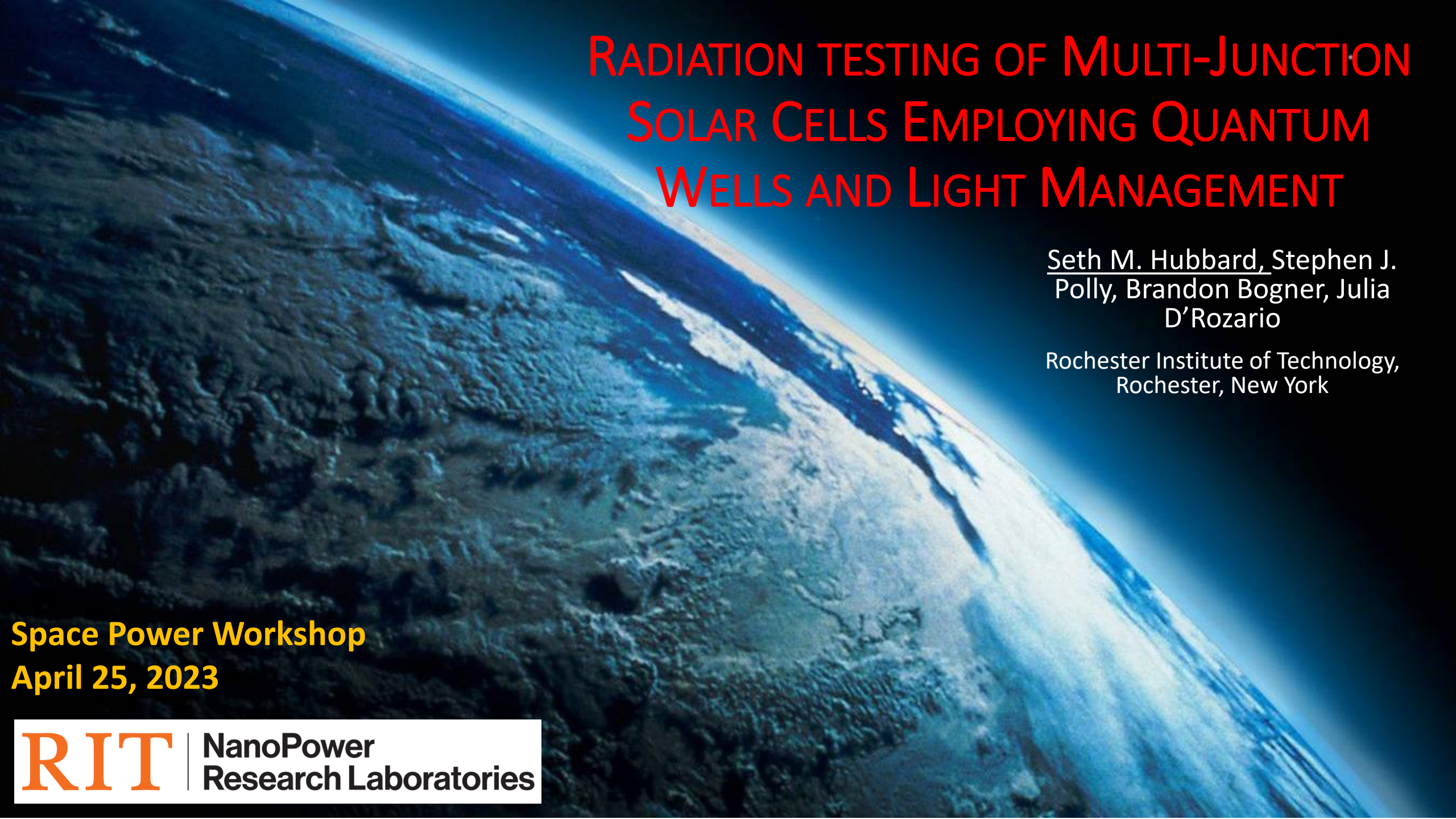

Radiation testing of Multi-Junction Solar Cells Employing Quantum Wells and Light Management

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

Rochester Institute of Technology, Rochester, New York

Space Power Workshop
April 25, 2023

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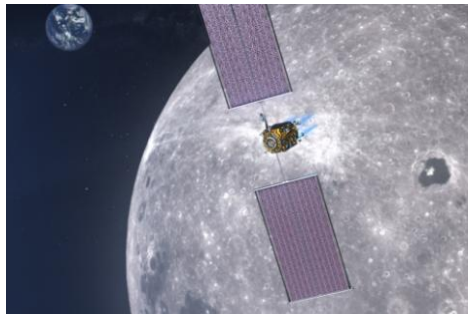
Space and Mobile Power

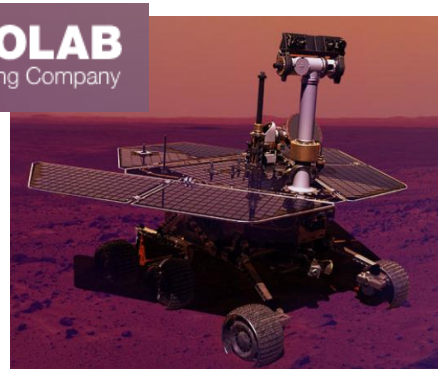
- III-V photovoltaics (PV) are leading power sources for satellites and area/mass constricted systems
- **Constant need for improved efficiency, lower weight, cost and radiation resilience!**

SolAero TECHNOLOGIES



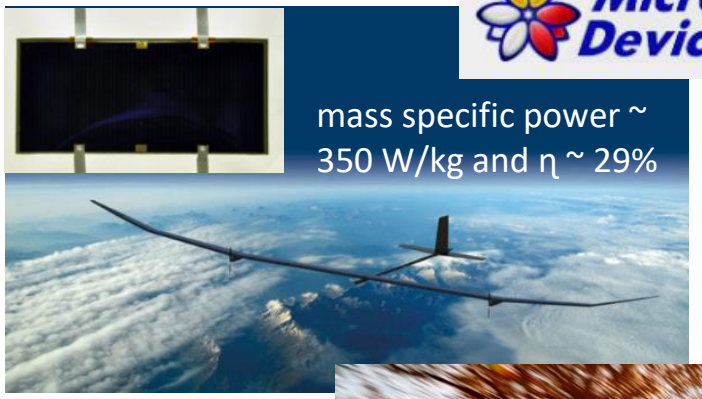


SPECTROLAB
A Boeing Company



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)



Strategies to increase EOL performance

1. Conventional optimization

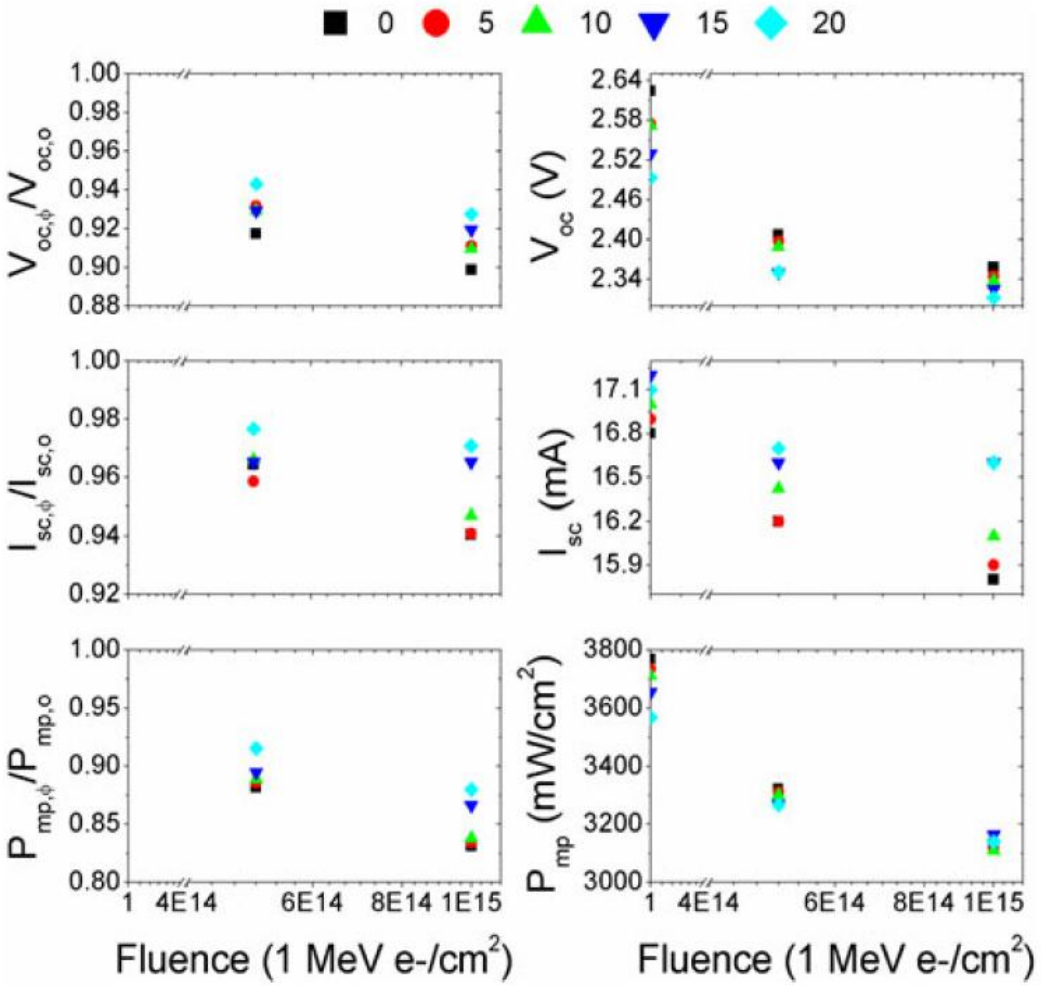
- Doping gradients, disordered InGaP, EoL current matching

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



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Initial Work on Nanostrucutred PV

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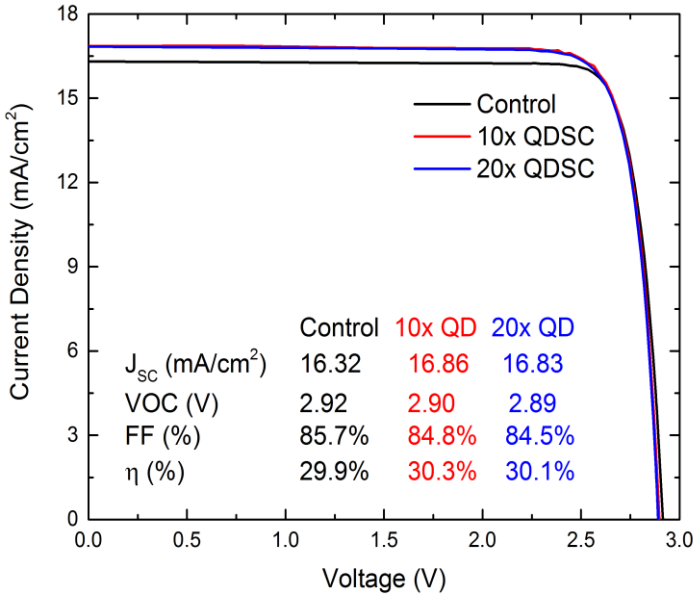
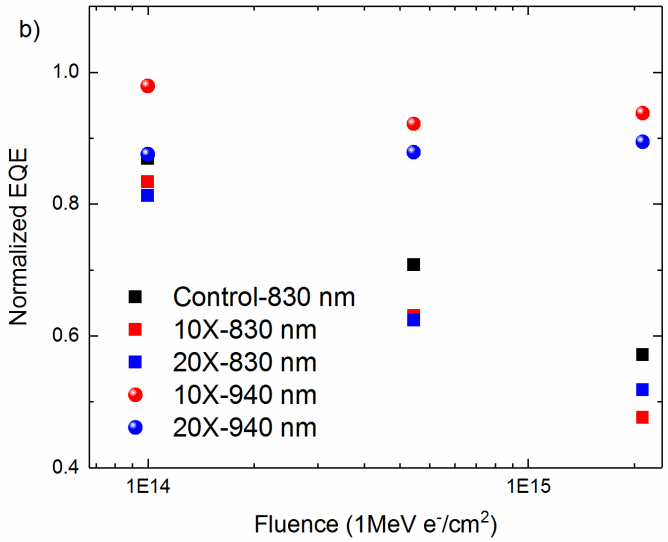
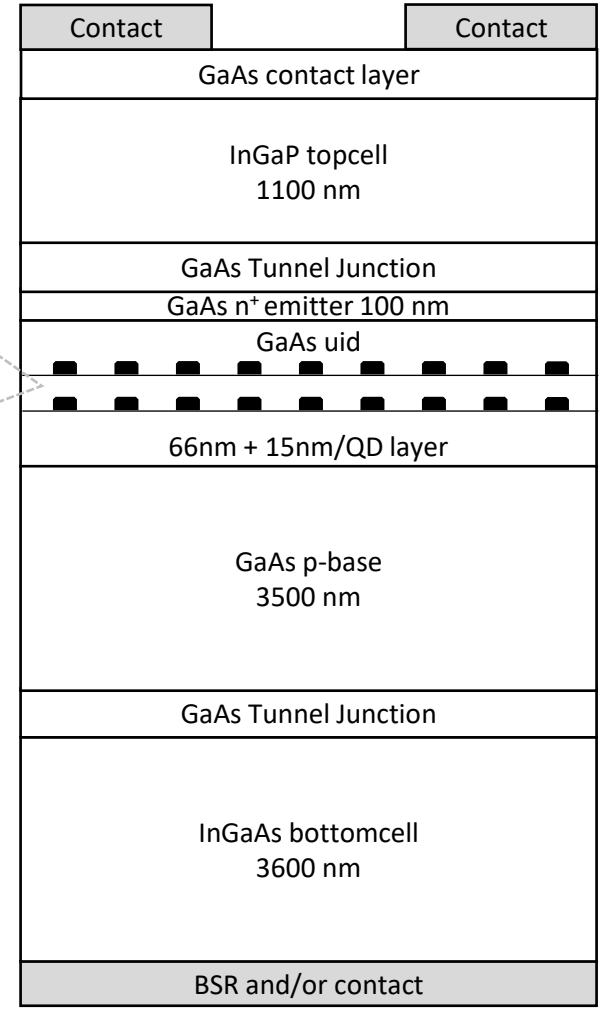
QD provided limited ΔJ_{SC} per layer!
Difficult to stain balance!







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

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Quantum Wells

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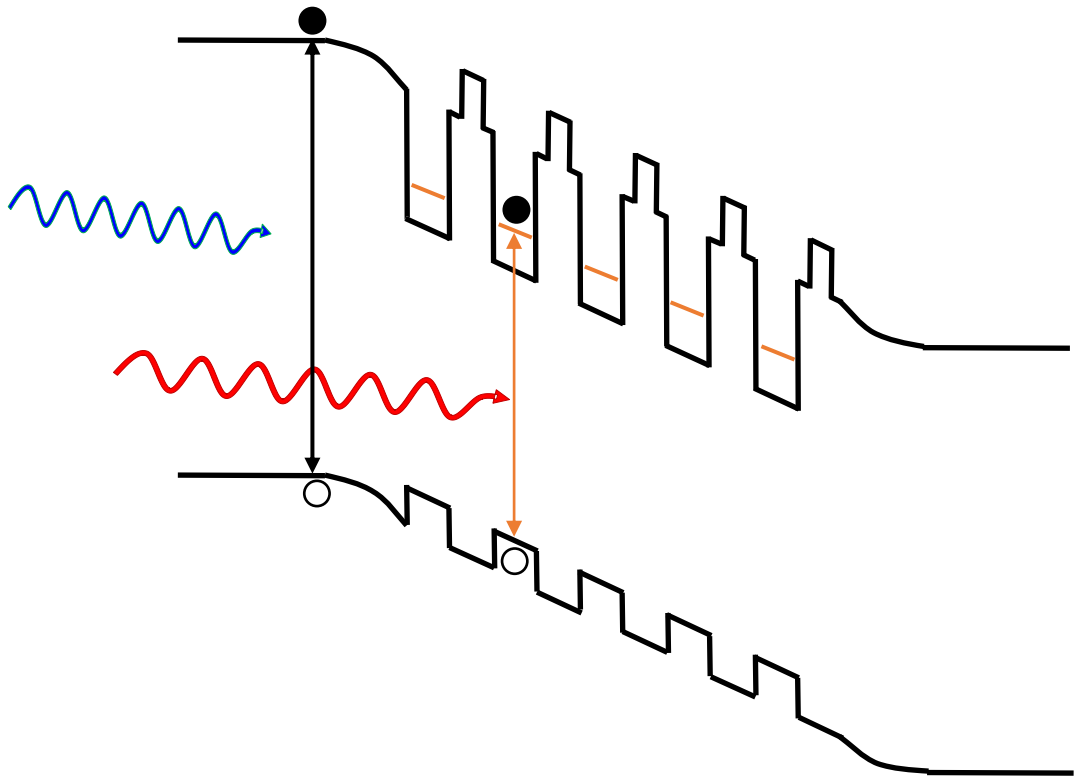

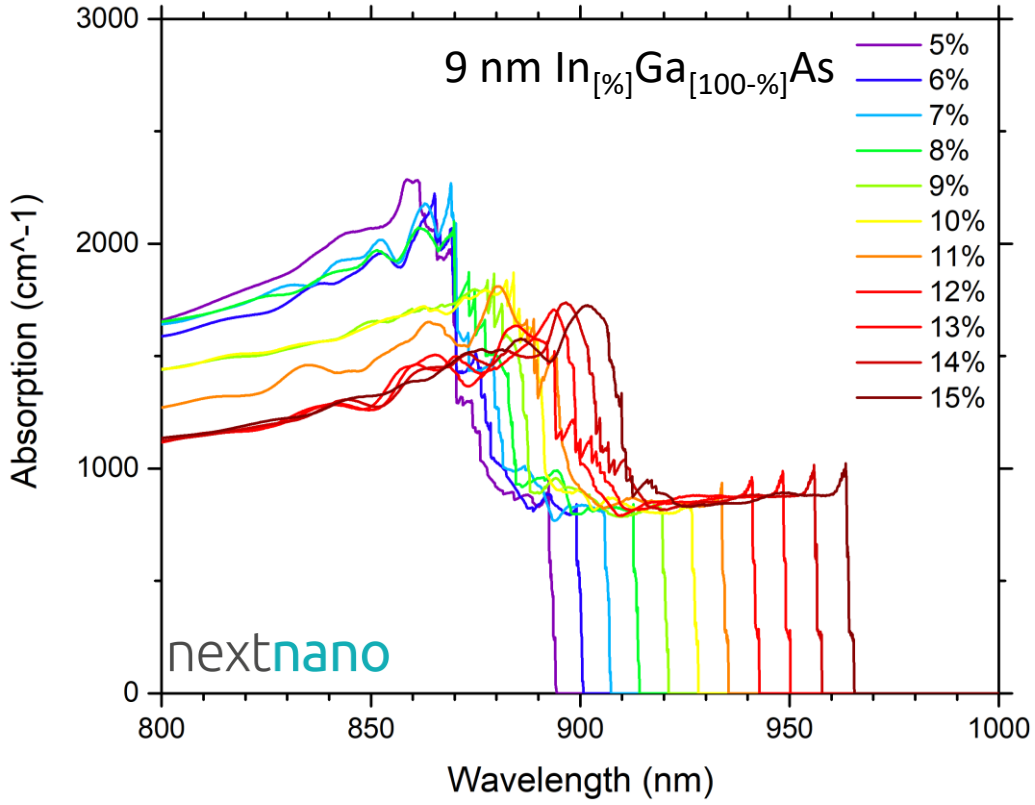

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Dual Junction Model

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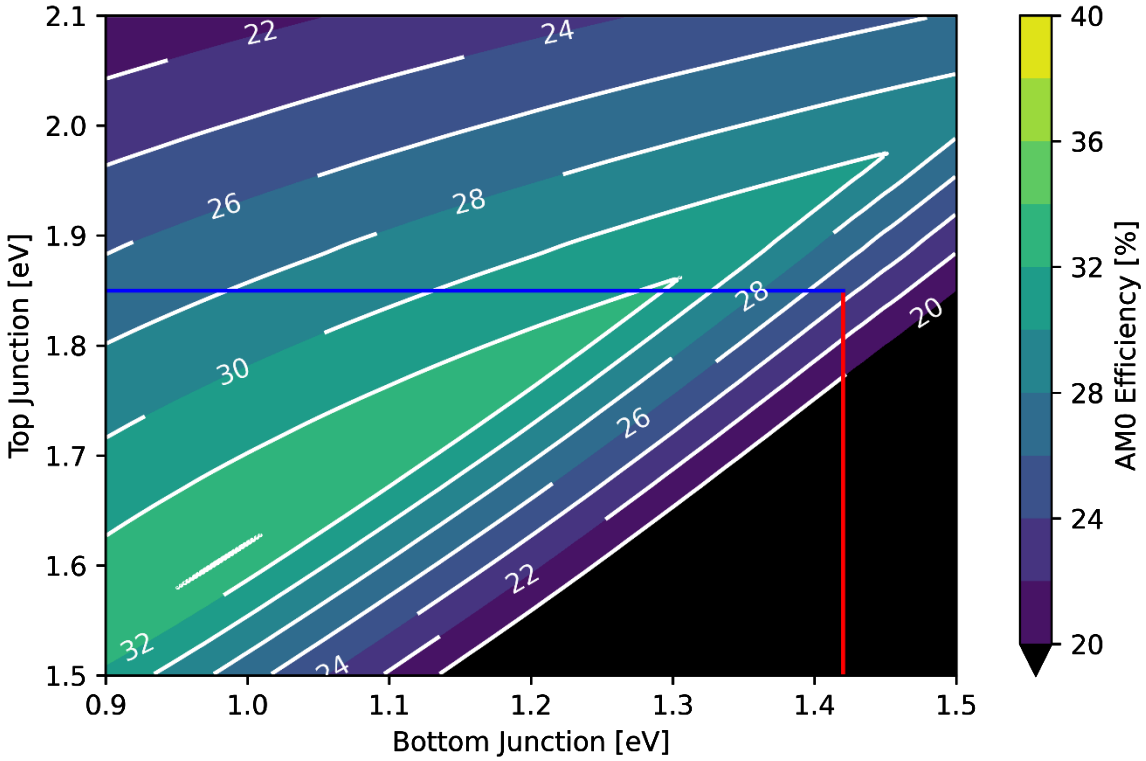
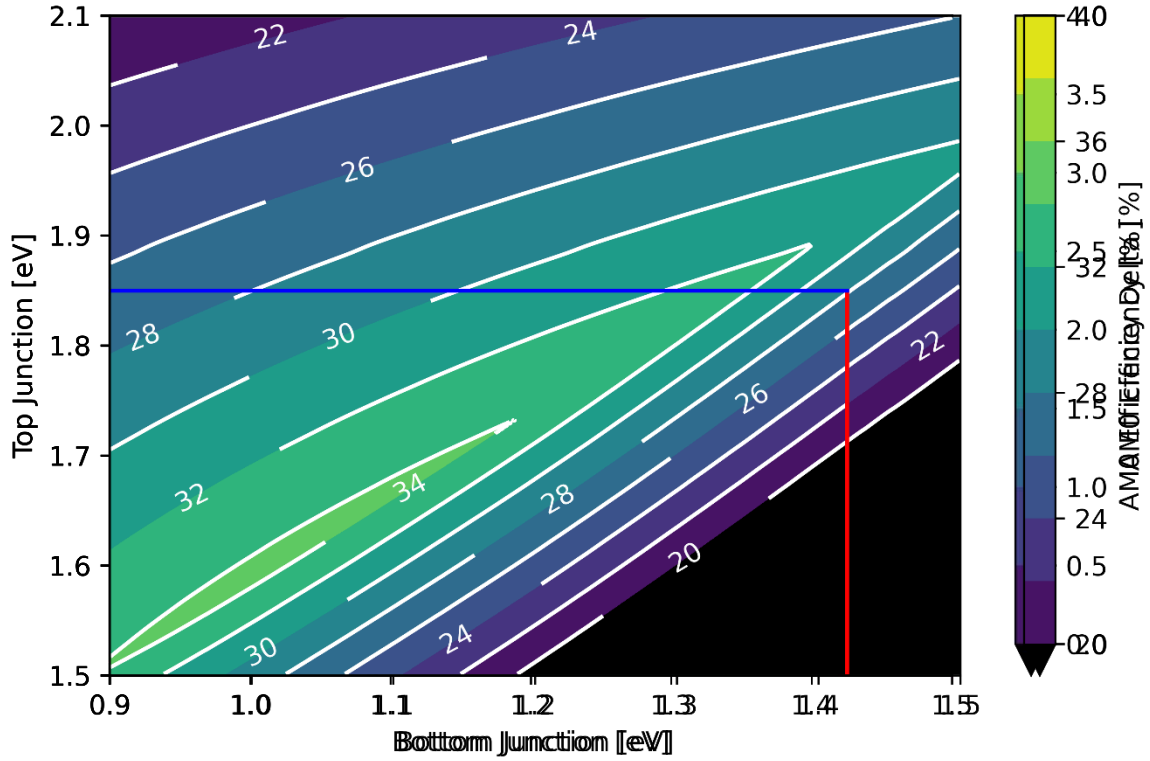
Control without QW



Addition of 2mA using QW



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

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RIT III-V EPICenter

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

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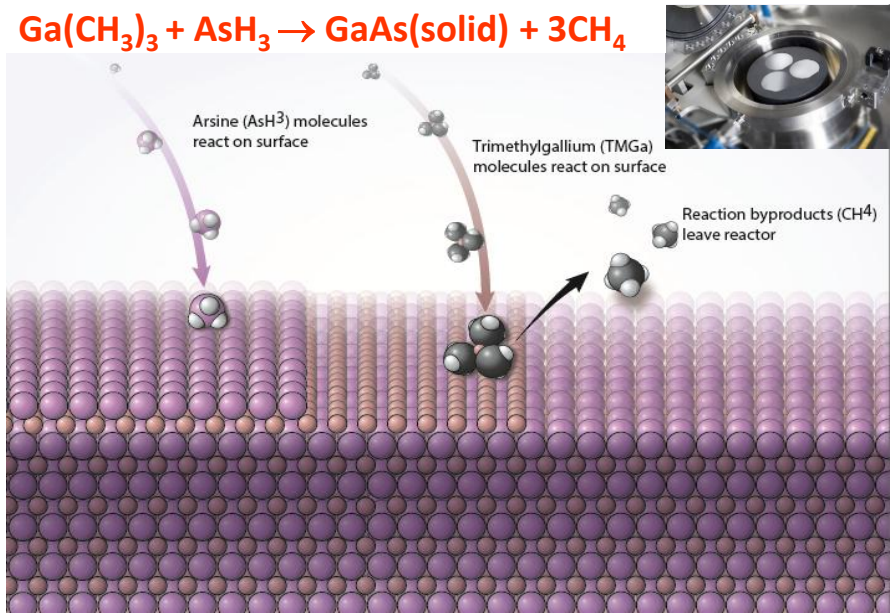
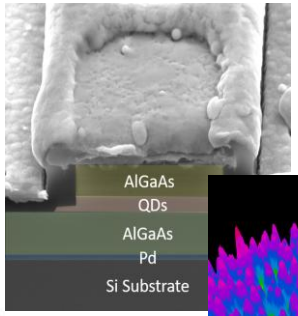
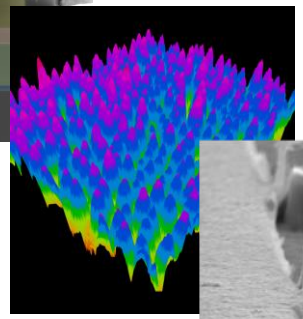
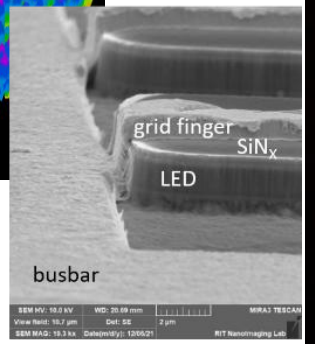
- Rapid prototyping of compound semiconductors Epitaxy of III-V compounds of As, P and Sb
  - Close Coupled Showerhead (CCS) MOCVD
    - 3x2”, 1x3” and 1x4” capability
  - In-situ diagnostics: temperature, stress, strain and surface roughness
  - Full complement of ex-situ characterization tools and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

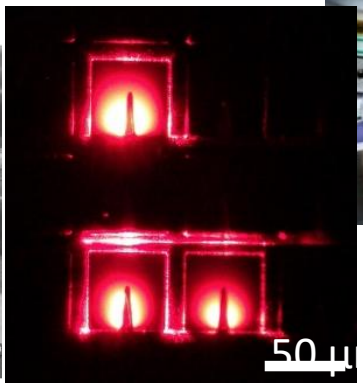














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Strained Quantum Wells

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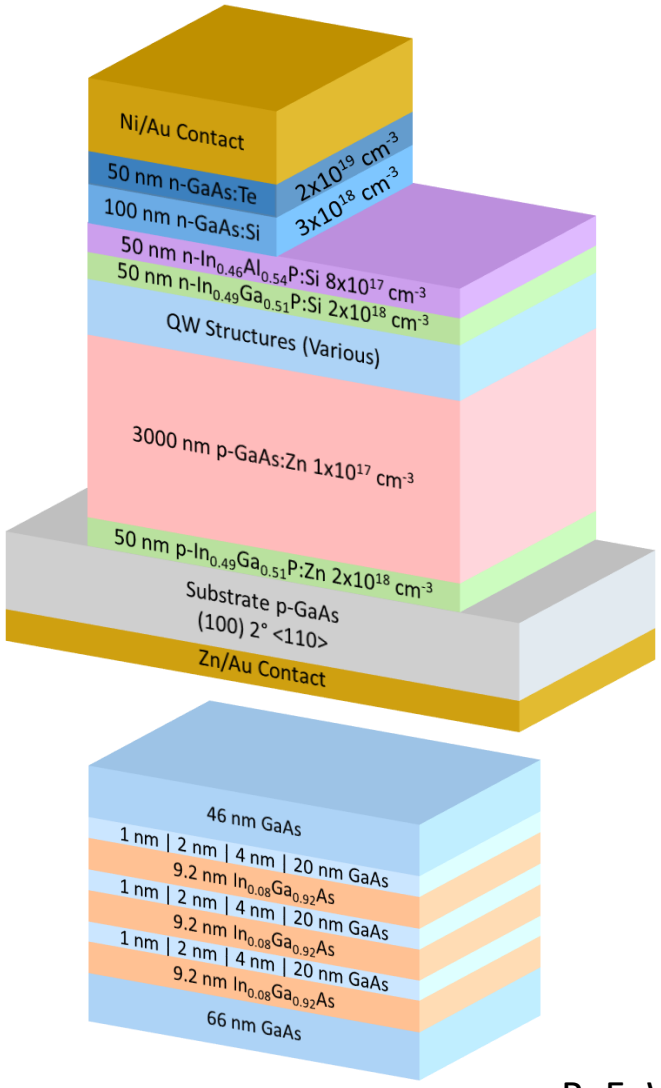
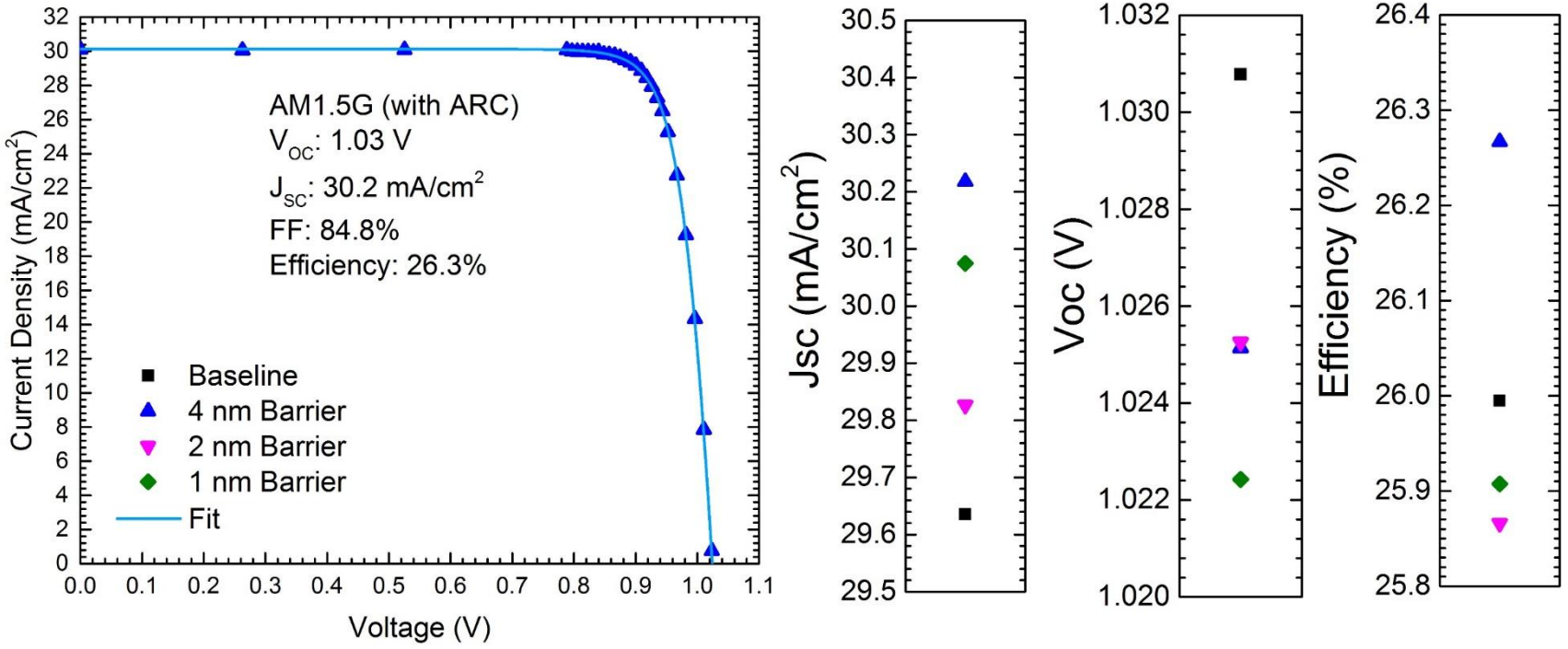
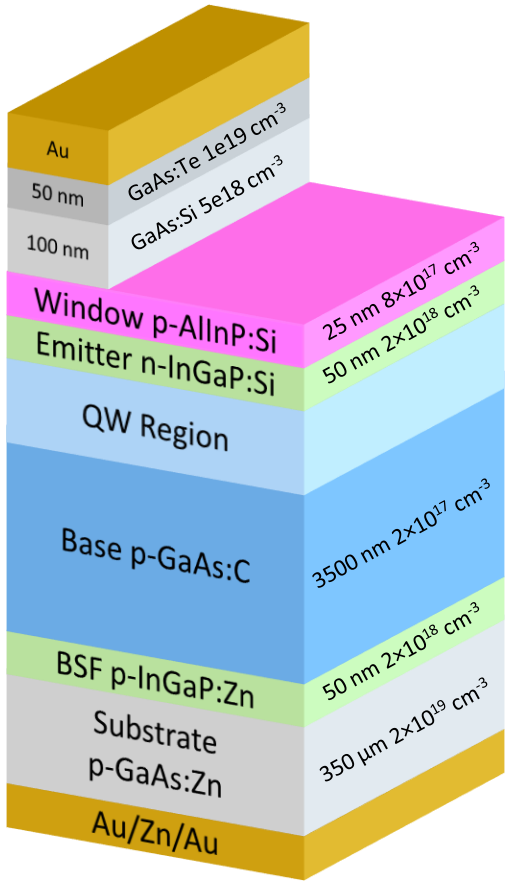


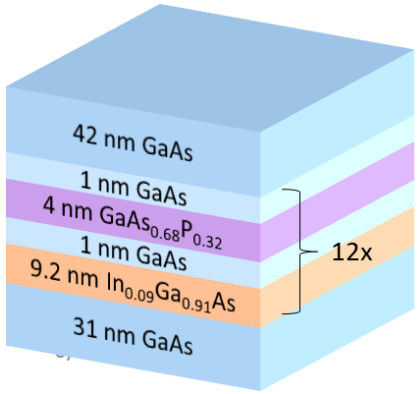


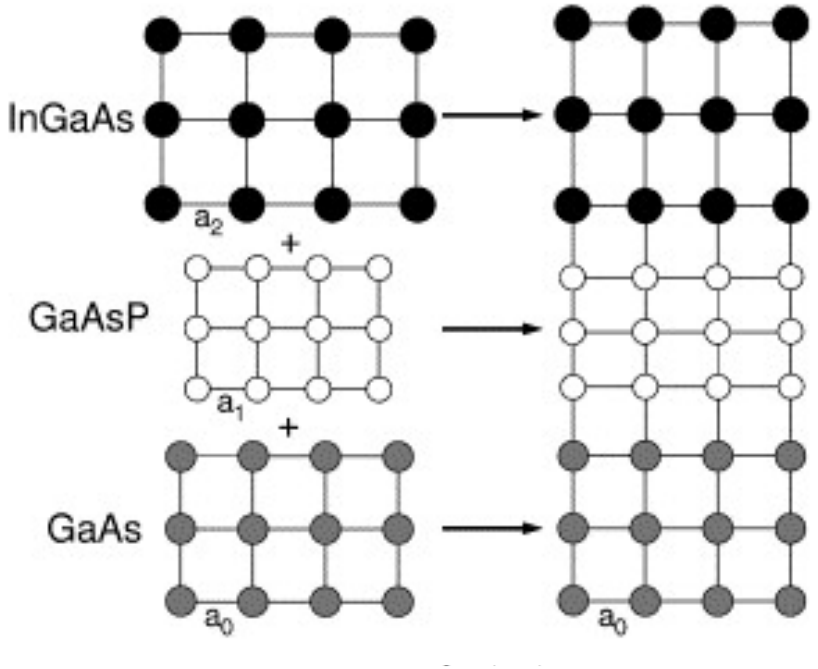
Improved efficiency over control by adding QWs, improving Jsc with minimal loss in Voc

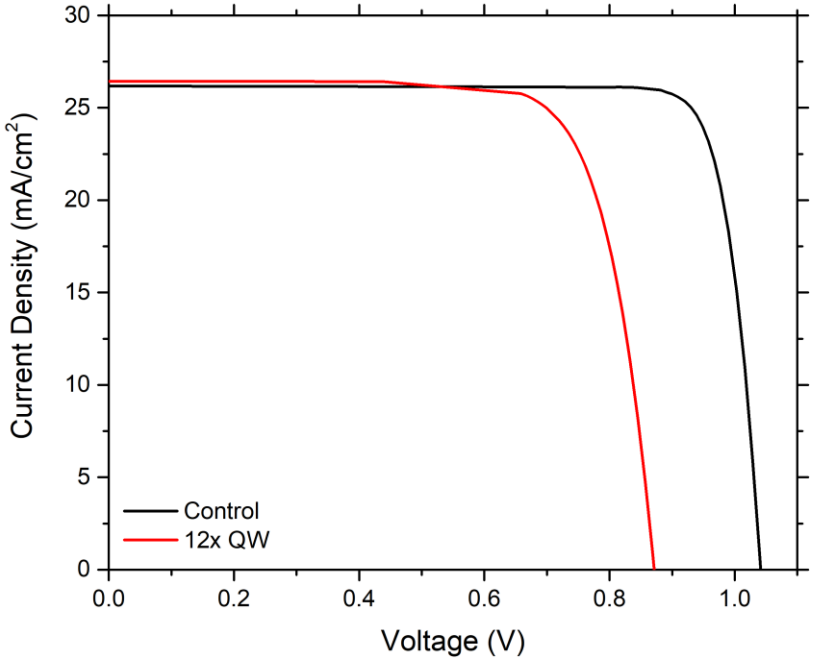
R. E. Welser, S. J. Polly, et al., S. M. Hubbard, *Scientific Reports*, 2019

Adding Strain Compensation









Significant drop in Voc by adding strain compensated QWs

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

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Offcut Effects on QW Growth

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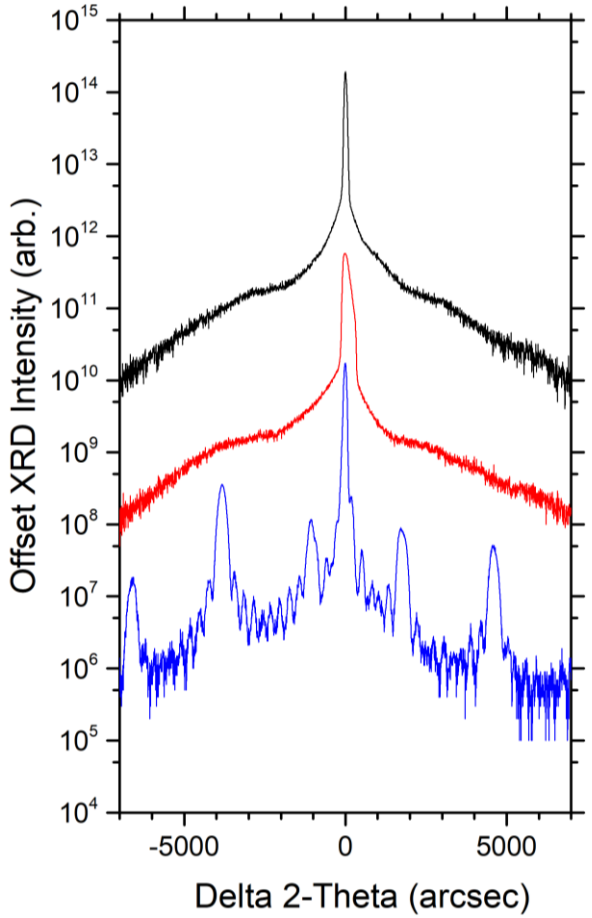
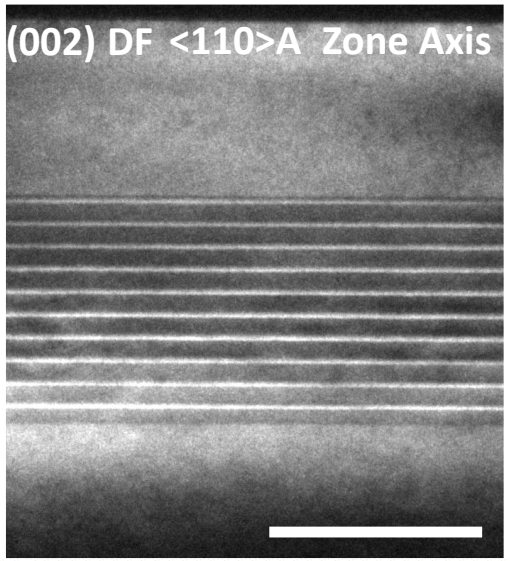
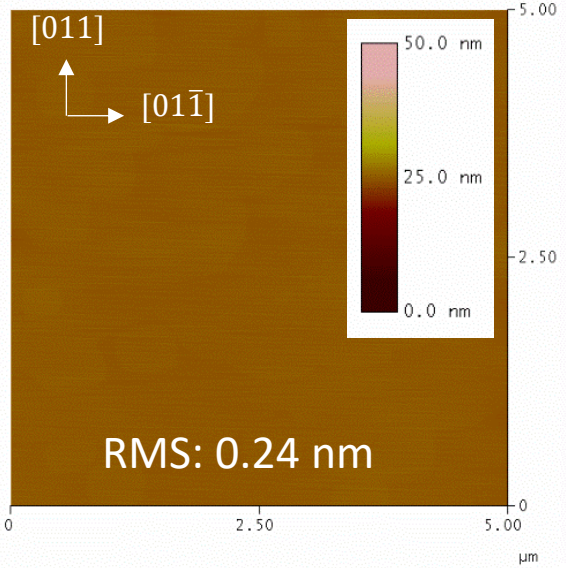
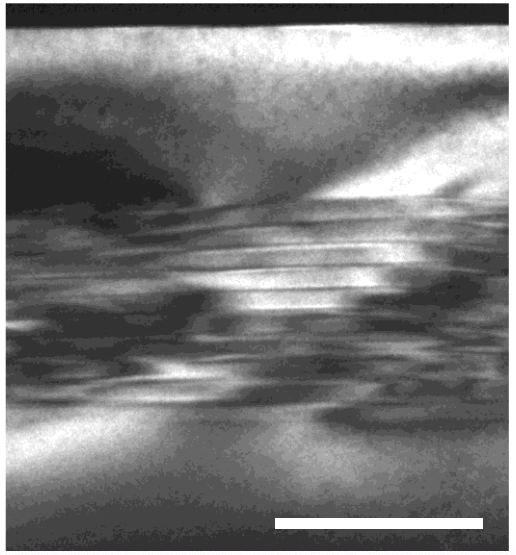


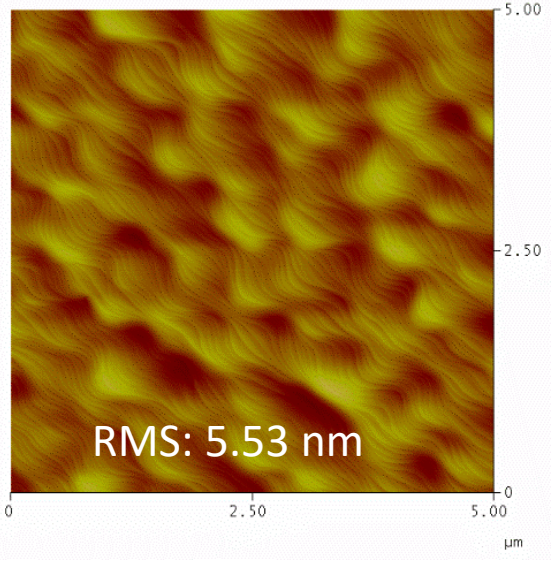
(100) on-axis





(100) 2° <110>





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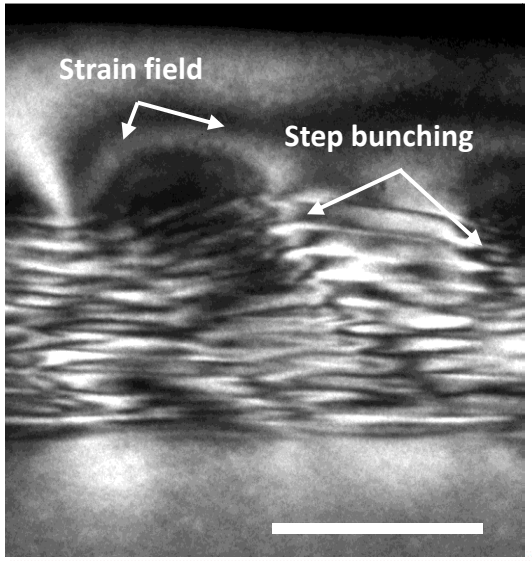
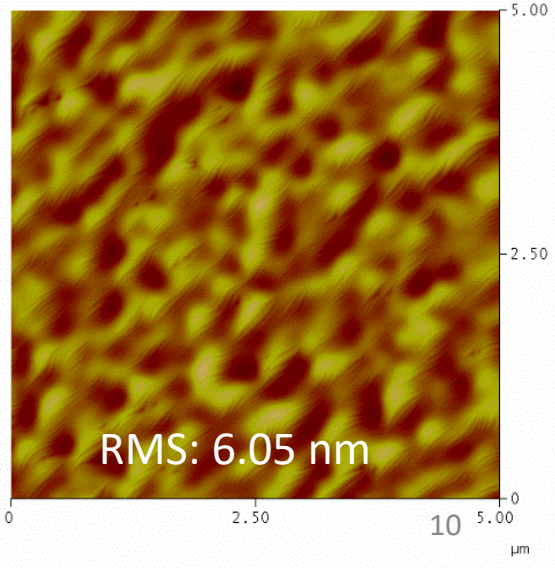
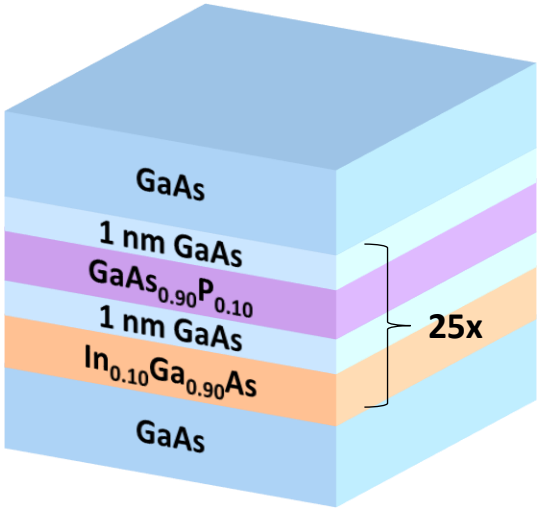




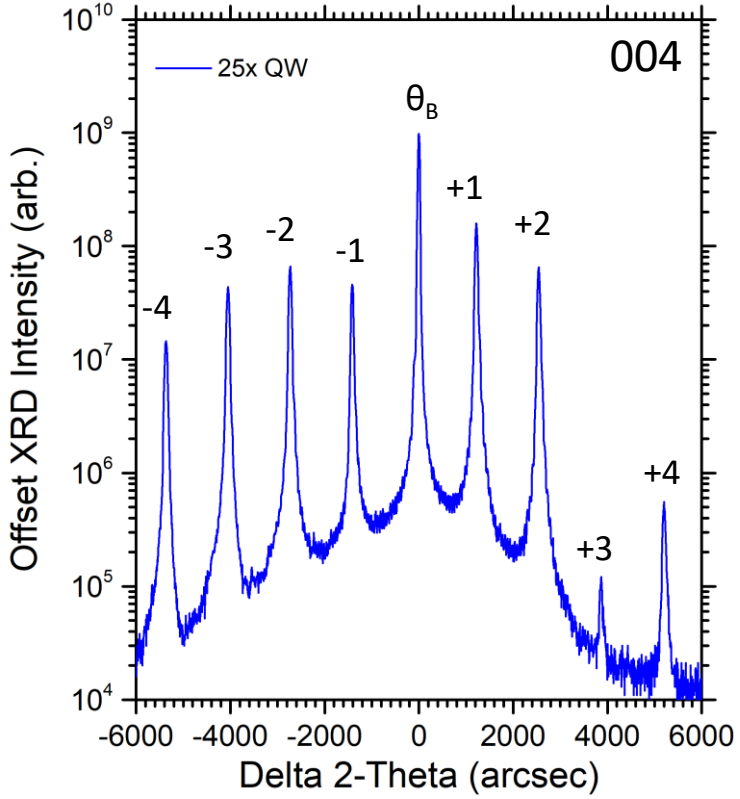
$In_{0.10}Ga_{0.90}As$ / $GaAs_{0.9}P_{0.10}$ Design

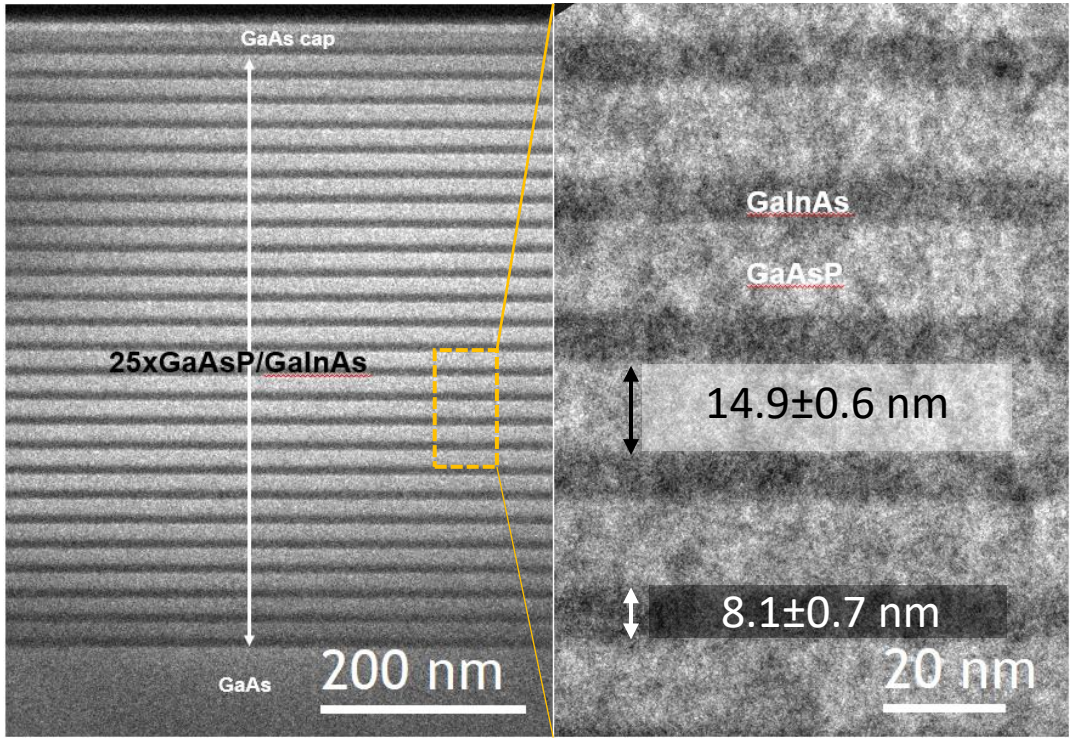


Optimize Growth Flow Sequence to mitigate step bunching

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)





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Distributed Bragg Reflectors

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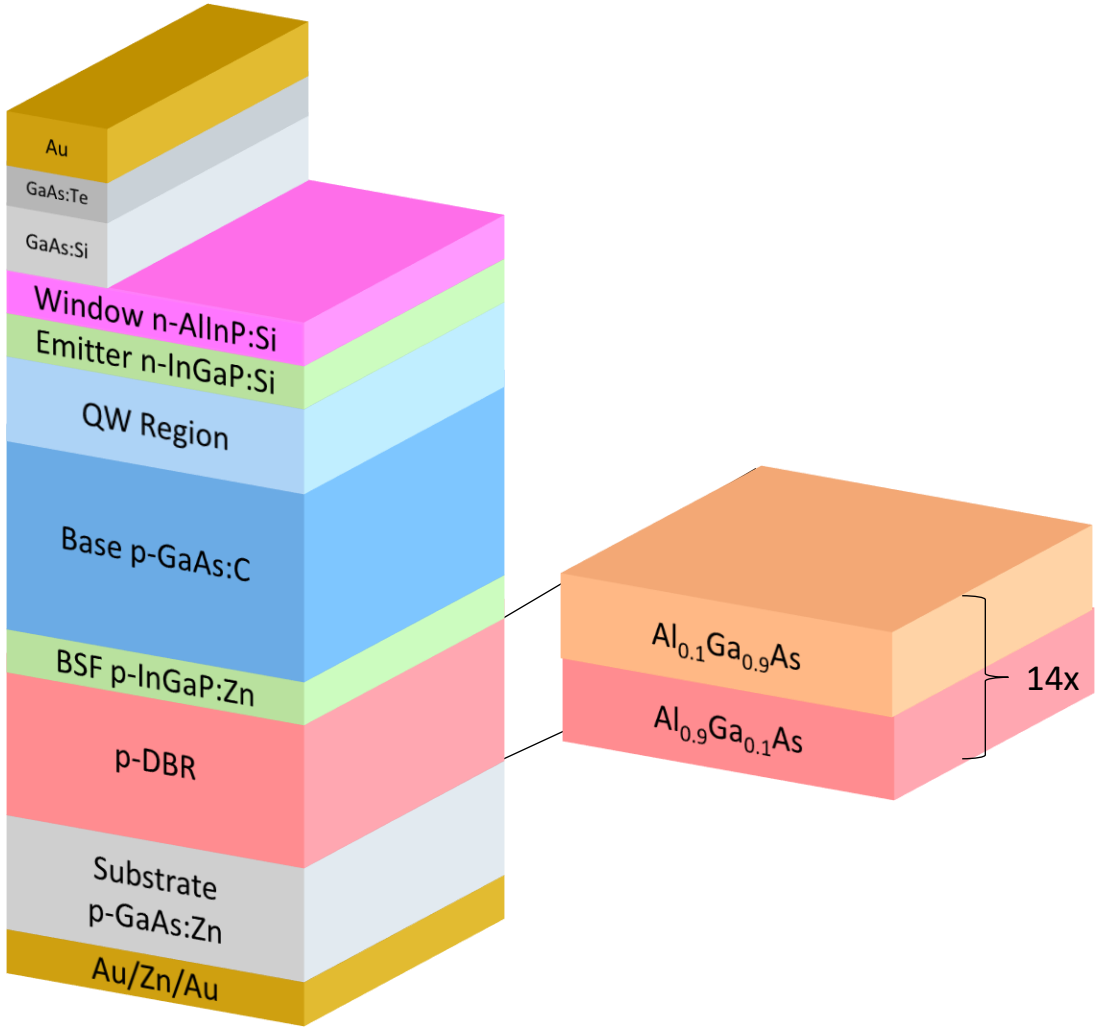

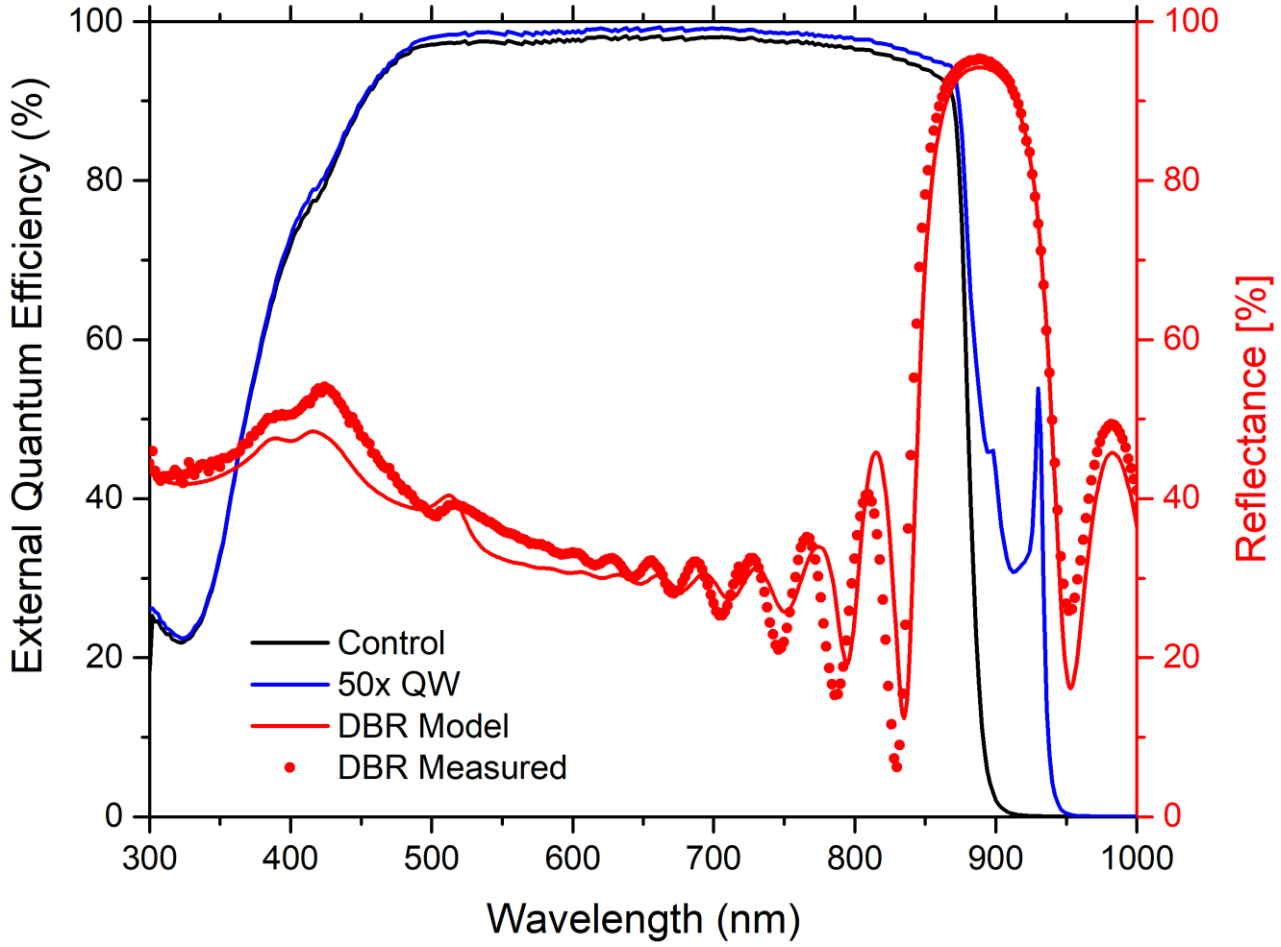

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50x QW Single Junction

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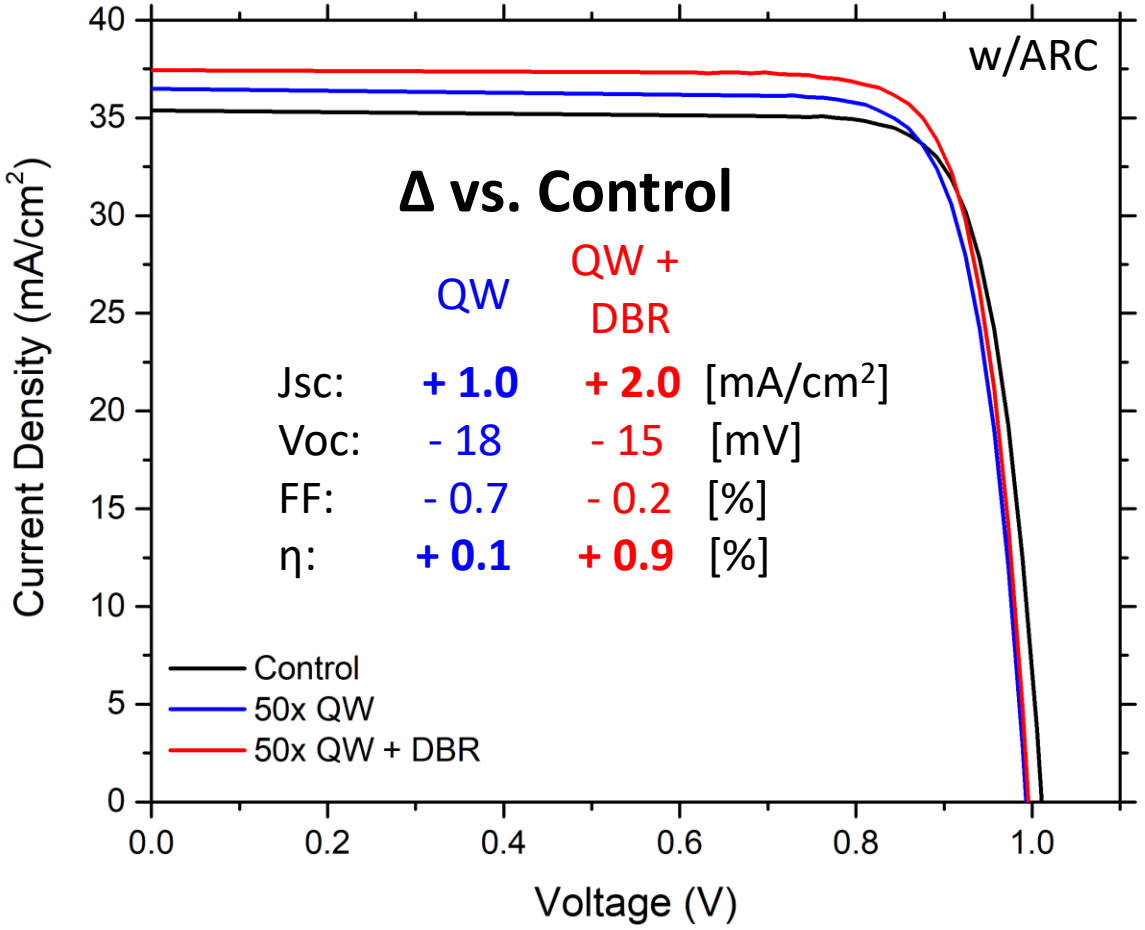

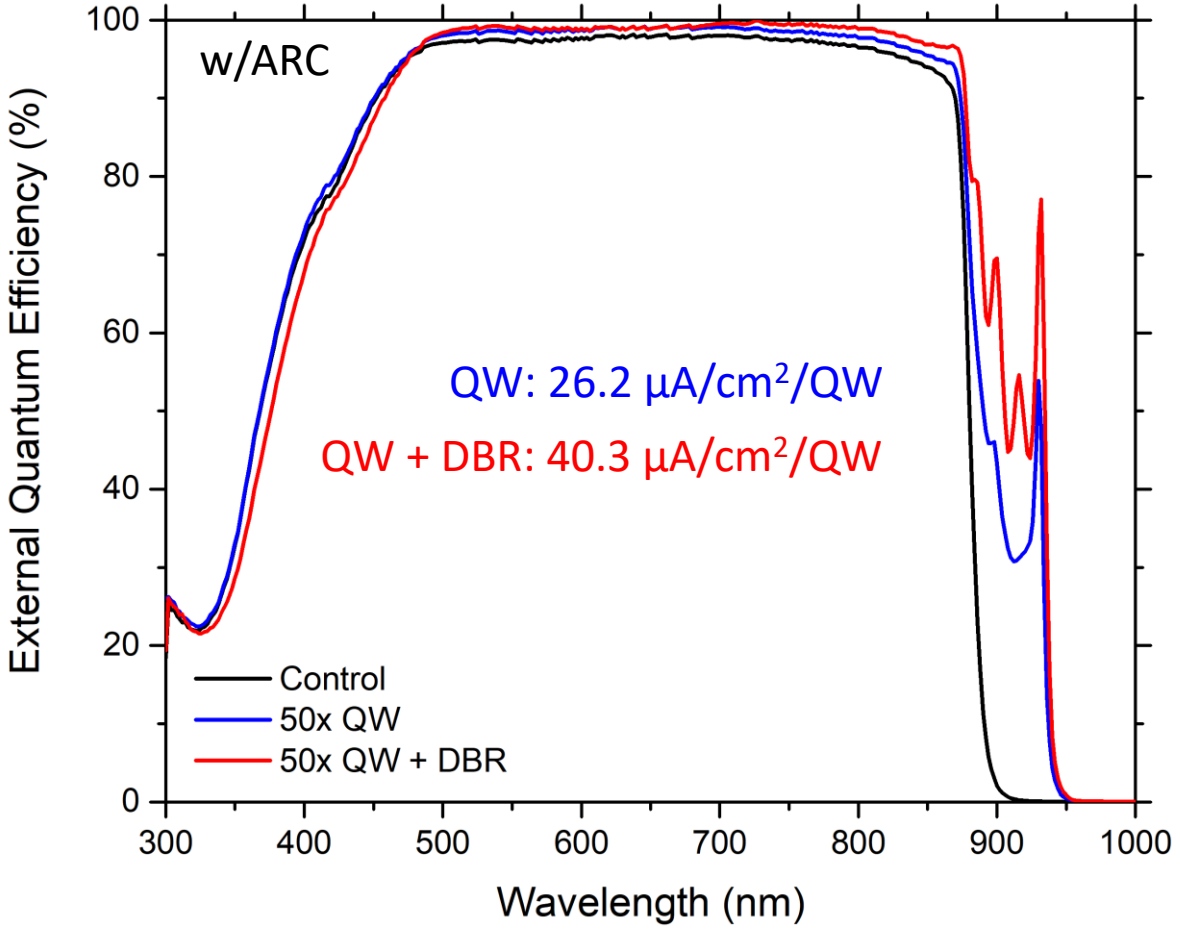

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Dual junction results, 50x QW + DBR

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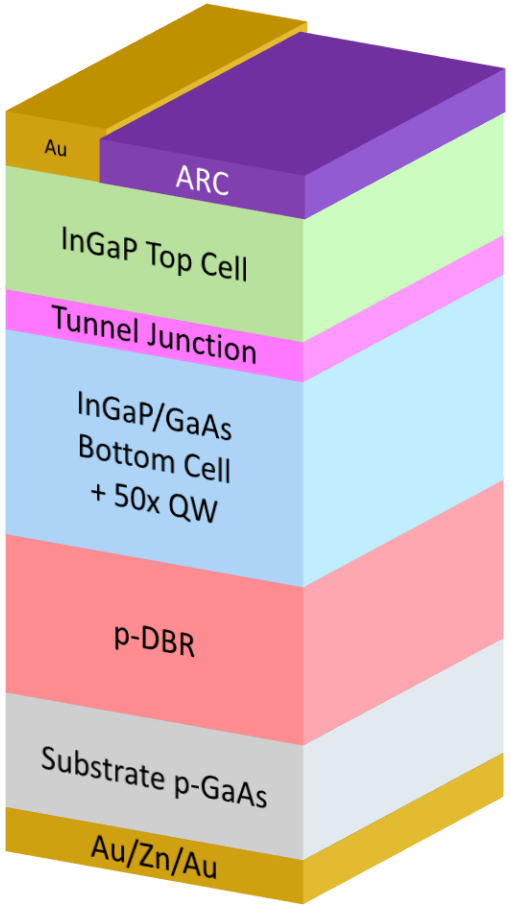

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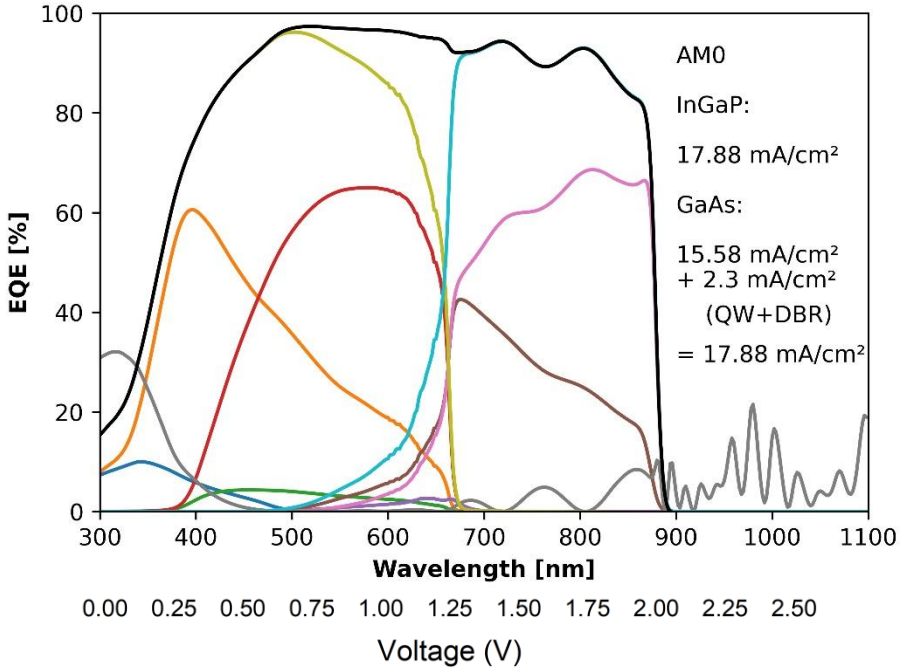

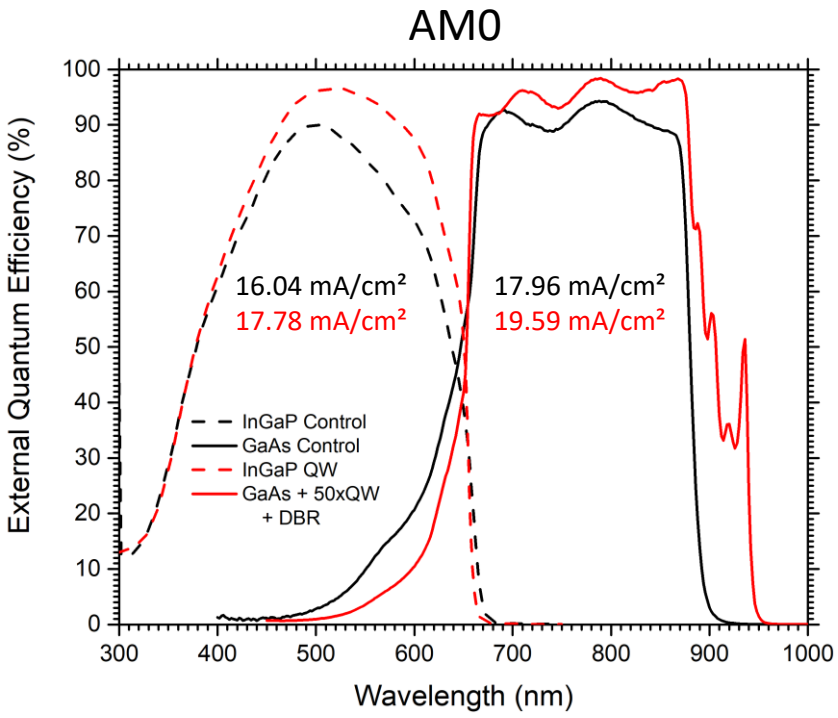

AM0:
23.9% → **27.5%** w/QW
Δ3.6% absolute
11 mV loss from QWs

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

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

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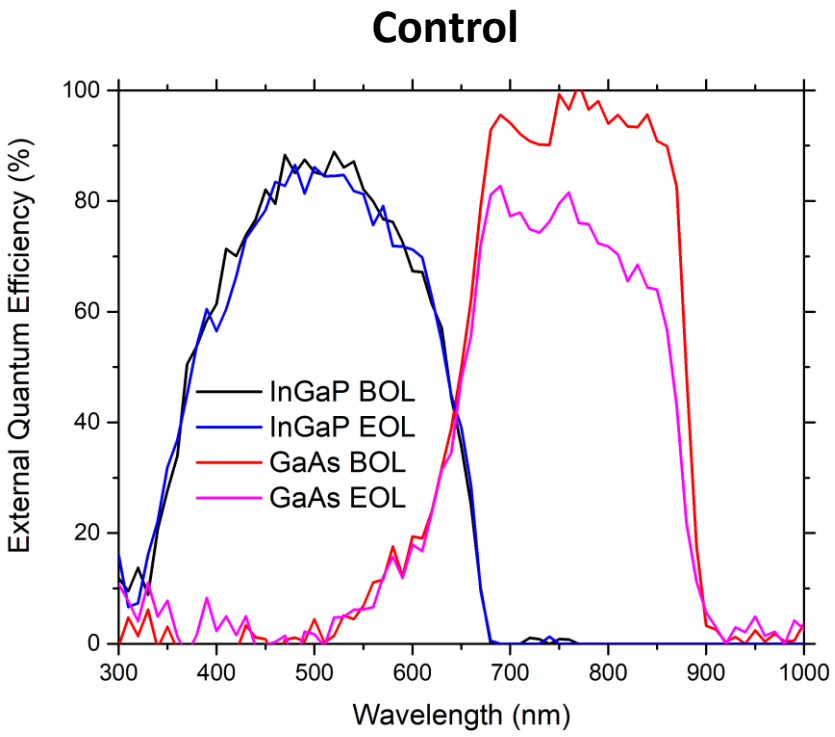

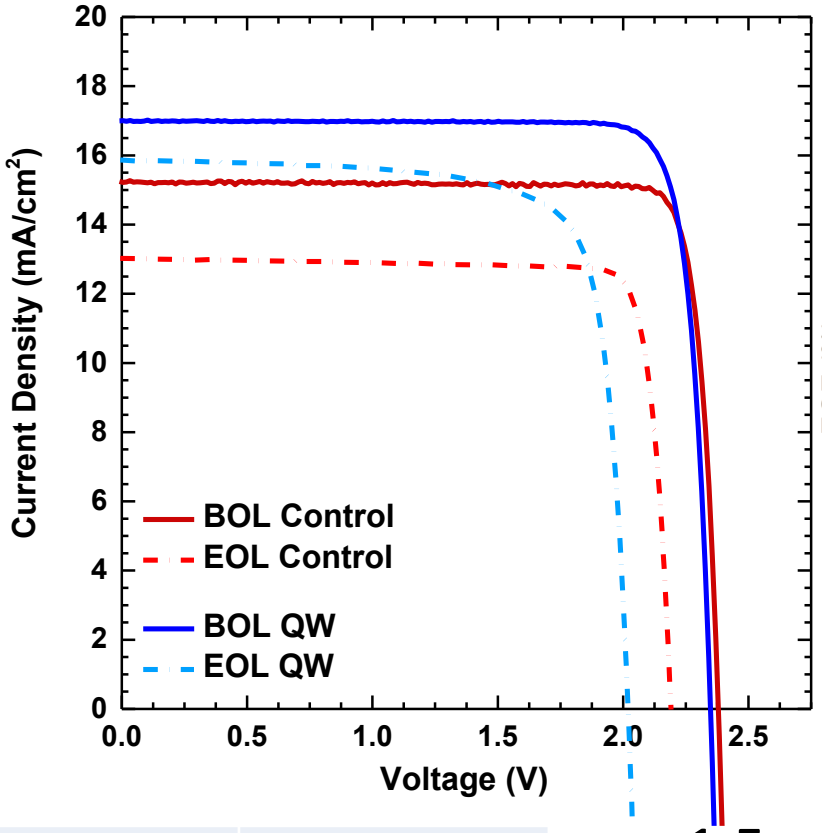

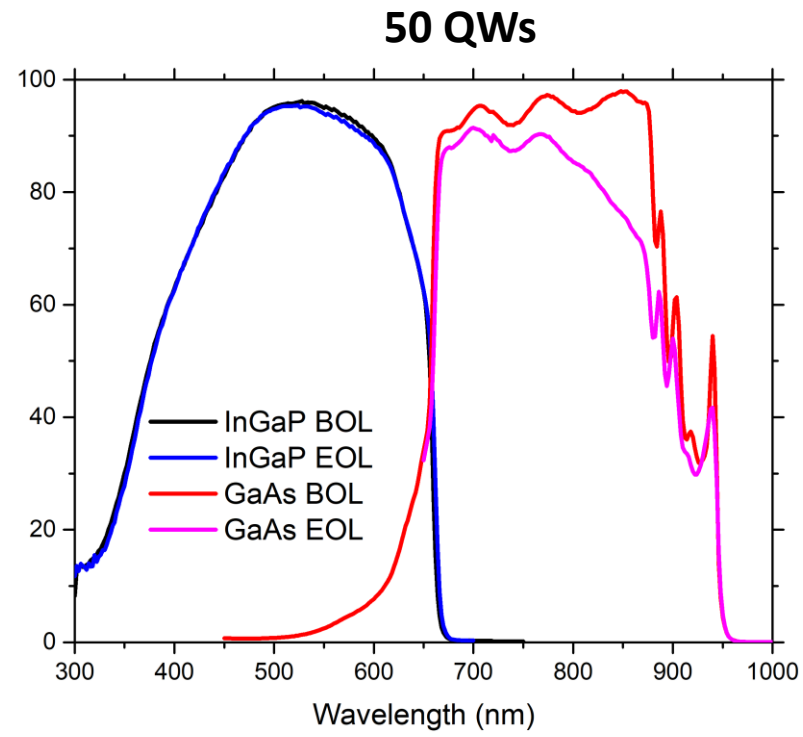

Remaining Factors

	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%

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Single Junction GaAs Results

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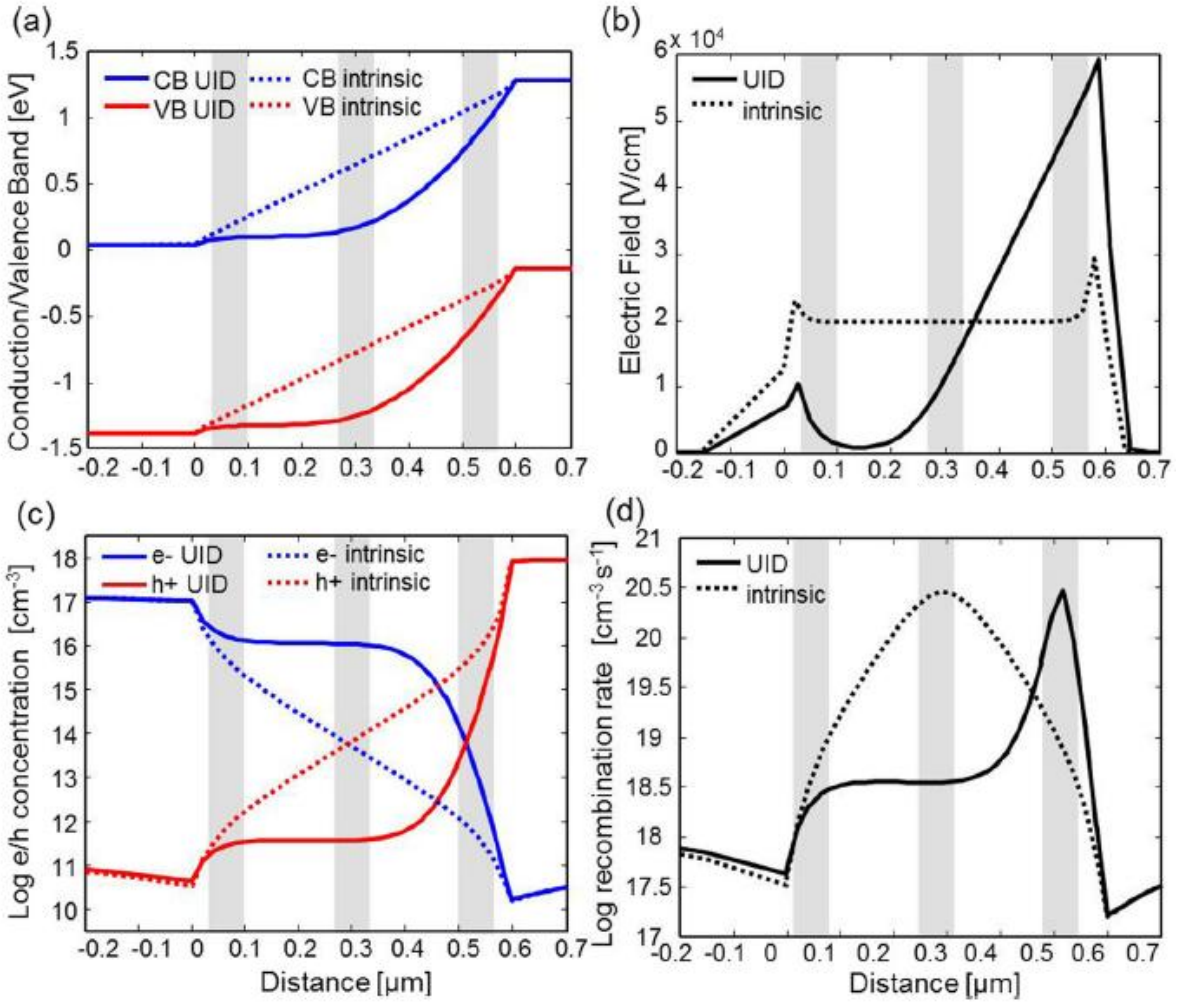
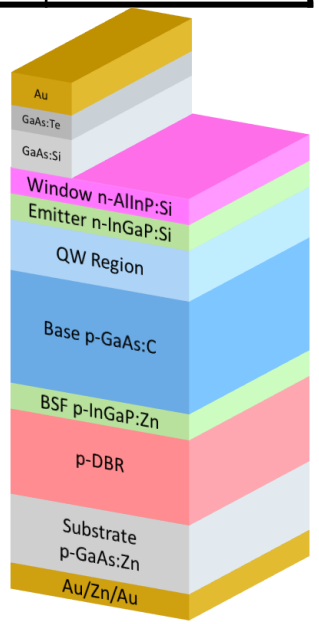


Sample	J_{sc} (mA/cm²)		V_{oc} (V)		FF (%)		η (%)	
	BOL	EOL	BOL	EOL	BOL	EOL	BOL	EOL
	Remaining Factor		Remaining Factor		Remaining Factor		Remaining Factor	
1J Control	35.55	28.95	1.012	0.887	82.0	82.2	21.59	15.45
	81.4%		87.6%		100.2%		71.6%	
50x QW + DBR	37.32	34.31	0.996	0.760	82.6	70.5	22.48	13.46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



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Comparison of Results

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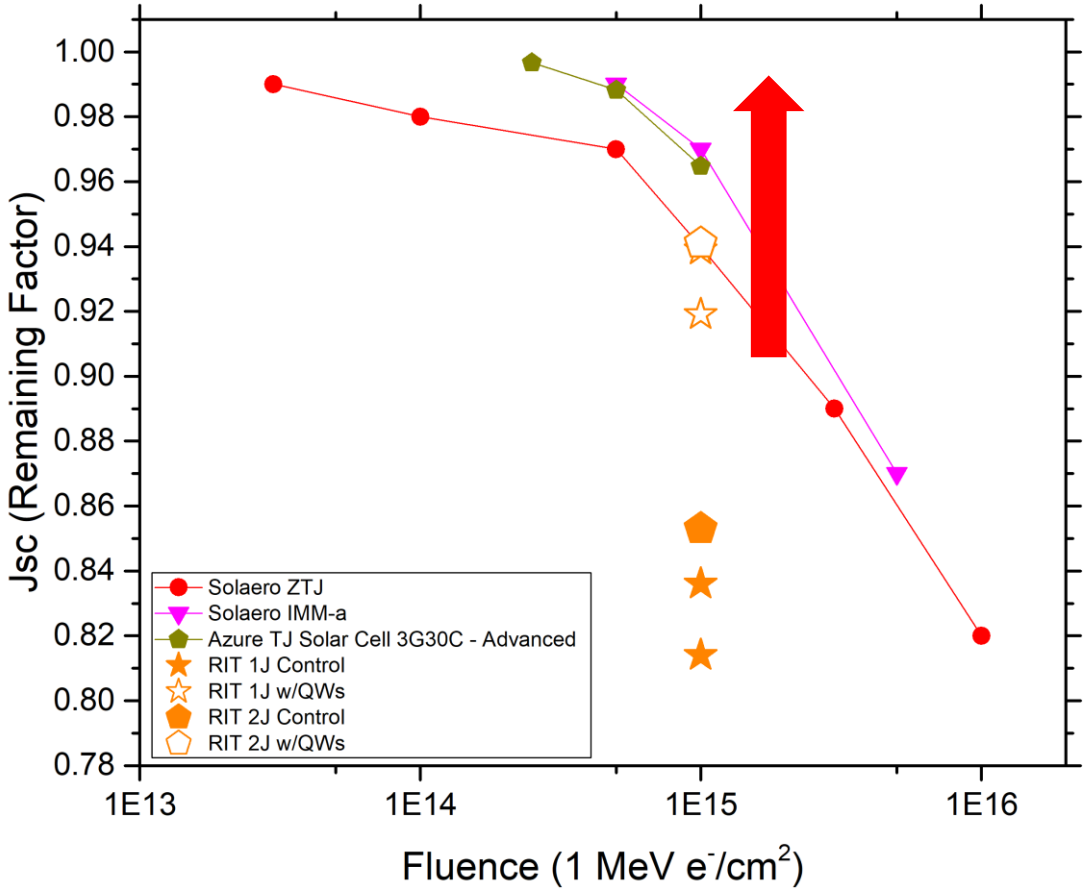
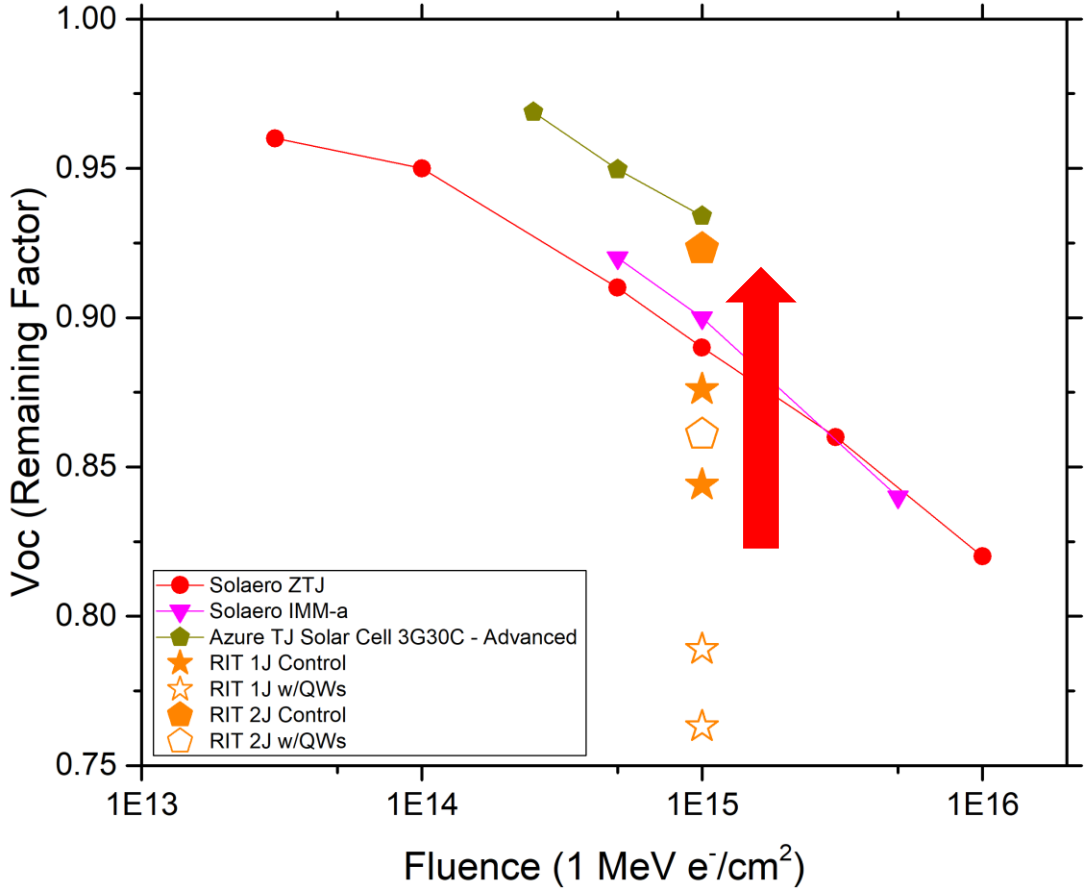
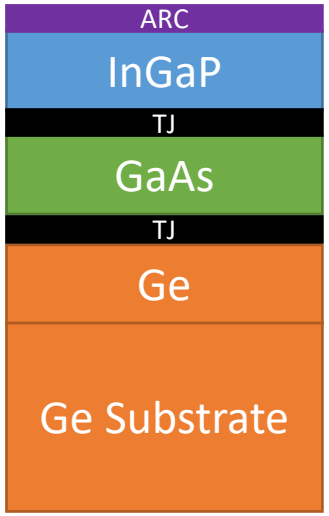


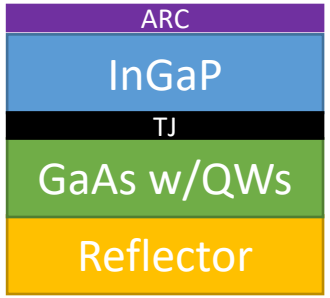


Increase well region, improved radiation hard cell design

QW placement, i-region, doping

Modeled Temperature Dependence

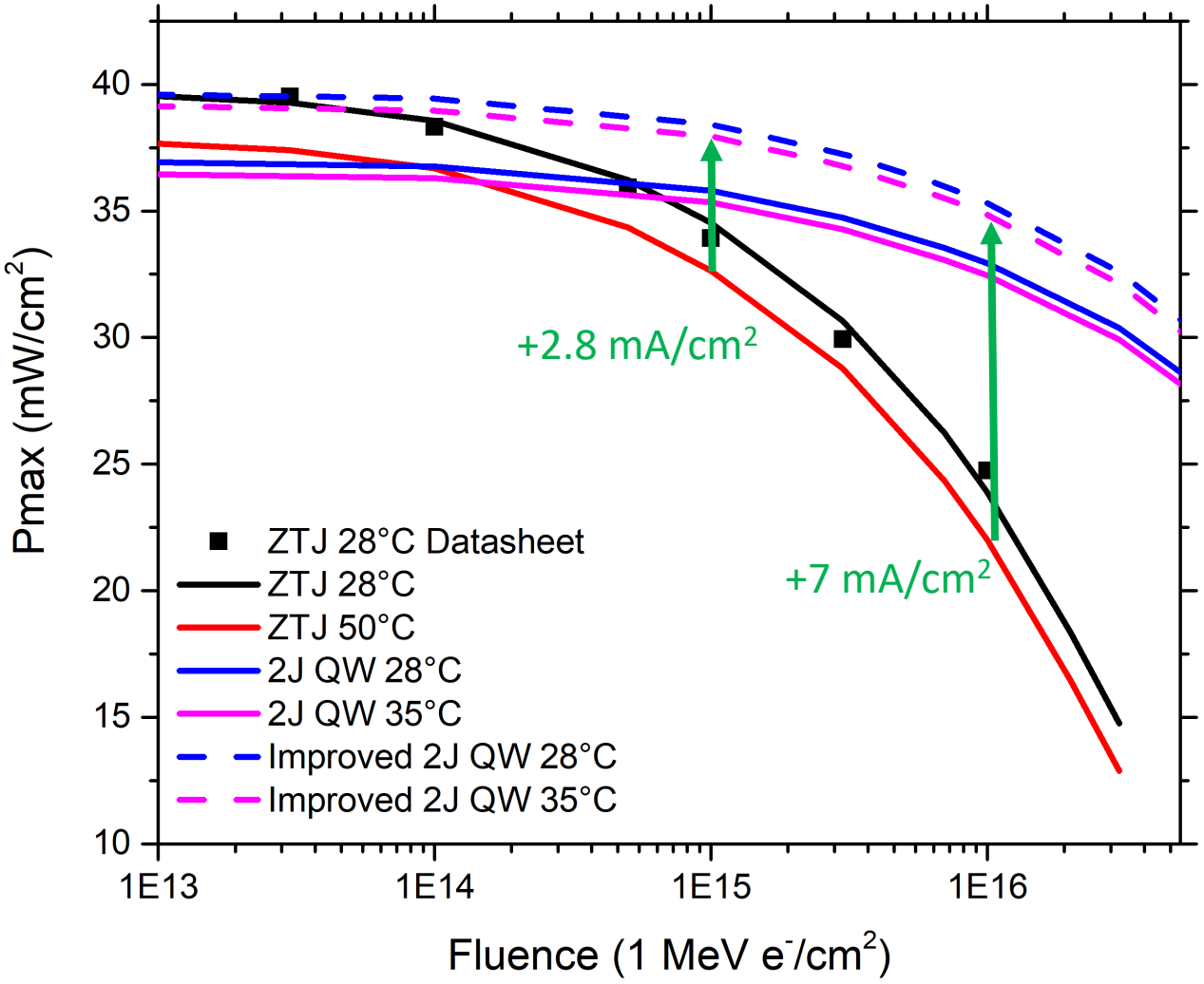




Back reflector → cooler operation, reflect sub-gap photons

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

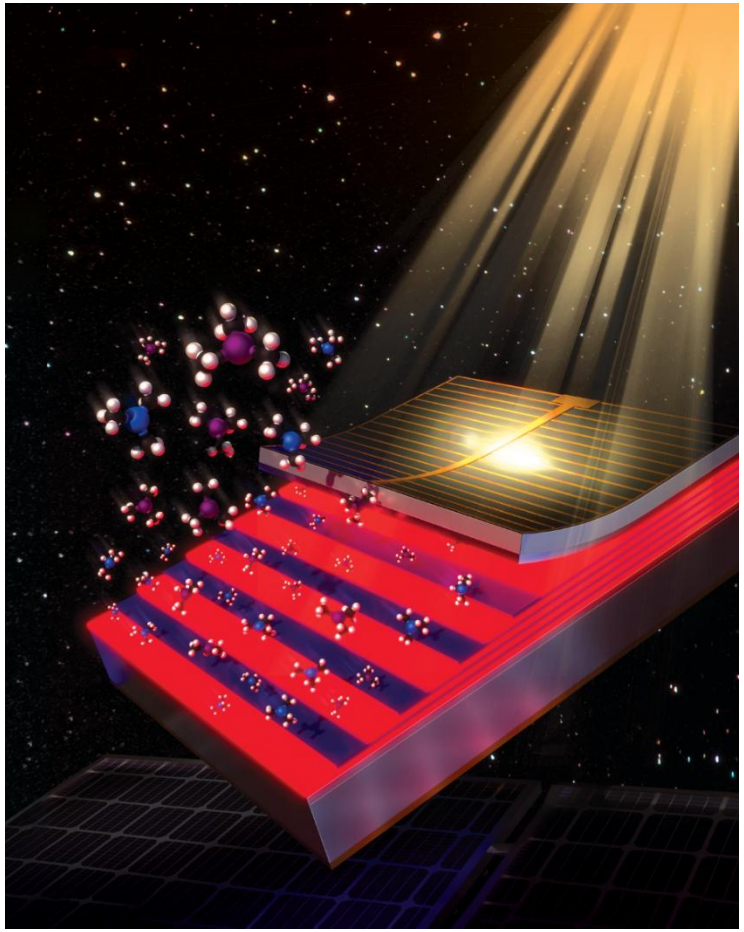
Significant increase in operational EOL performance



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

Conclusions and QW Outlook

- ✓ **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

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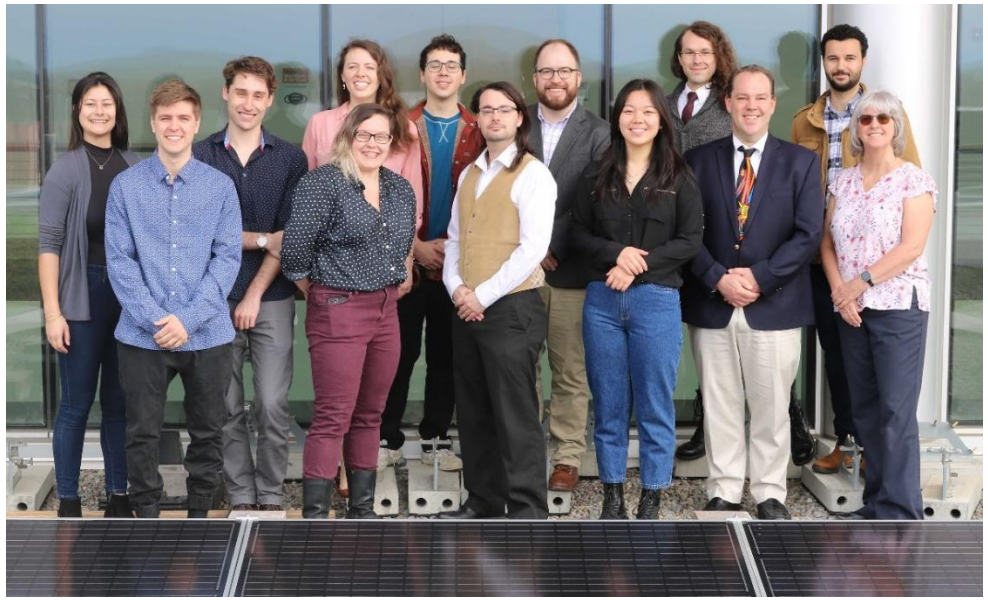

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