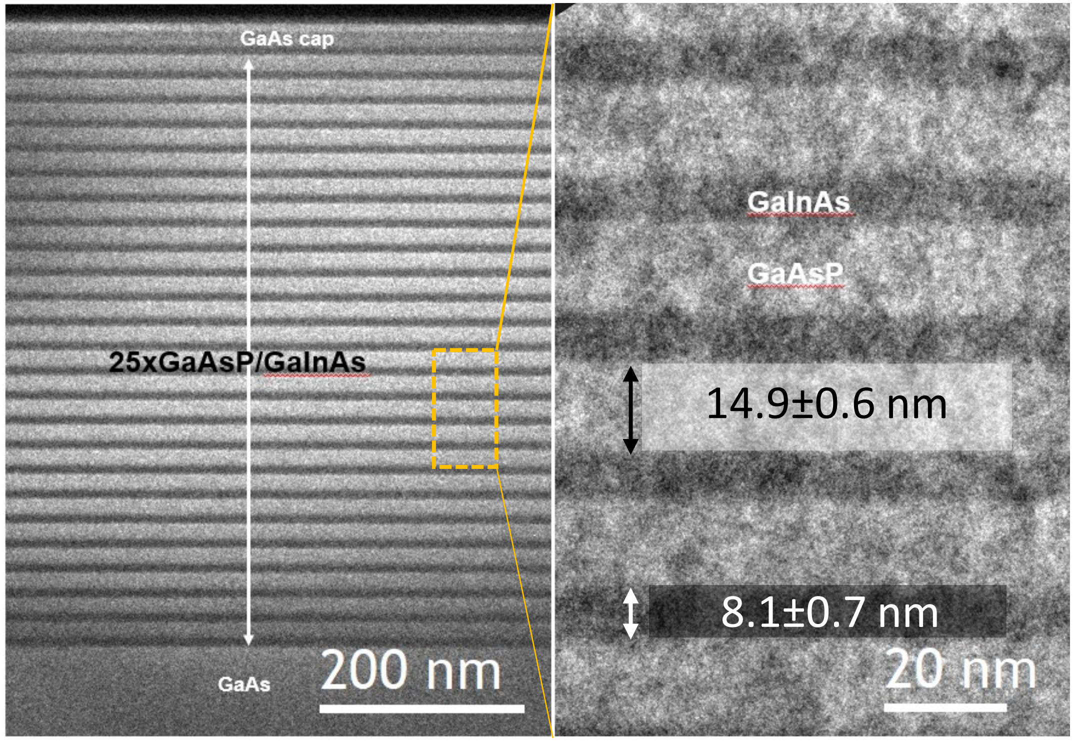


Optimize Growth Flow Sequence to mitigate step bunching

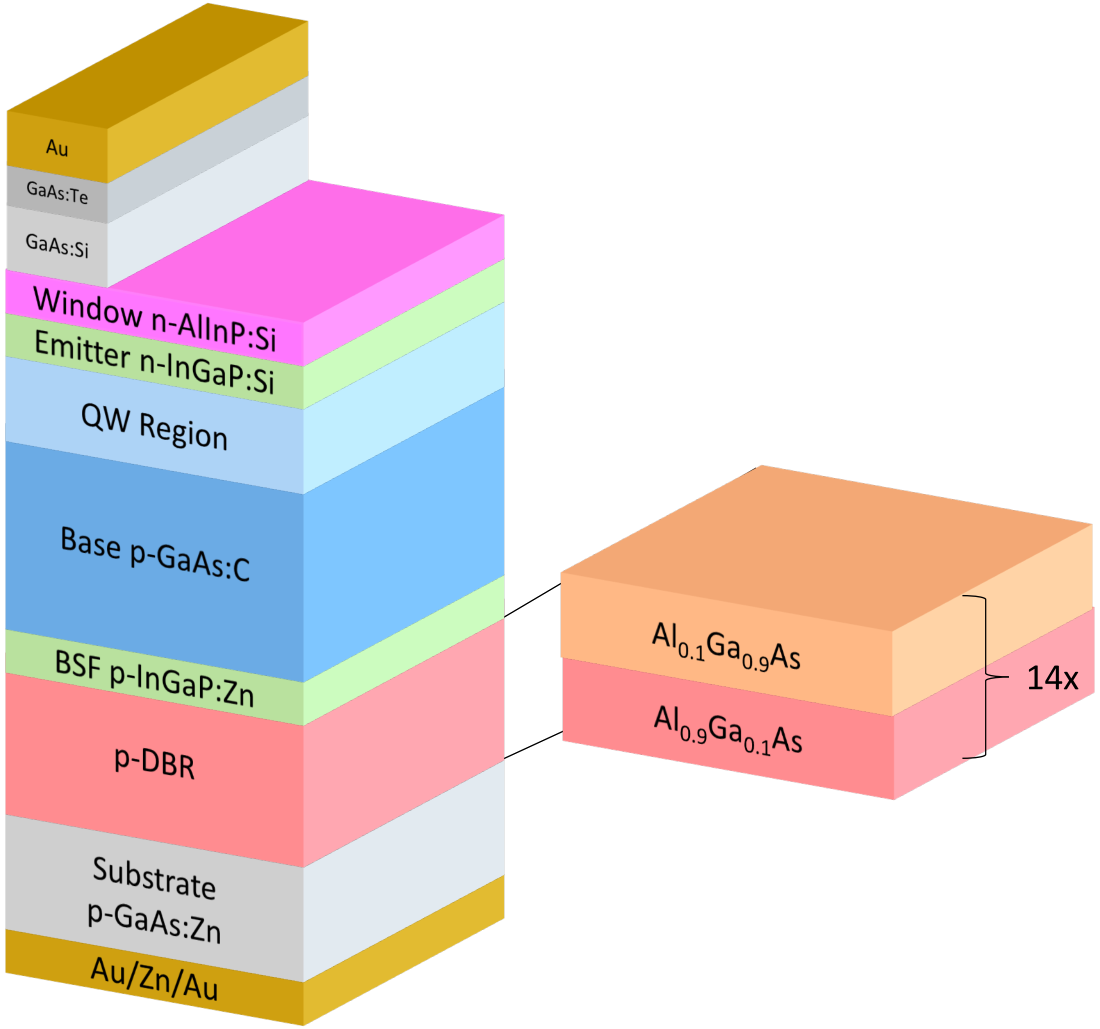
Lower %P in $GaAs_{1-y}P_y$ barriers – lower localized strain at QW/barrier interface

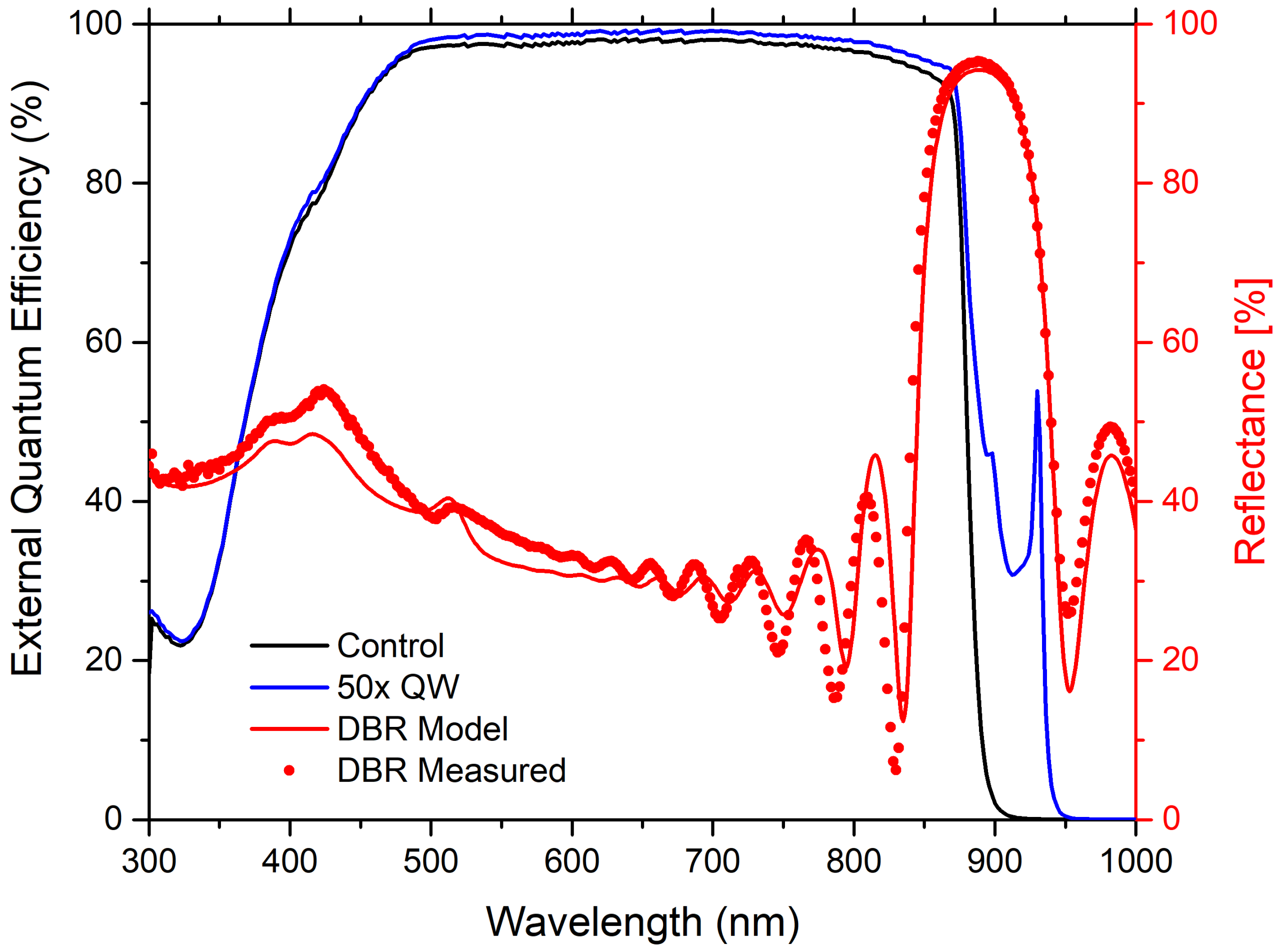
Period: 29.3 ± 0.8 nm
Strain: 340 ± 20 ppm (compressive)



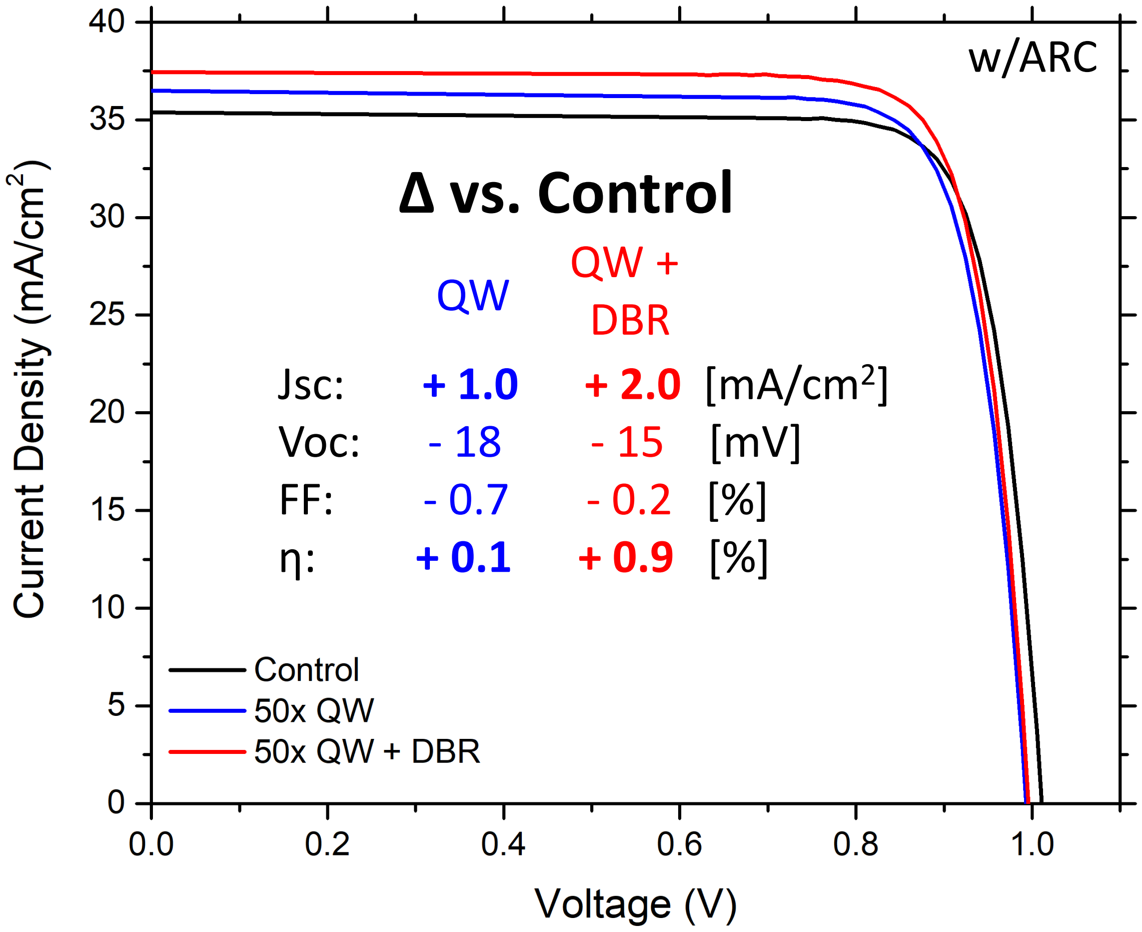


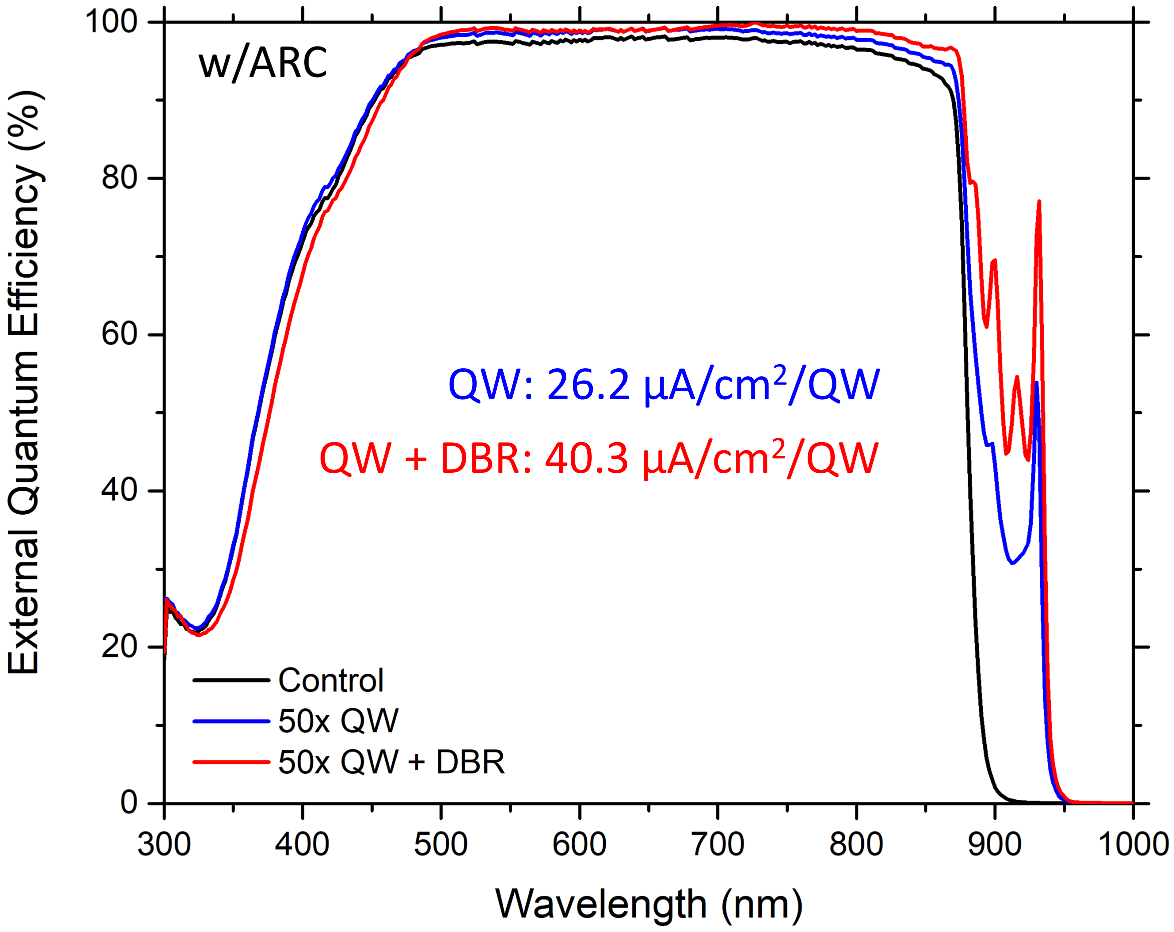
Distributed Bragg Reflectors





50x QW Single Junction

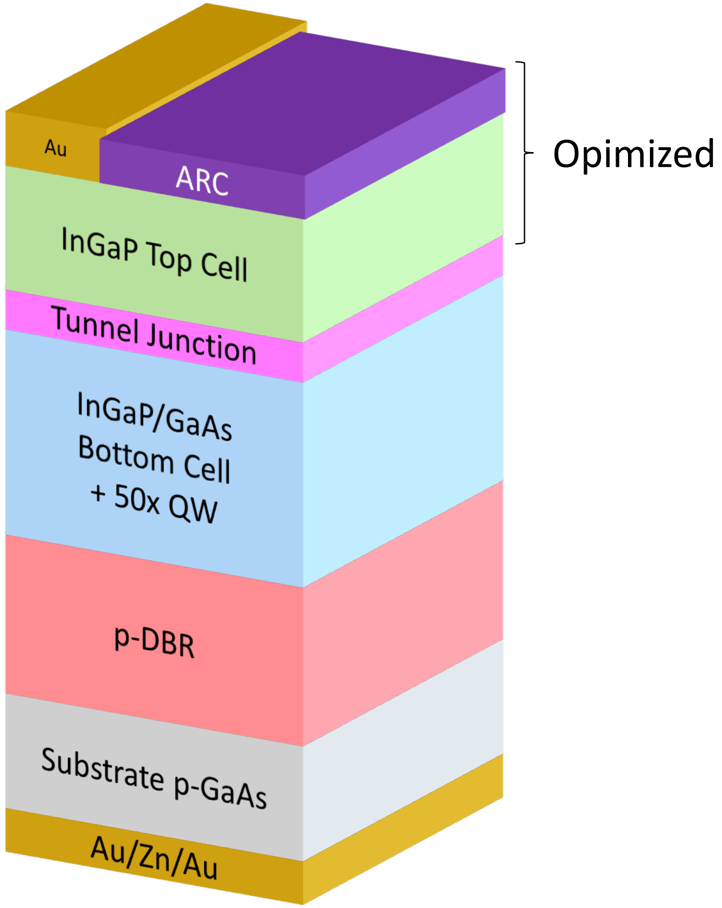


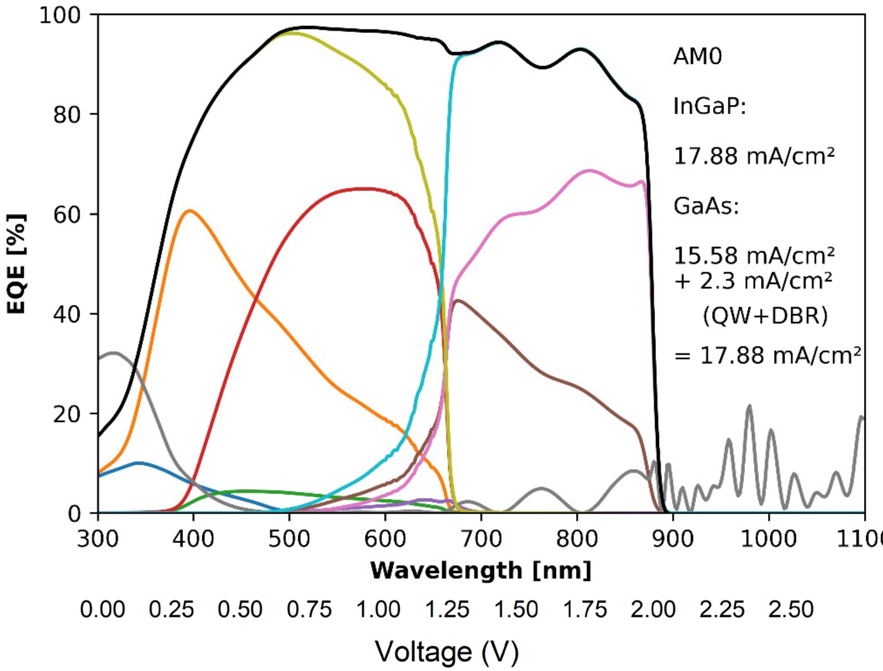


RIT
NanoPower Research Laboratories

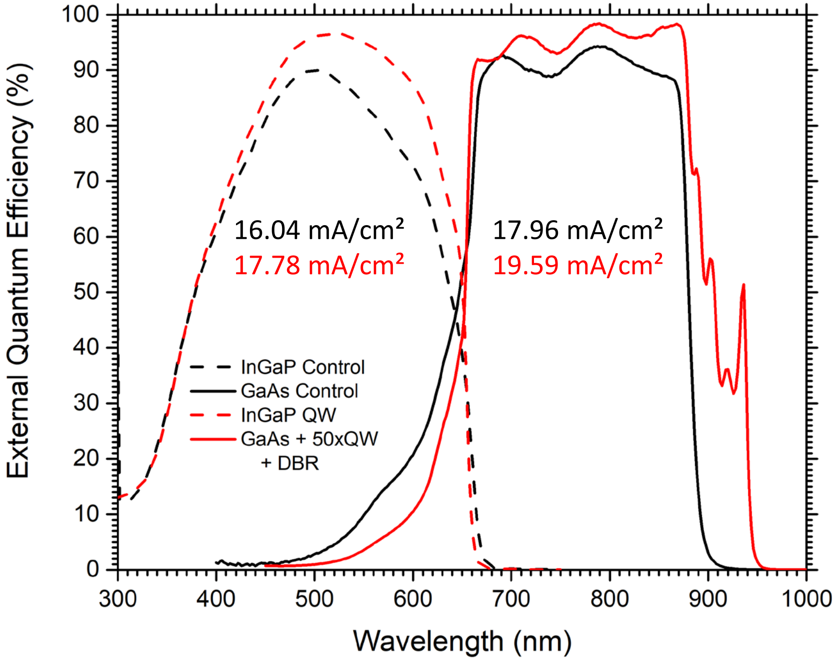
Dual junction results, 50x QW + DBR

SPW
April 25, 2023





AM0

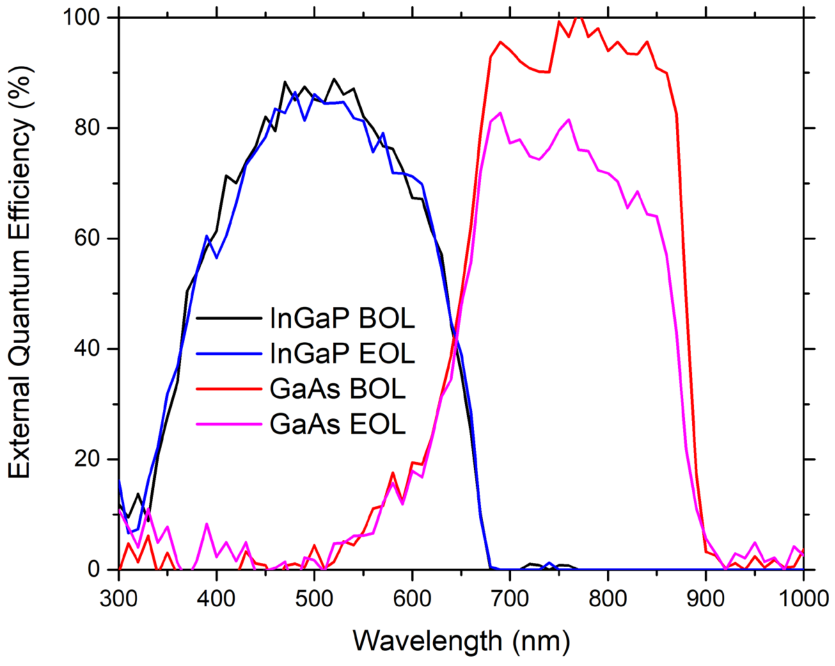


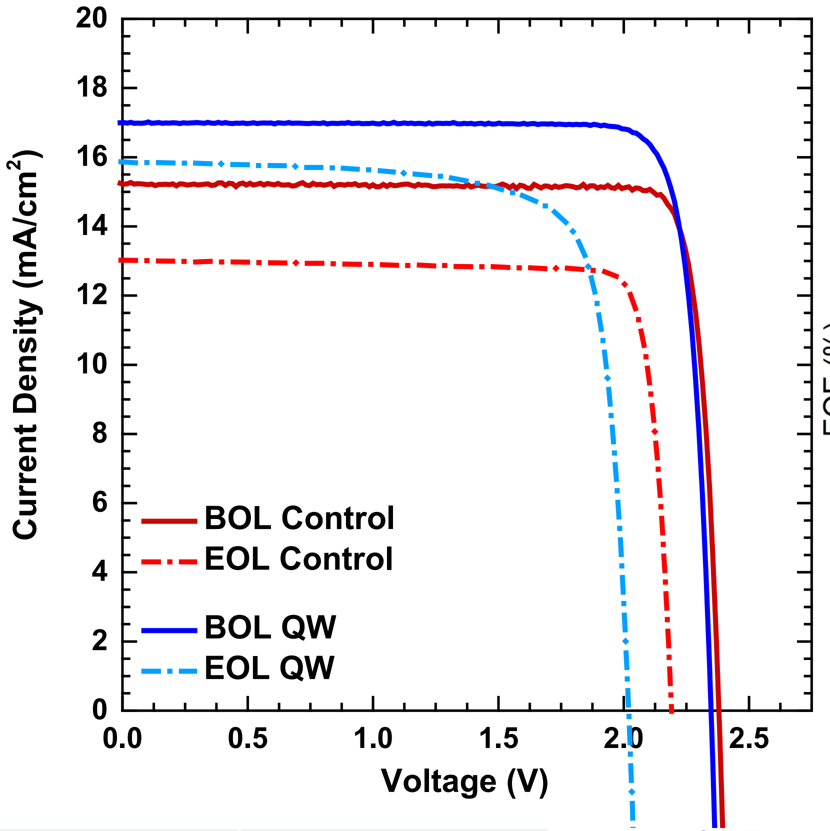
AM0:
23.9% → **27.5%** w/QW
Δ3.6% absolute
11 mV loss from QWs

AM1.5G:
28.5 → **30.3 %** w/QW
Δ1.8% absolute
3 mV loss from QWs

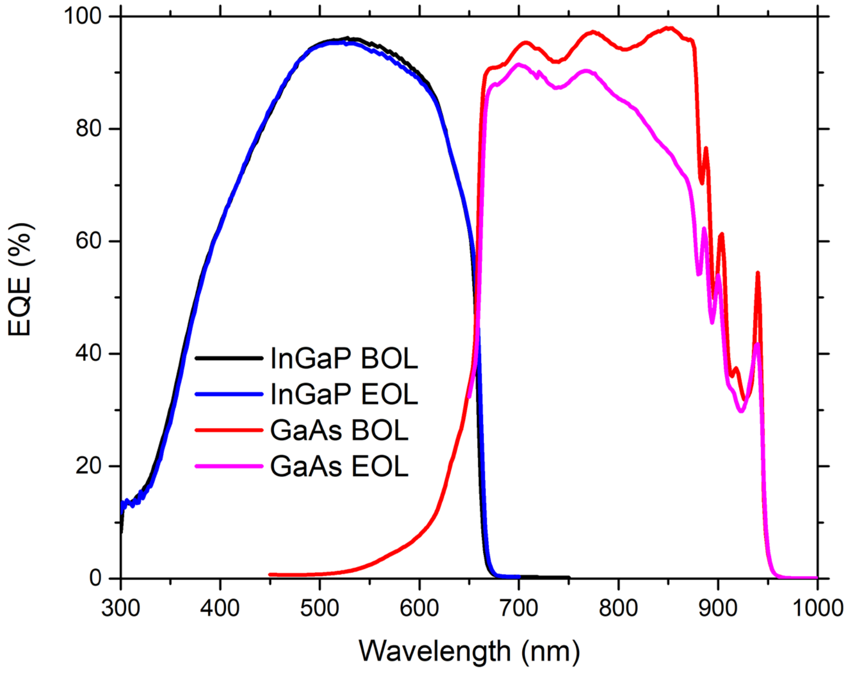
$1x10^{15}$ e^-/cm^2 1 MeV Radiation

Control





50 QWs

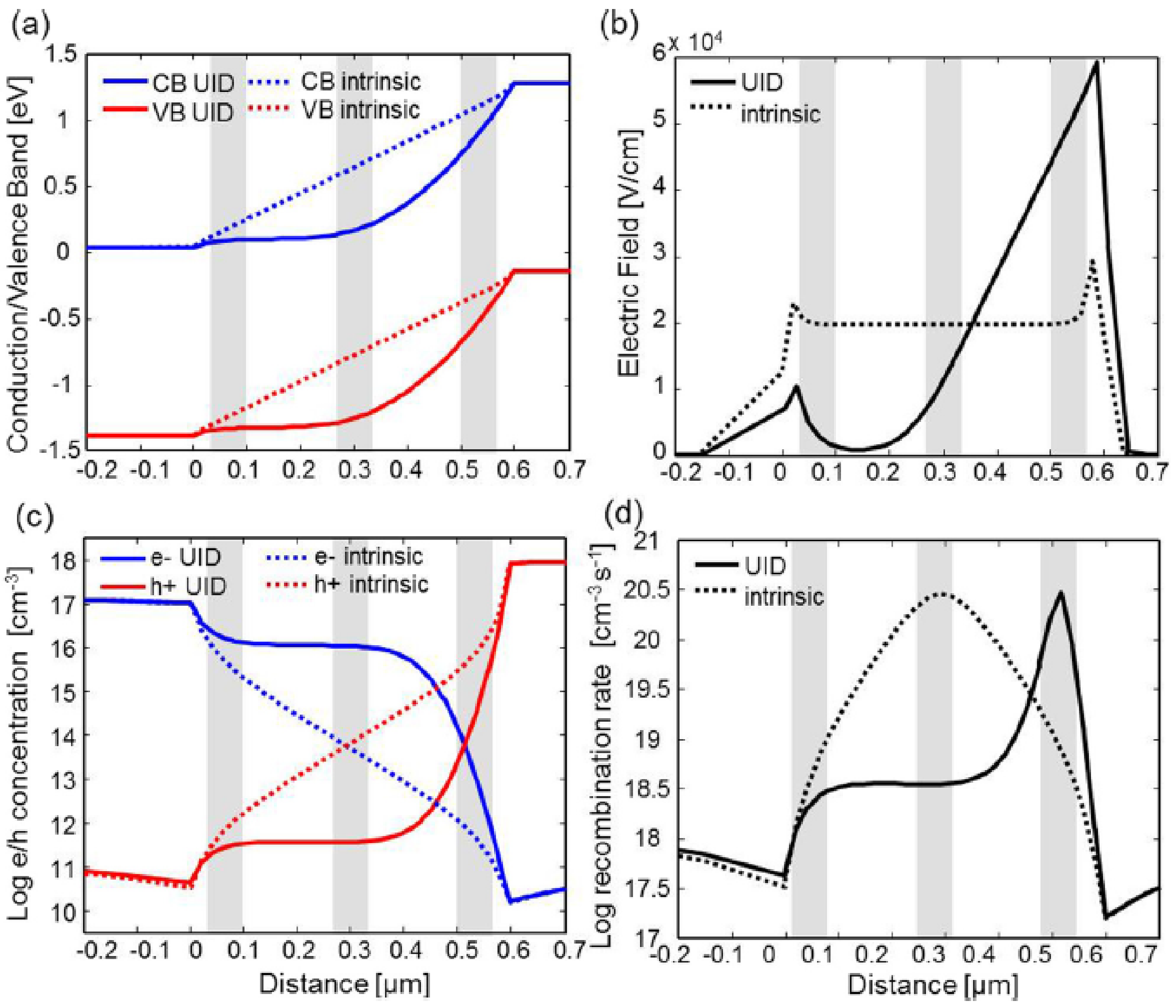


Remaining Factors

	Control	50 QW
Jsc	0.85	**0.93**
Voc	**0.92**	0.86
FF	**0.98**	0.91
Eff	**0.77**	0.73

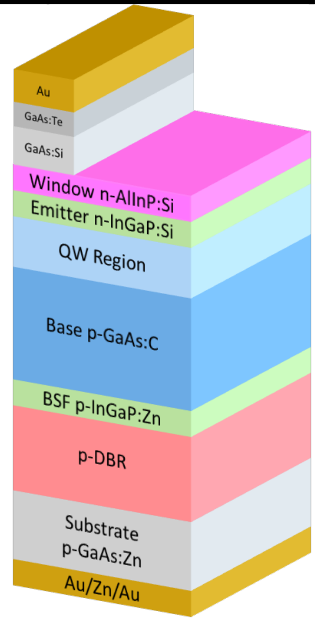
- 1.5 um intrinsic region for 50 QW vs. 200 nm for Control
- Jsc remaining in QW region (880-1000nm) is 91%

Single Junction GaAs Results



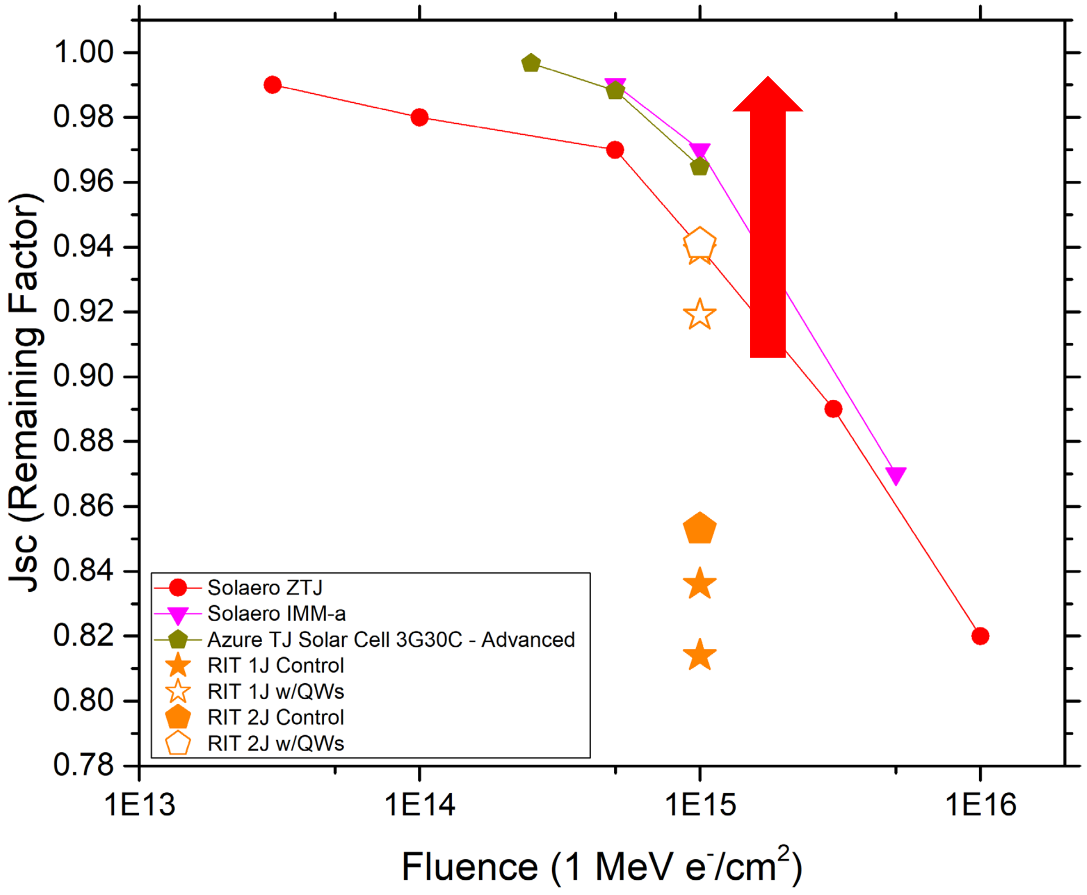
Sample	J_{sc} (mA/cm²)		V_{oc} (V)		FF (%)		η (%)	
	BOL	EOL	BOL	EOL	BOL	EOL	BOL	EOL
	Remaining Factor		Remaining Factor		Remaining Factor		Remaining Factor	
1J Control	35.55	28.95	1.012	0.887	82.0	82.2	21.59	15.45
	81.4%		87.6%		100.2%		71.6%	
50x QW + DBR	37.32	34.31	0.996	0.760	82.6	70.5	22.48	13.46
	91.9%		76.3%		85.4%		59.9%	

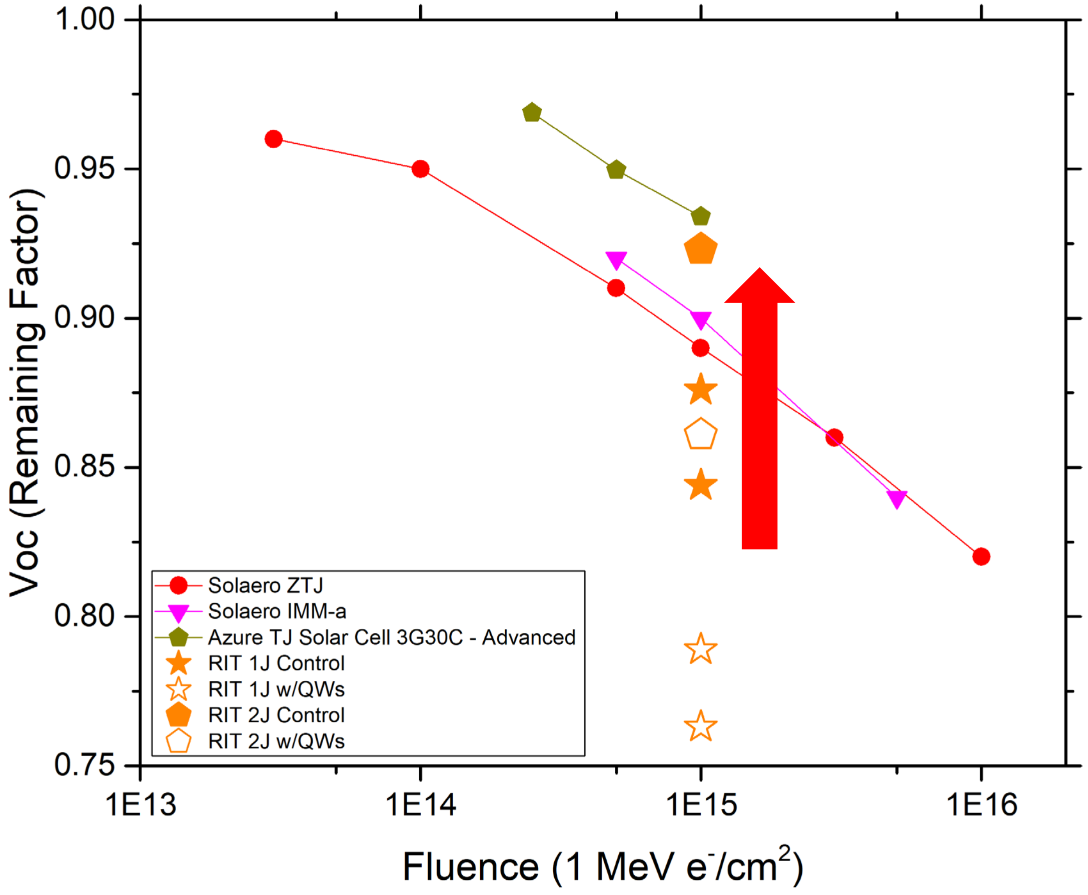
- 1.5 um intrinsic region plus QW improve J_{sc} at EOL
  - Line of sight improvements to 0.98 using more rad-hard designs
- V_{oc} impacted by carrier removal, J_{02}, increased recombination
  - Seen before in QDSC, can be modified by compensation and QW placement
    - K. Driscoll et al. *Applied Physics Letters,* 2014.



RIT
NanoPower Research Laboratories

Comparison of Results

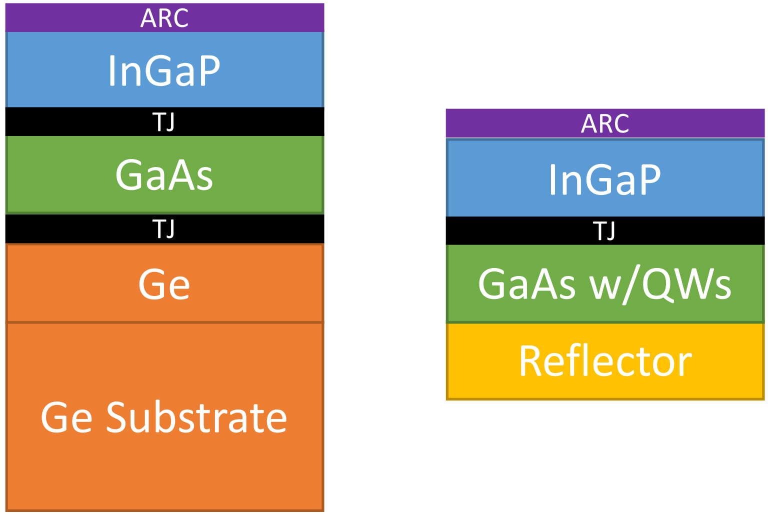




Increase well region, improved radiation hard cell design

QW placement, i-region, doping

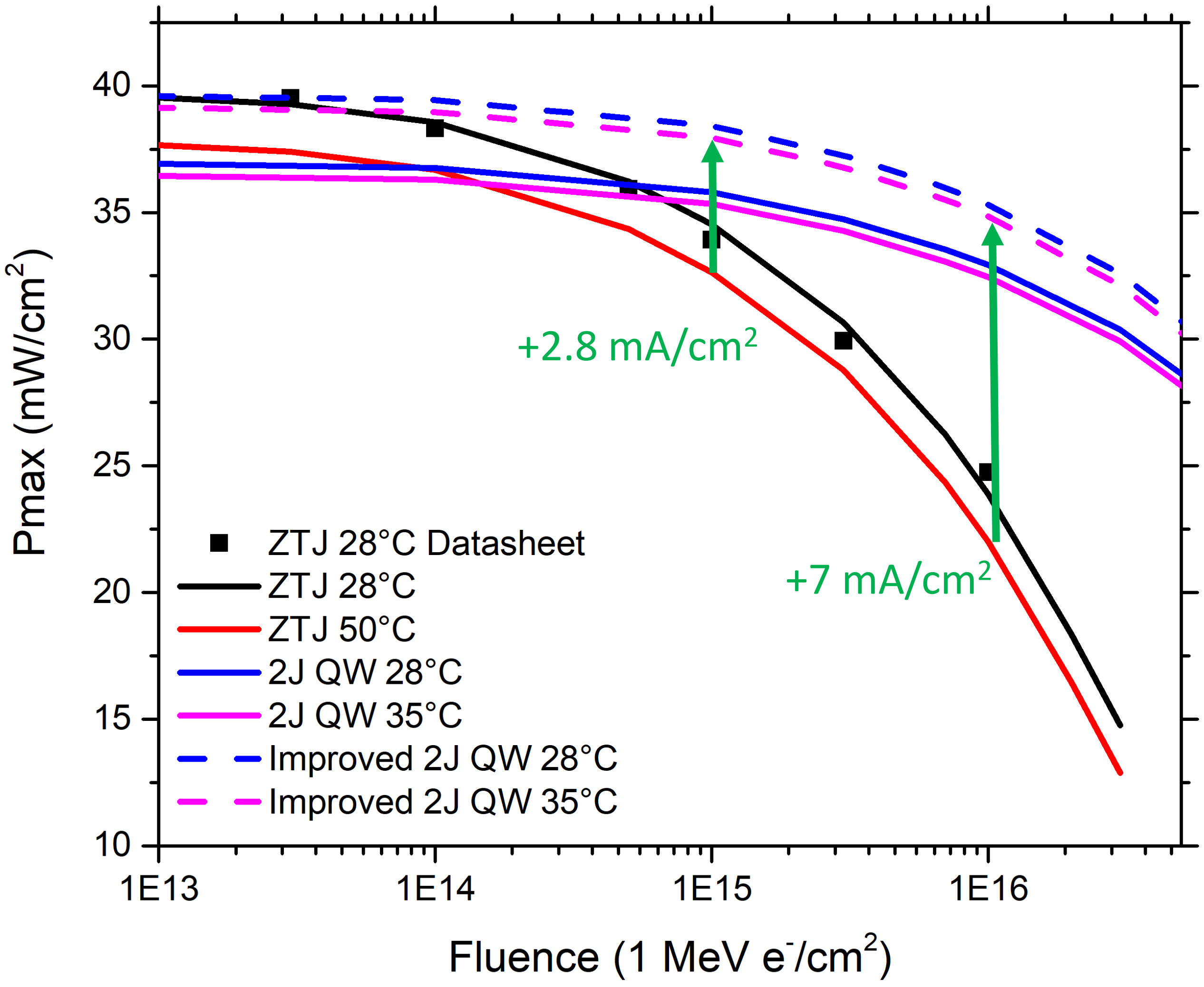
Modeled Temperature Dependence



Back reflector → cooler operation, reflect sub-gap photons

Here, QW devices, exhibiting a smaller Pmax negative temperature than the 3J, runs 15°C cooler terrestrially

Significant increase in operational EOL performance



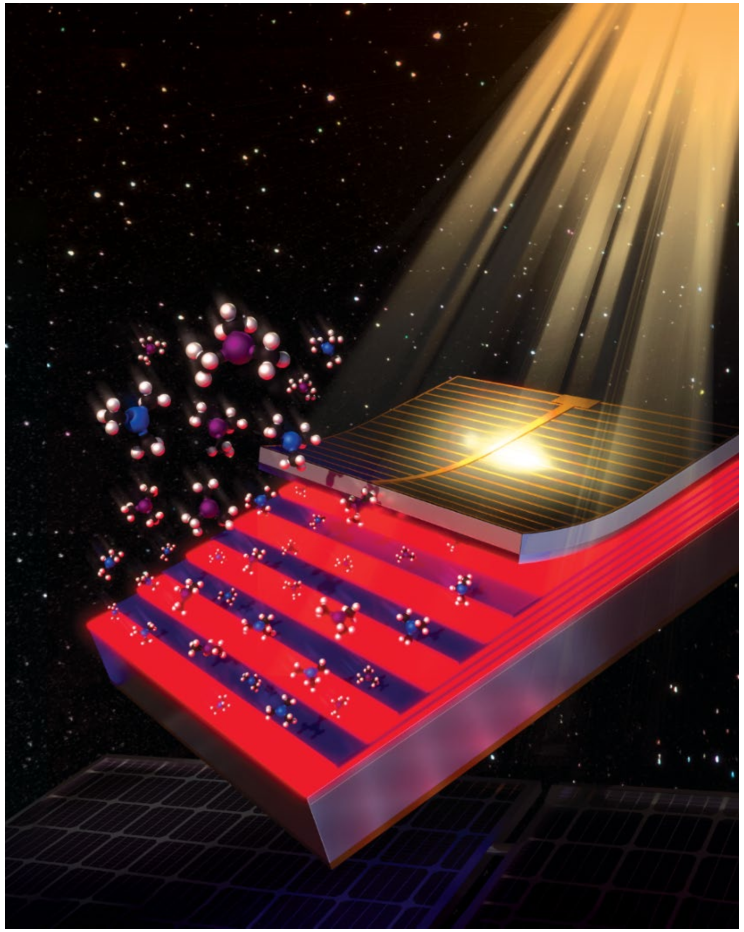
N. P. Irvin, et al., "Thermal Impact of Rear Insulation, Light Trapping, and Parasitic Absorption in Solar Modules," *IEEE JPV*, 12, 2022

RIT NanoPower Research Laboratories

Conclusions and QW Outlook

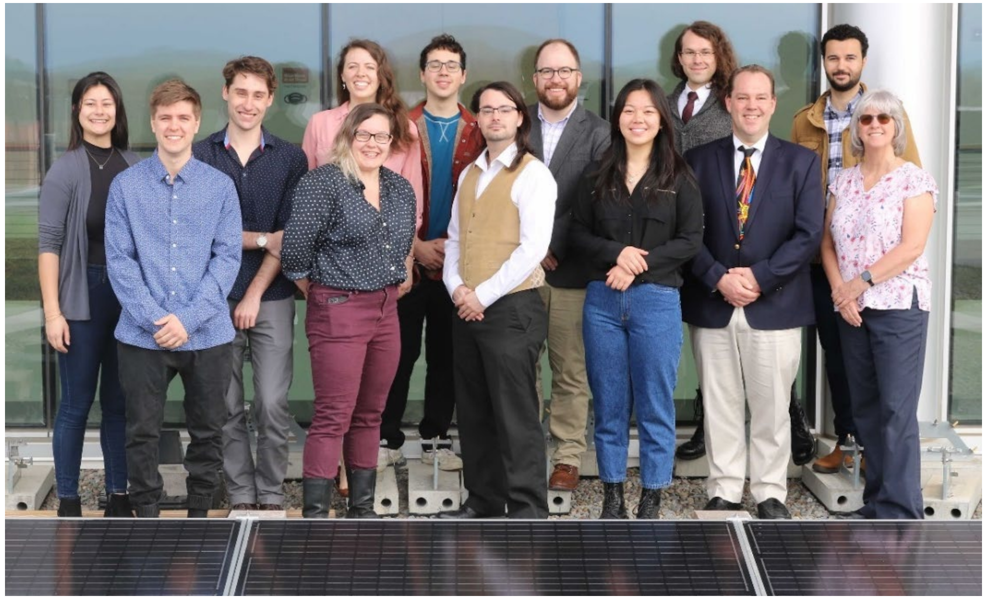
SPW
APRIL 25, 2023

- ✓ Demonstrated 50 pairs of SBQW with 3.6% absolute improved efficiency over a control under AM0 and only 11 mV loss in Voc.
- ✓ QW technology can likely be grown optically thick, thus allowing think and highly doped base
  - ✓ Increase the design space for rad-hard multijunction
- ✓ Bandgap engineering allows realistic potential for 2J QW devices with AM0 efficiency over 30%
- ✓ Potential for 2J QW devices with rear IR rejection, operating at least 15°C cooler than SOA
- ✓ Over full operation life, optimized 2J QW devices could outperform and cost less than incumbent technology



S. J. Polly, et al., *Cell Reports Physical Science*, 2023

Acknowledgements



Roger Welser, Rao Tatavarti
Microlink Devices, Inc.
Nikhil Pokharel, Phil Ahrenkiel
South Dakota School of Mines and Technology
Mitsuru Imaizumi
Japan Aerospace Exploration Agency, Chōfu, Tokyo, Japan
Subhra Chowdhury, Dhrubes Biswas
Magnolia Optical Technologies, Inc., Woburn, Massachusetts

MicroLink Devices, Inc.

MAGNOLIA Optical Technologies, Inc.

AIR FORCE RESEARCH LABORATORY

NASA