

# Integrated Photon Management in Multijunction Photovoltaics

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Rochester Institute of Technology

AFOSR Space Power Workshop 2017

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# Motivation: Space and Military Power Systems

- **The Electric Power System is 20 - 35% of total mass and cost for earth-orbiting satellites**
- **Need for enhanced mass specific power and radiation tolerant solar cells**
- **Terrestrial applications in mobile PV and UAV**

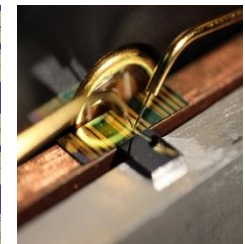
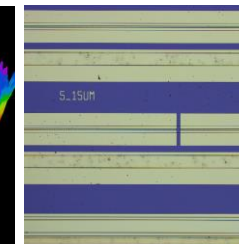
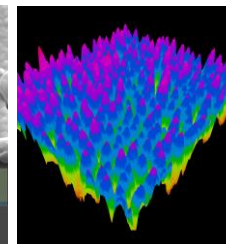
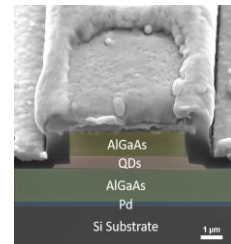






- Drs. Michael Slocum, Hyun Kum, Alessandro Giussani: **Postdoctoral Fellows**
- Zac Bittner, Yushuai Dai, Brittany Smith, Elisabeth McClure, George Nelson, Mitsul Kacharia: **Microsystems Eng. PhD**

- RIT recently completed installation of a new Aixtron Close Coupled Showerhead (CCS) MOCVD
  - 3x2", 1x3" and 1x4" capability
  - **Epitaxy of III-V compounds of As, P and Sb**
  - In-situ diagnostic LayTec EpiTT-Curve system gives real time information of temperature, stress, strain and surface roughness
  - Materials used for advanced applications in solar energy, integrated photonics, nanomanufacturing, infrared detectors and next generation electronics







RIT SMFL III-V Processing

## III-V Processing technology

- Wet/Dry Etching, lithography
- Dedicated III-V fabrication and metallization tools
- Annealing furnace up to 150mm

## Characterization

- TS Space systems 300 mm close-match solar simulator
- Optronics and Newport spectral response
- Janis cryogenic (2K) probe station
- Photoluminescence and Photo-reflectance
- DLTS, FTIR, Raman, Hall
- Hitachi and Tecscan FE-SEM
- Brucker HRXRD and AFM

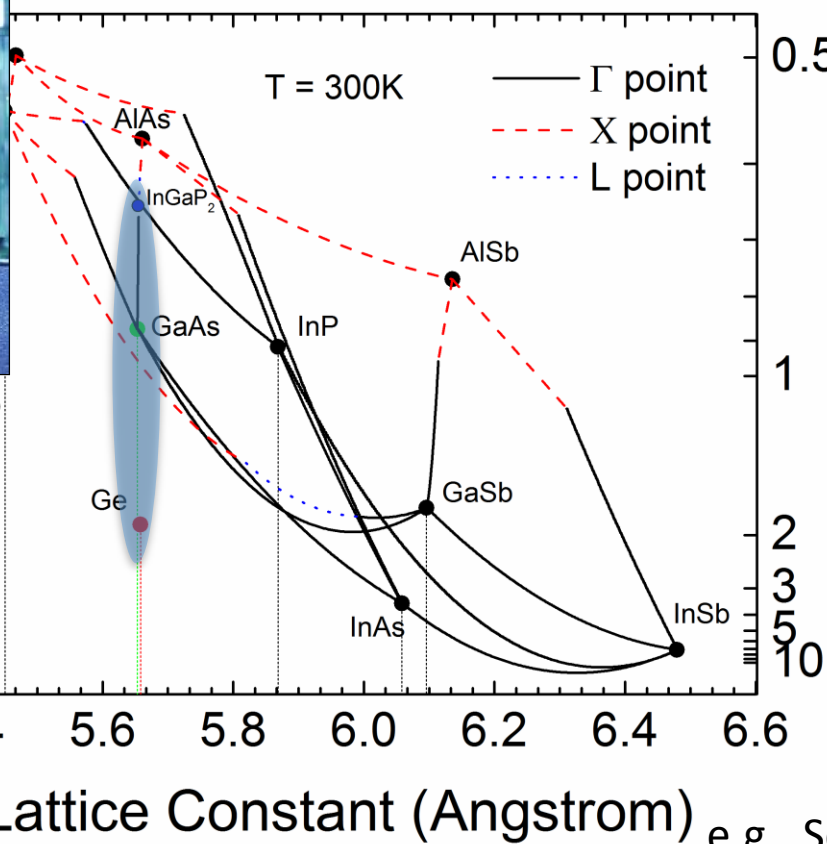
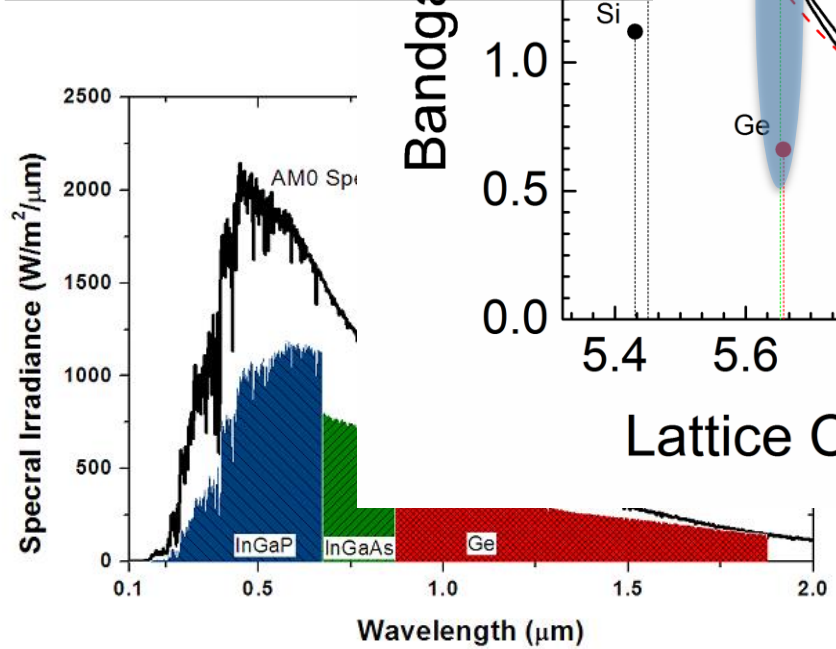
## Device Characterization



- I. Background and Introduction to Multijunction Solar Cells
- II. Light Trapping In Single Junction Cells  
How it applies to radiation hard environments
- III. Light Trapping in Multi-junction Cells  
End of life (EOL) current matching
- IV. Bandgap/Absorption Engineering & work at RIT



# The Lattice Matched Triple Junction

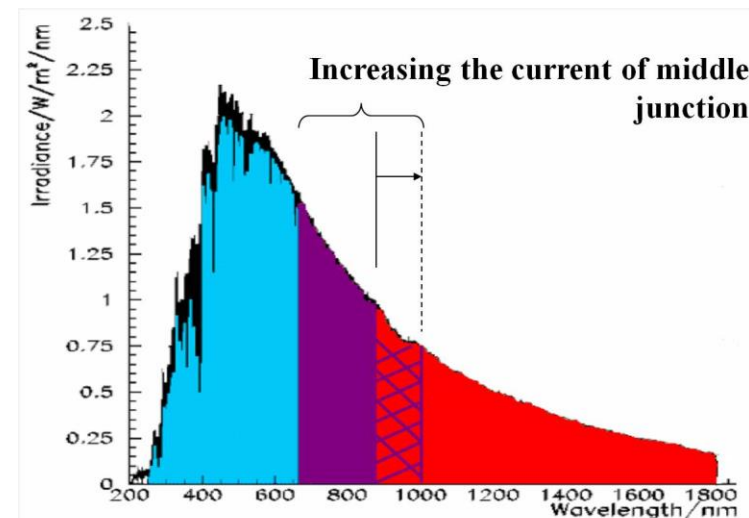
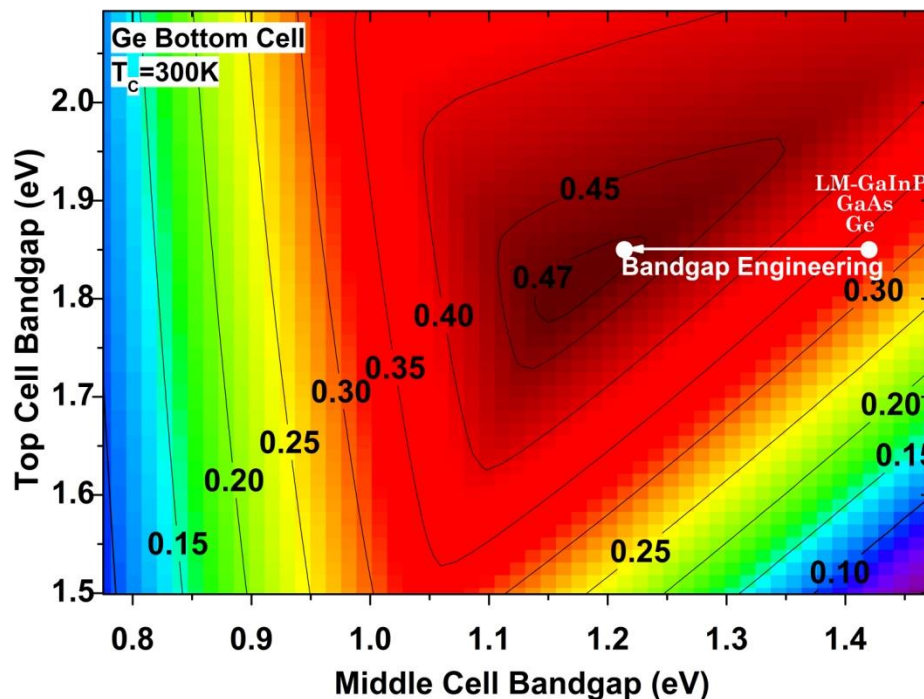


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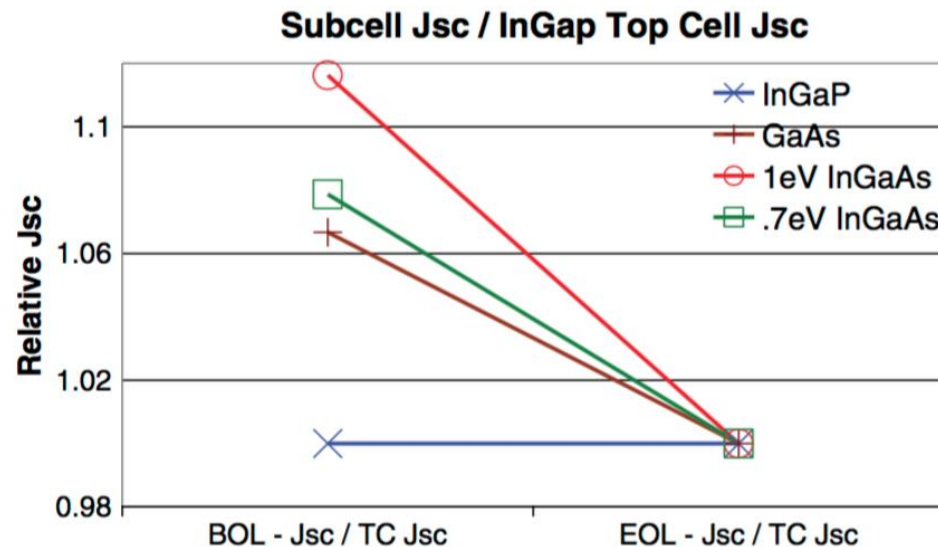
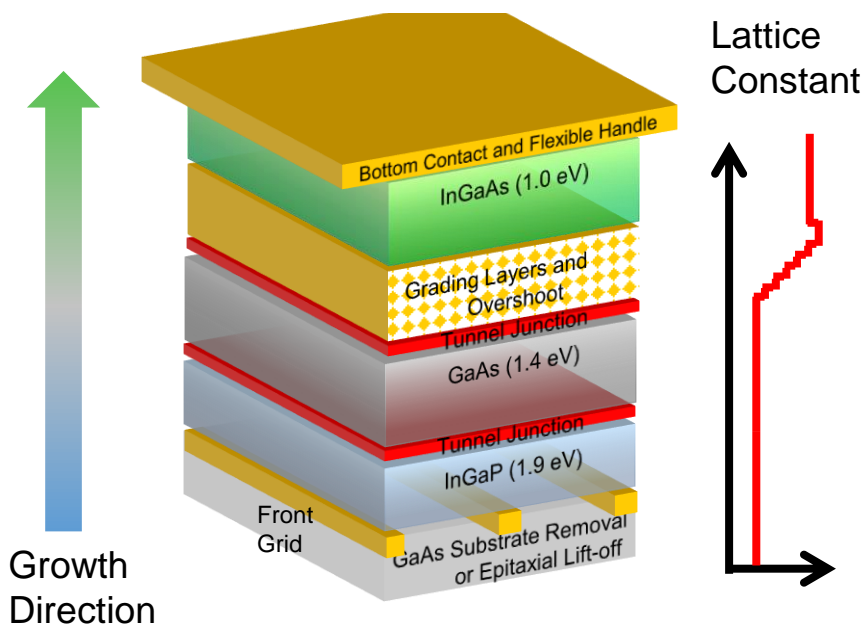
e.g. SolAero, Inc. ZTJ  
Boeing XTJ Prime

Lot averages are ~30% efficient under 1 Sun AM0  
Fully space qualified (AIAA S-111/S-112)  
Power ~85% of maximum at  $1 \times 10^{15} cm^{-2}$  1MeV e<sup>-</sup>



- Middle cell (MC) is current limiting in traditional lattice matched structure
- MC is also weakest at EOL due to radiation effects
- Efficiency can be increased though a number of methods:
  - 1 eV bottom cell, metamorphic approach
  - QW and QD bandgap engineering in MC
  - New materials for BC (GaAsN) or new materials for entire cell structure (lattice match to InP)



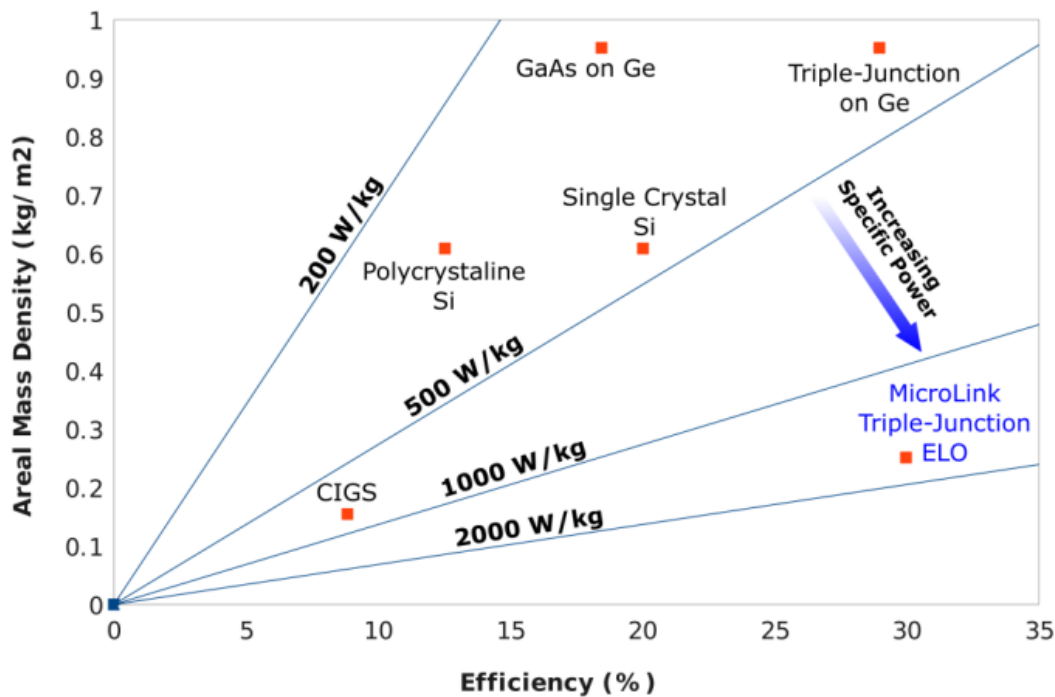


Patel et. al., *Photovoltaic*, 2.3337 (2012)

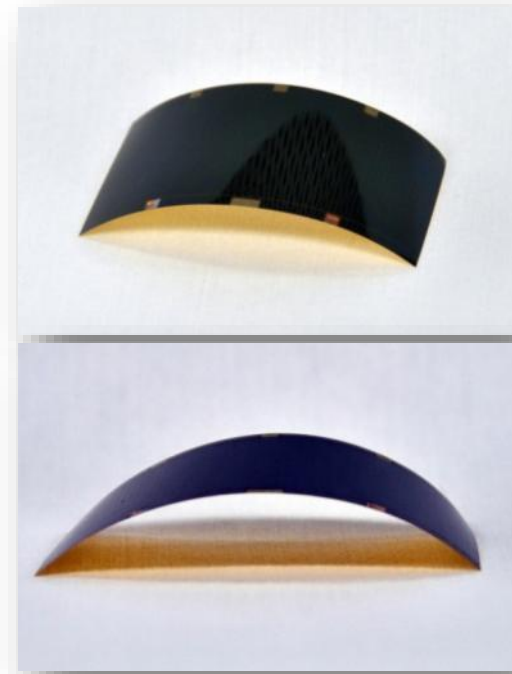
Lattice Constant (Angstrom)

- **Current matched inverted metamorphic multijunction device**
- Several micron thick metamorphic buffer to grade lattice constant
- Bottom cell is now the weakest link for radiation
  - Next generation rad hard IMM qualification to AIAA S-111 in progress

## Areal Mass Density and Efficiency

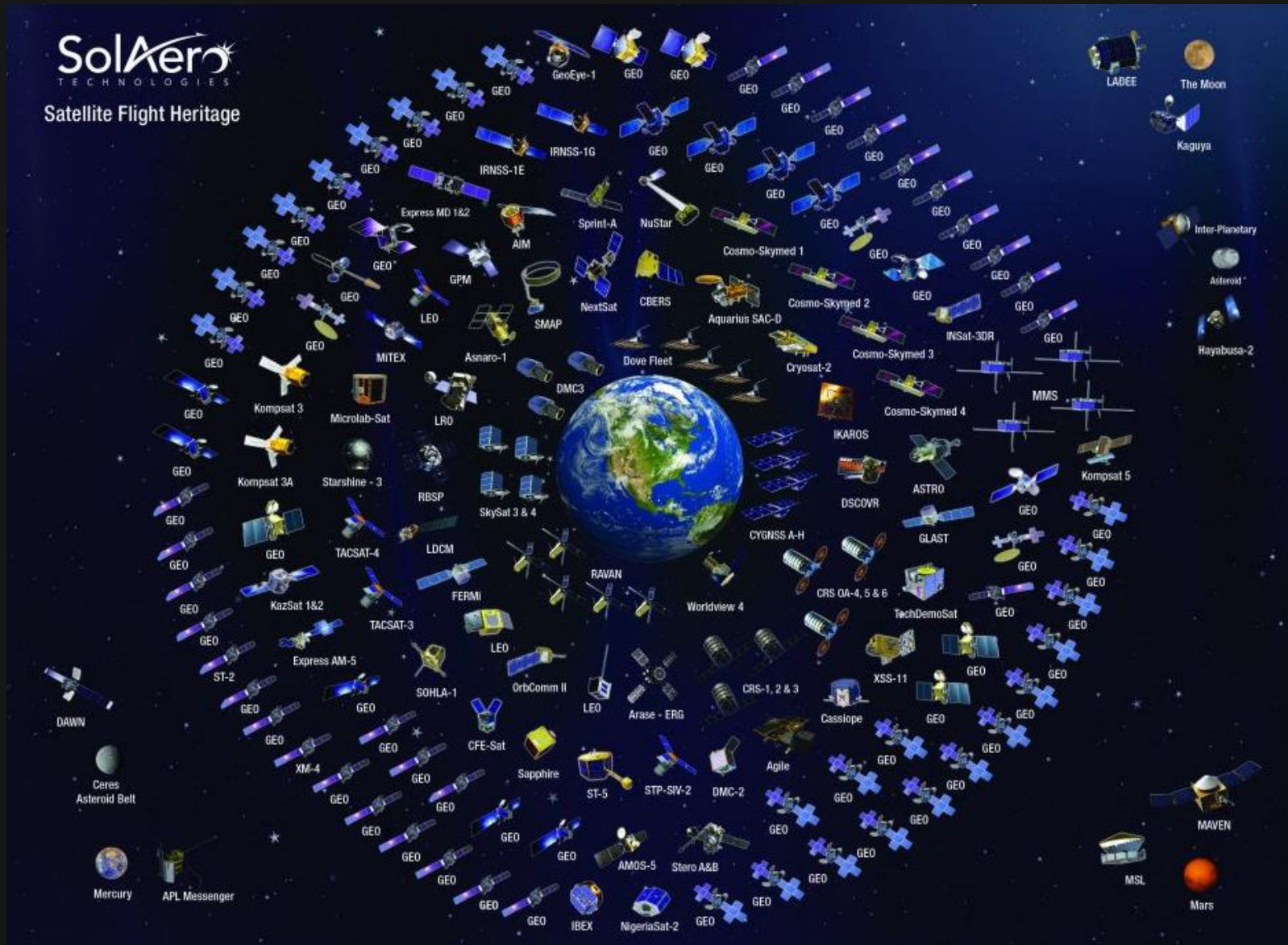


## 20 cm² Cell



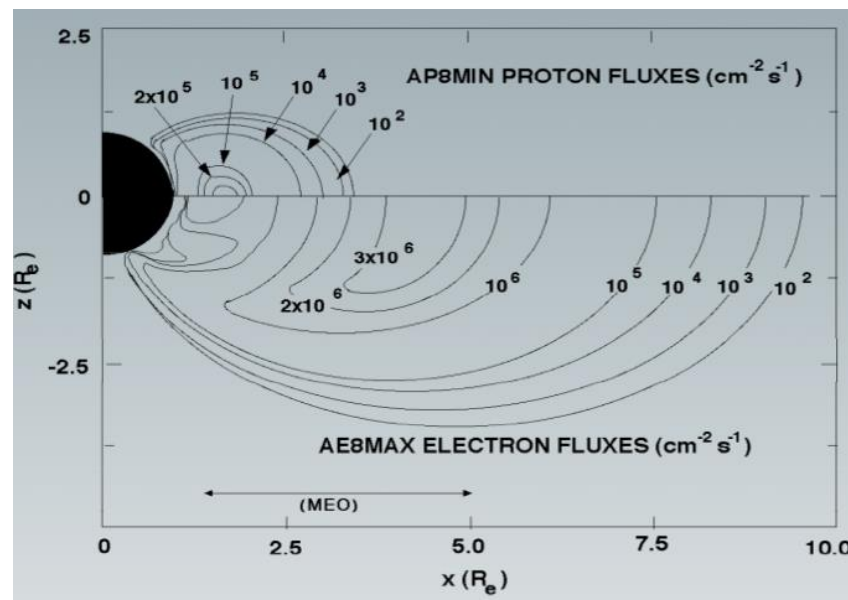
- Low Areal Mass Density – Substrate is removed
- Lower Cost – Substrate reuse reduces solar cell bill of materials
- High Efficiency – Structure based on space cell technology
- Flexibility – Cells can be bent without degrading performance





## Van Allen Belts

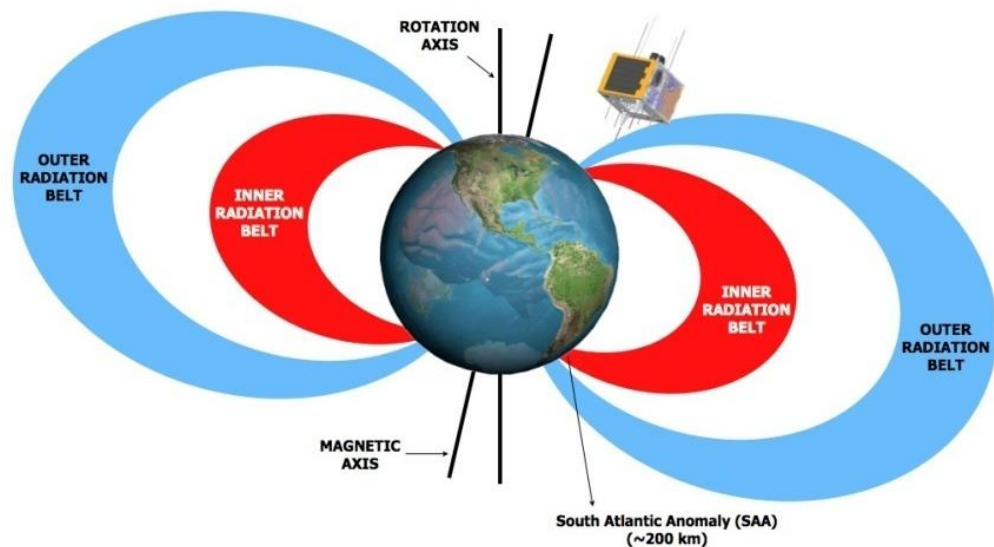
- Radiation trapped in Earth's magnetic field
- Peak 1+ MeV  $e^-$  flux of  $3 \times 10^6 \text{ cm}^{-2} \text{ s}^{-1}$



Mitigating In-Space Charging Effects NASA Technical Handbook

## Solar winds

- Up to  $10^{10}$  particles/s\* $\text{cm}^2$  (1 AU along ecliptic plane)



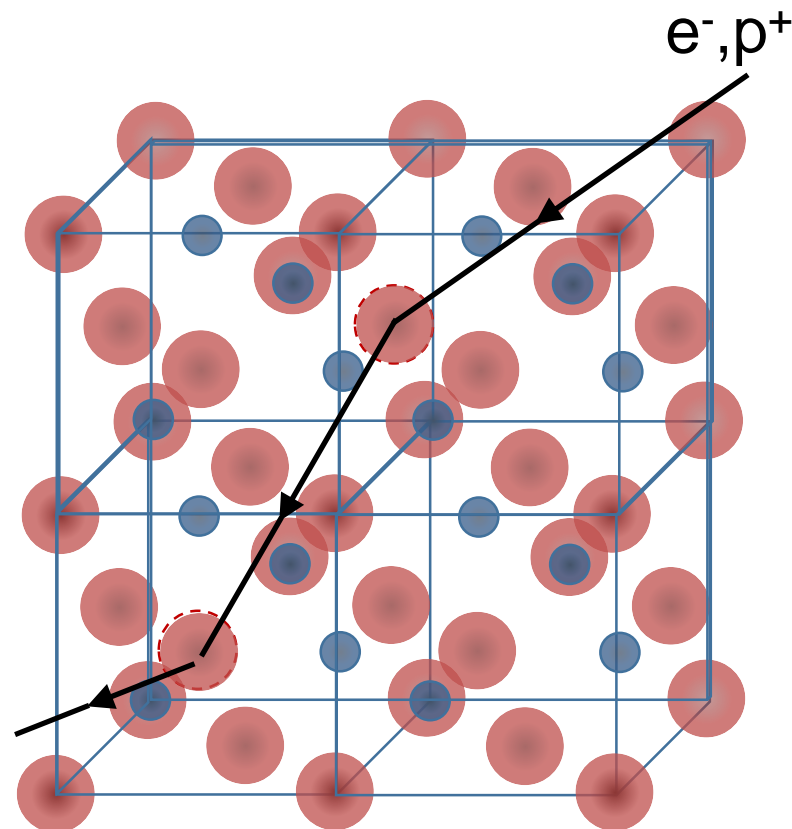


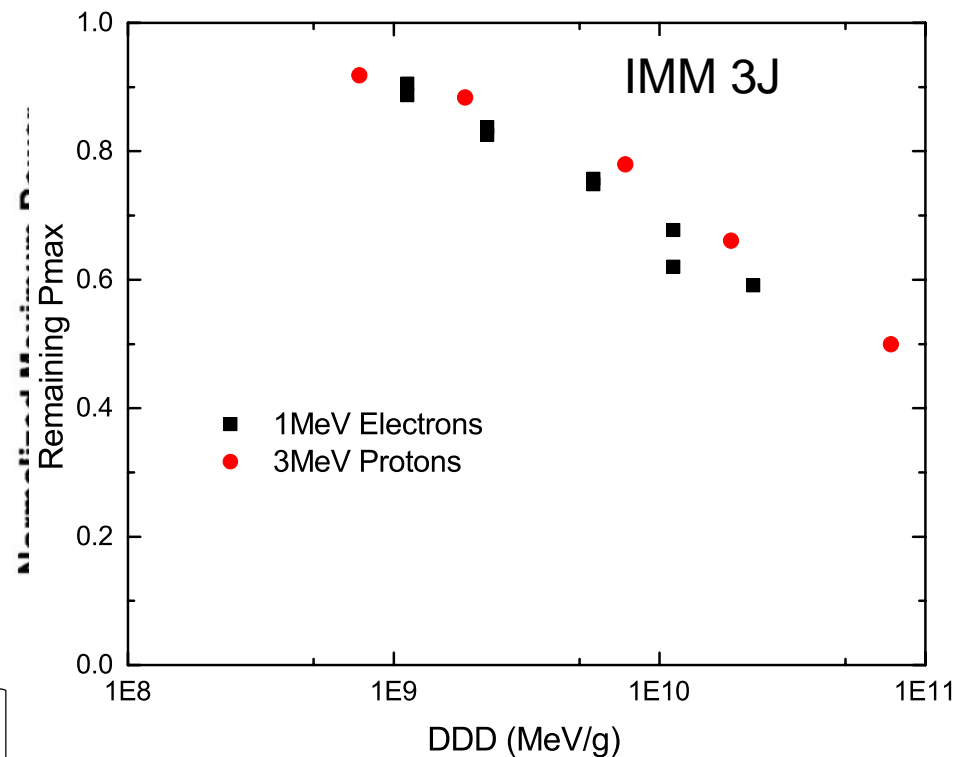
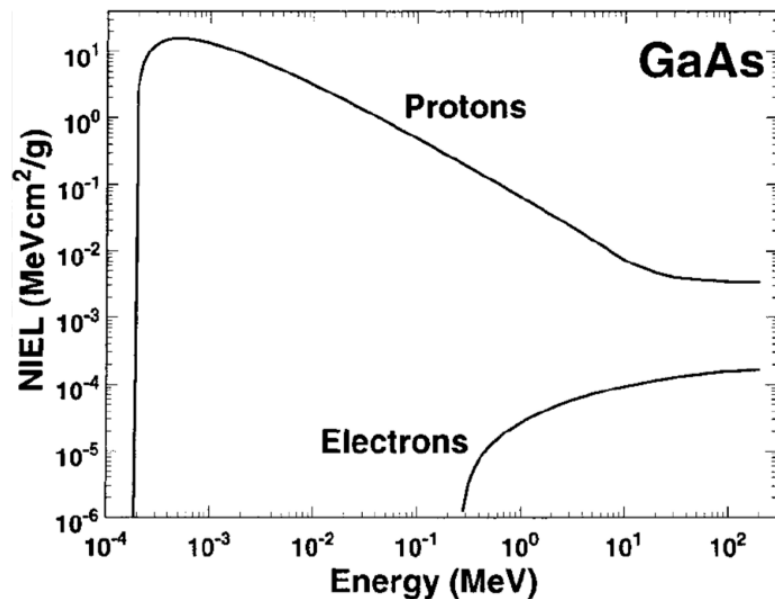
## Radiation energy dispersal

- Ionizing
  - No permanent damage
- Non-ionizing
  - Results in atomic displacement
  - <1% particle energy

## Effects

- Cumulative
- Decreased carrier lifetime
- Trap assisted tunneling (shunting)
- Increased resistivity
- Changed doping & film type conversion (special case)





Rate at which energy is lost to non-ionizing events

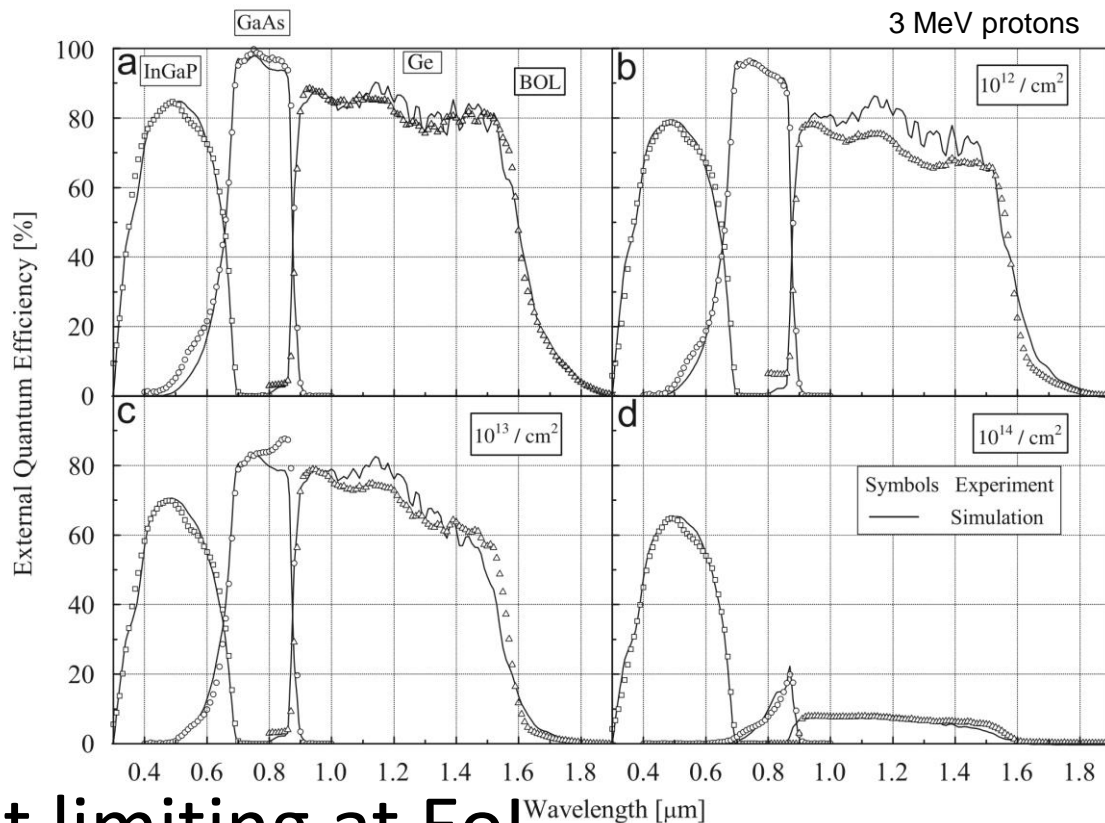
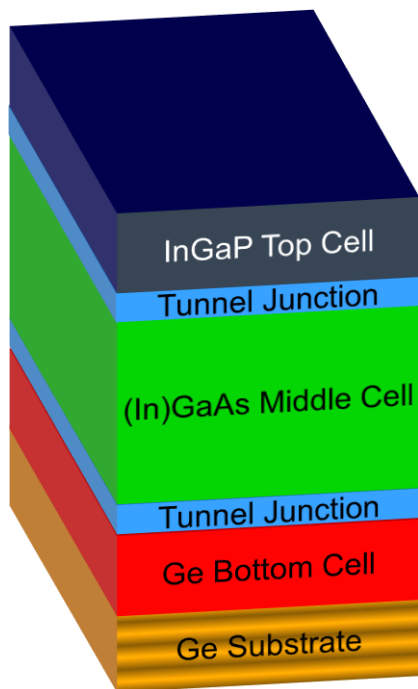
• Flux of non-ionizing radiation

## Models to predict radiated devices

- NASA-JPL: Relative damage Coefficients (RDC)
- NRL: Displacement damage dose ( $D^3$ )

$$D^3 = \int NIEL(E) \cdot \frac{d\Phi(E)}{dE} dE$$

Messenger et al. Prog. Photovolt: Res. Appl. 2001; 9:103-121



- GaAs subcell current limiting at EoL
- 85% remaining  $P_{MAX}$  @EoL due to
  - EoL Matched subcell thicknesses
  - Graded base doping

Sato et al. Solar Energy Materials & Solar Cells 93 (2009) 768-773



## 1. Conventional optimization

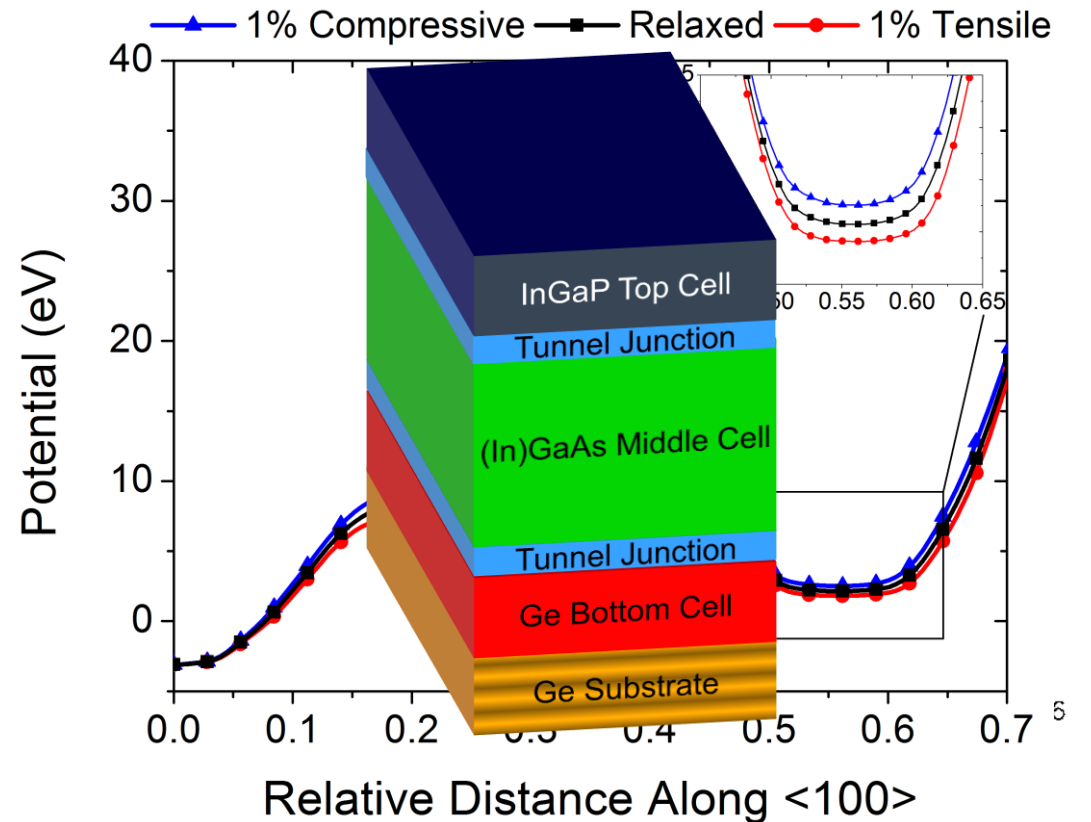
- Doping gradients, disordered InGaP, EoL current matching

## 2. Use radiation Hard Materials

- InP was seen as candidate
- Difficult to integrate into 3J

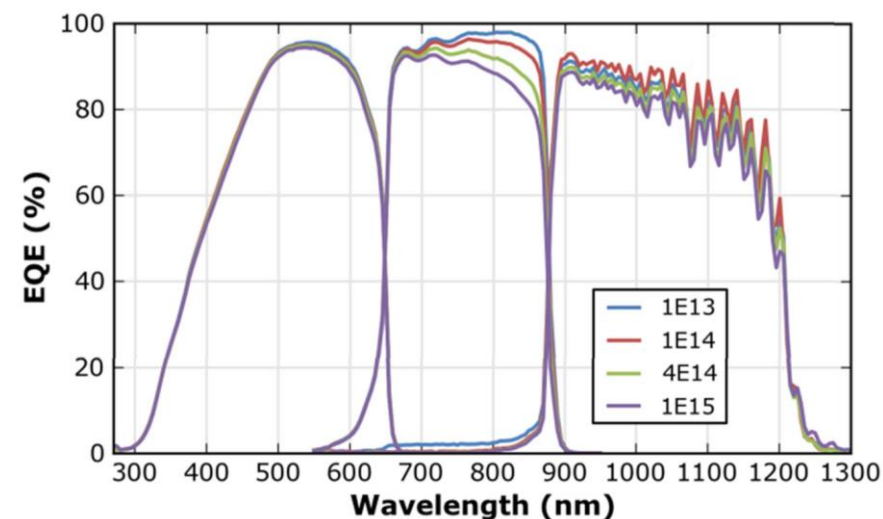
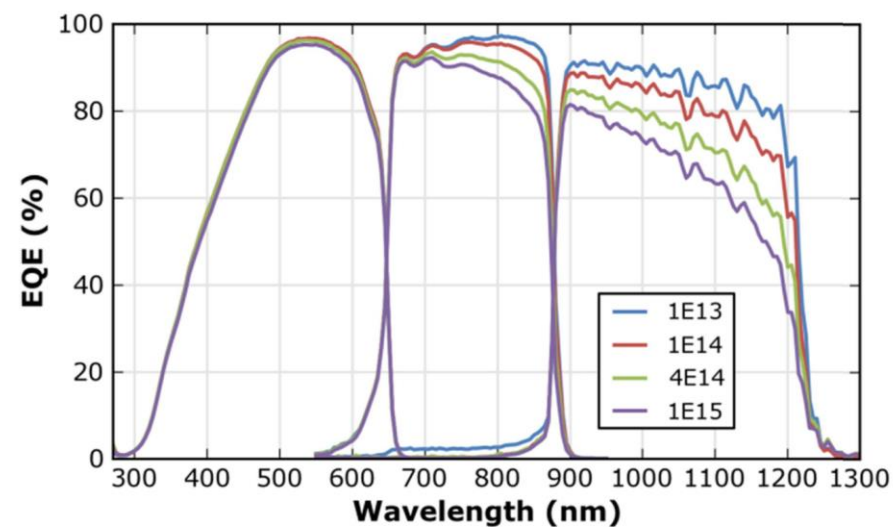
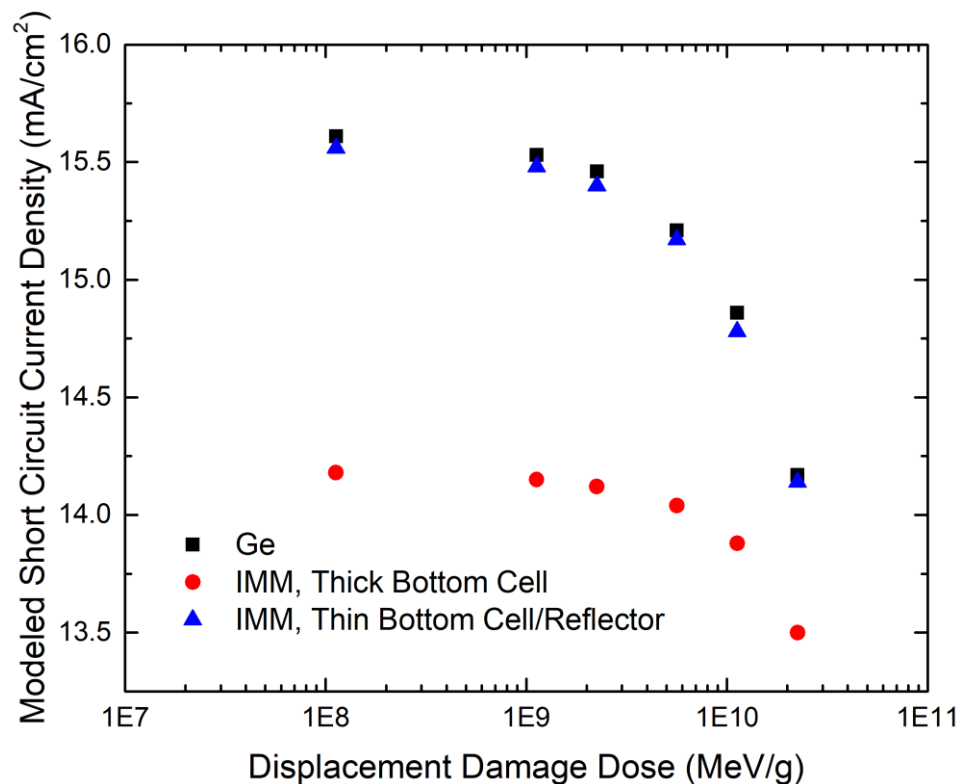
## 3. Use strained materials to increase PKO $E_A$

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



Kerestes et al. IEEE JOURNAL OF PHOTOVOLTAICS, VOL. 4, NO. 1, JANUARY 2014

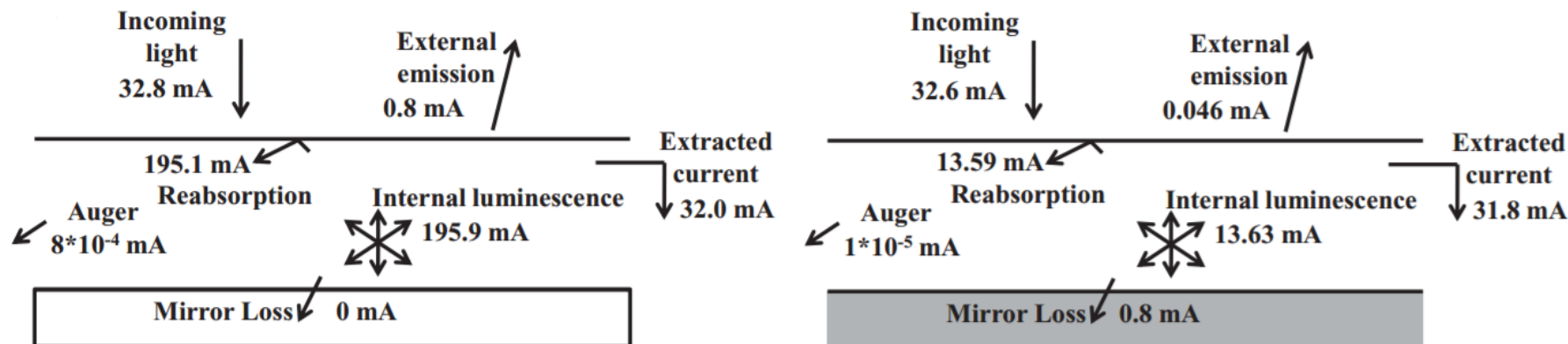
Thinning InGaAs subcell drast  
tolerance allowing for thicker  
higher EoL  $J_{SC}$ .



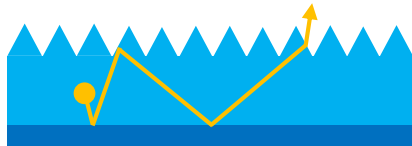
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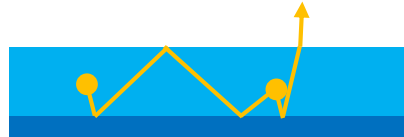
- Relies on high internal luminescence efficiency
  - Nearly perfect material quality
  - Difficult to maintain in space environment
  - Less compatible with multi-junction solar cells



O. D. Miller et al., "Strong Internal and External Luminescence as Solar Cells Approach the Shockley-Queisser Limit," *IEEE Journal of Photovoltaics*, vol. 2, no. 3, pp. 303–311, Jul. 2012.



Front Texture

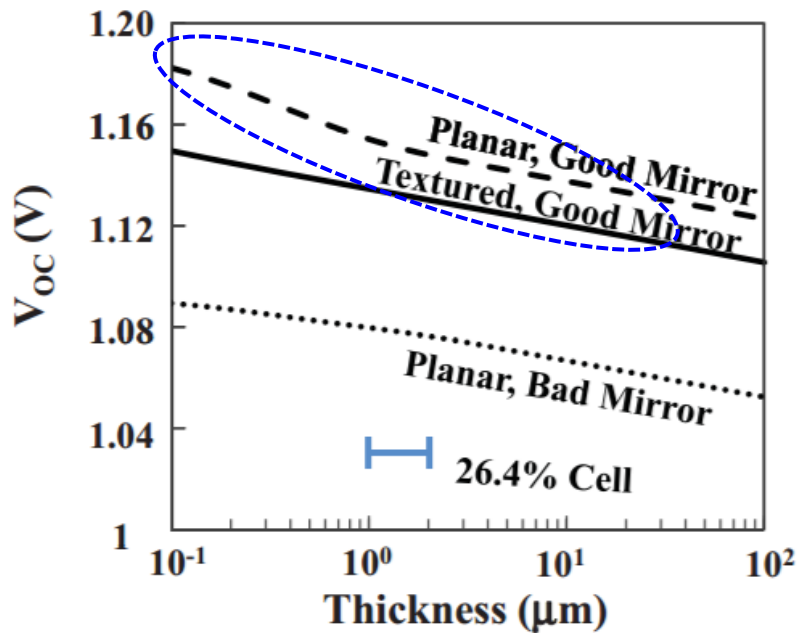


Planar

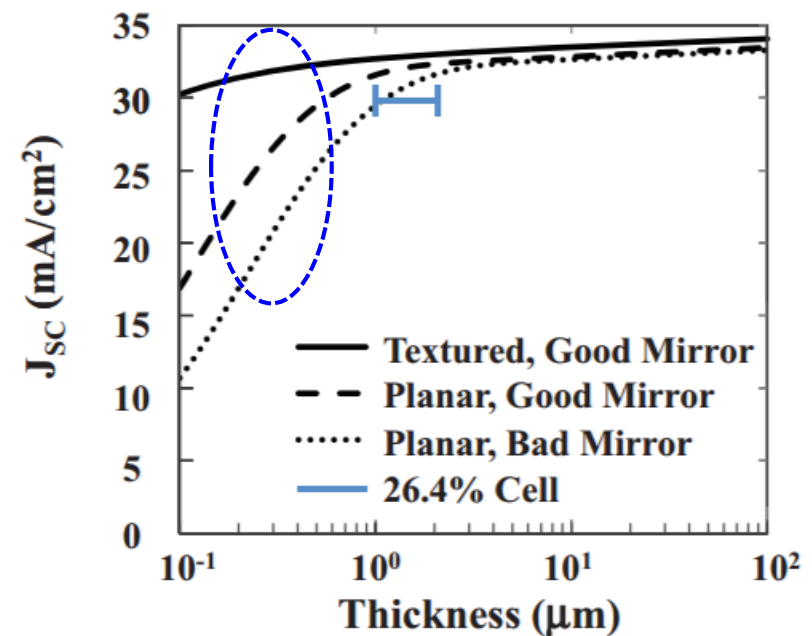


Index-matched substrate

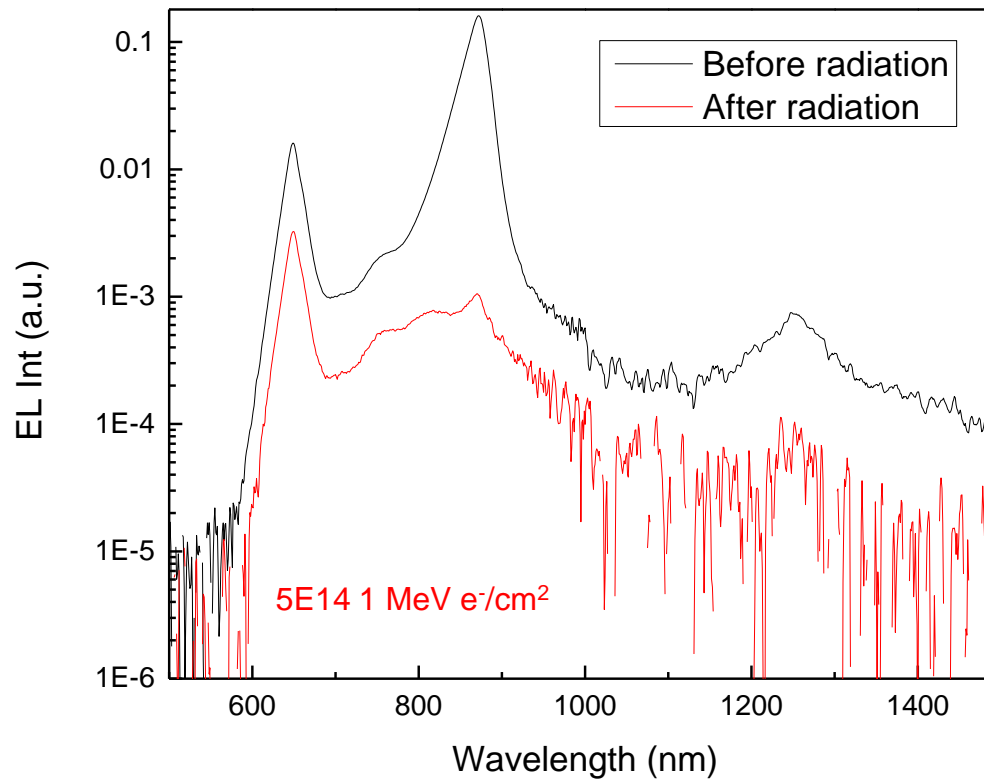
Enhanced  $\eta_{\text{ext}}$  from photon recycling with planar mirror



Texture provides greater OPL Enhancement



O. D. Miller et al., "Strong Internal and External Luminescence as Solar Cells Approach the Shockley-Queisser Limit," *IEEE Journal of Photovoltaics*, vol. 2, no. 3, pp. 303–311, Jul. 2012.

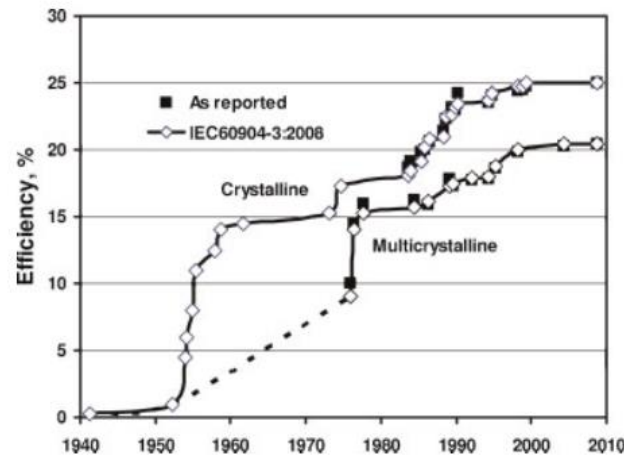
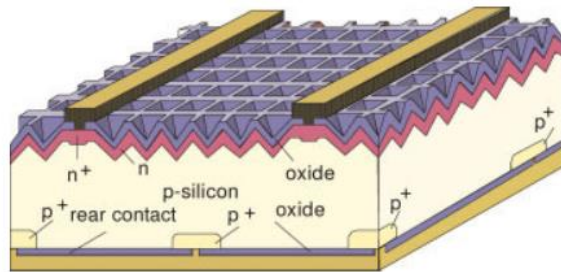


**Radiative efficiency does not hold up  
to radiation exposure**



- Heritage in high efficiency Si PV

Single-crystal silicon

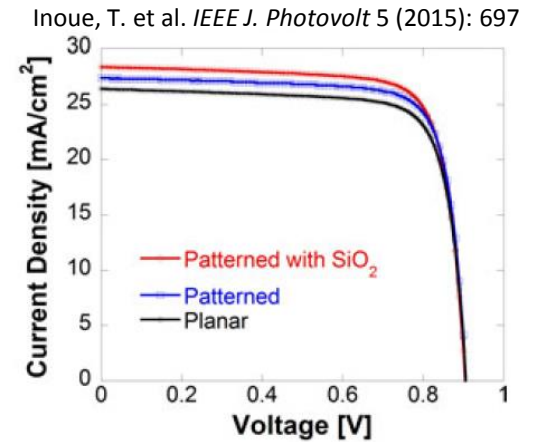
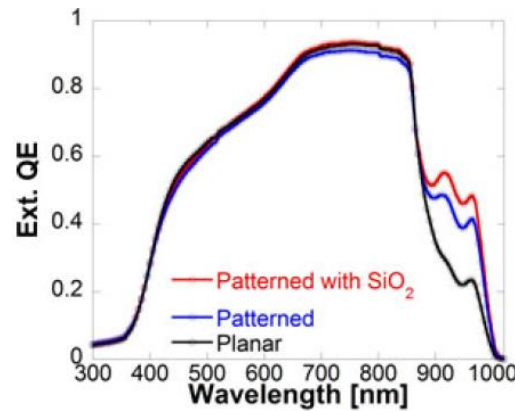
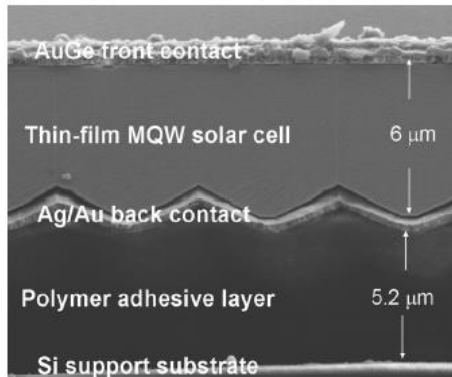


Green, M.A Prog. Photovolt: Res. Appl. 2009; 17:183–189

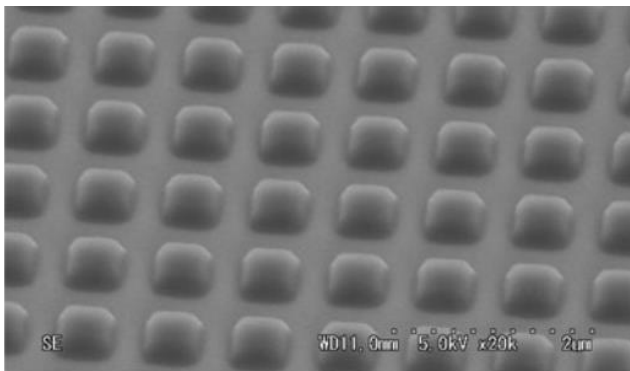
- Renewed interest in III-V to increase absorption in nanostructures

Potential method for improving radiation tolerance by thinning device structure

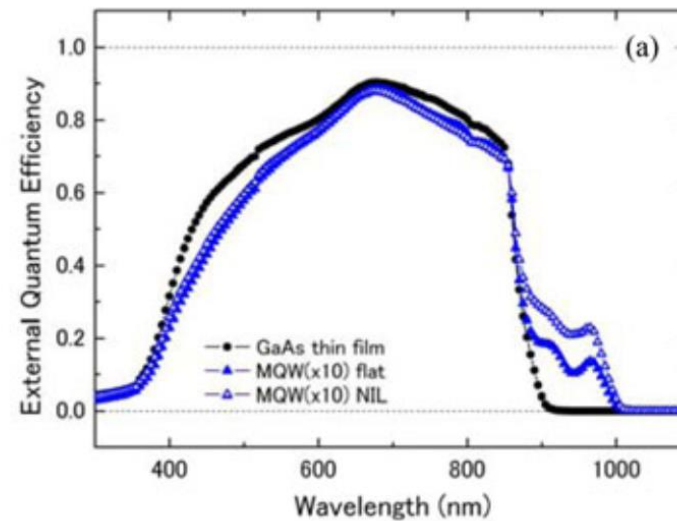
## MQW - anisotropic etch



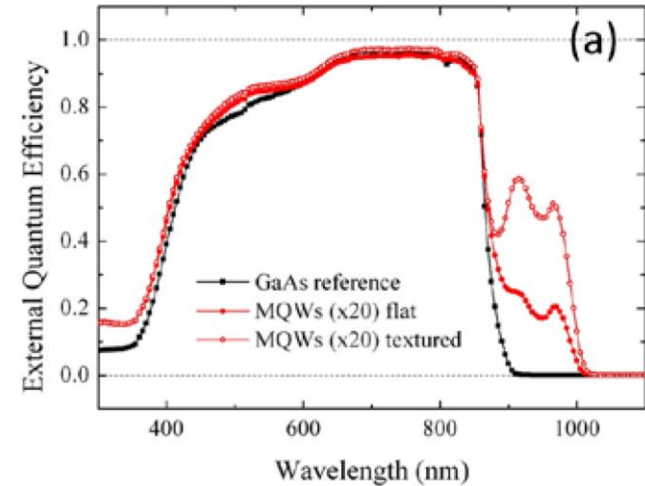
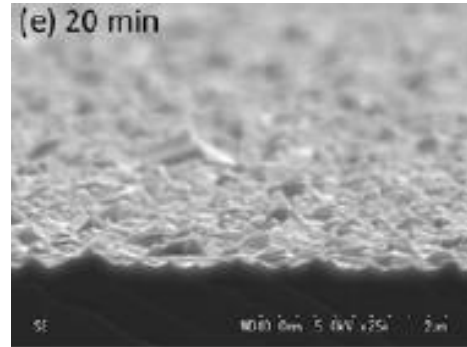
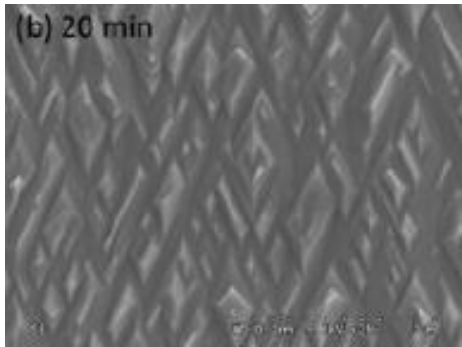
## MQW – Nanoimprinting



Watanabe, K. et al. *IEEE J. Photovolt* 4 (2014): 1086

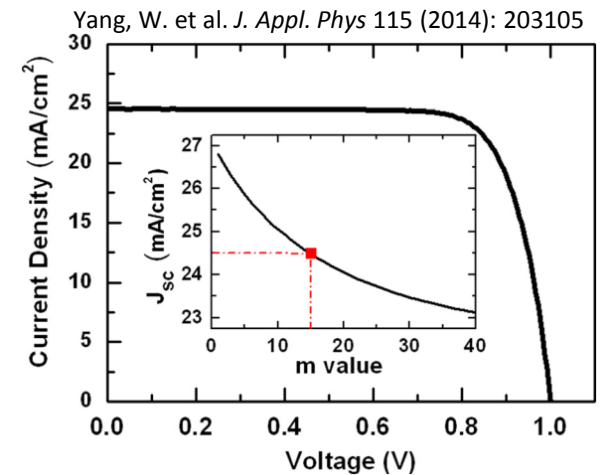
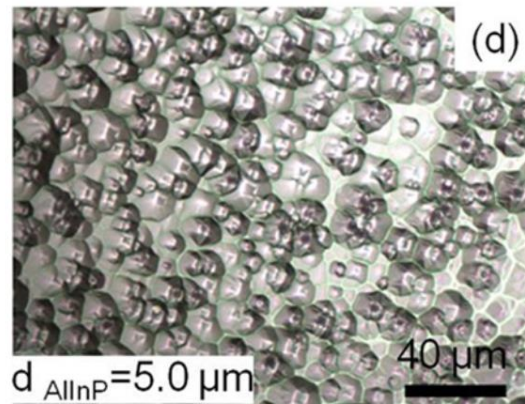
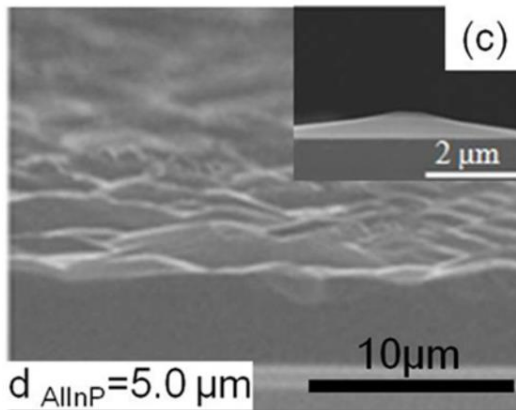


## MQW – Maskless crystallographic etch

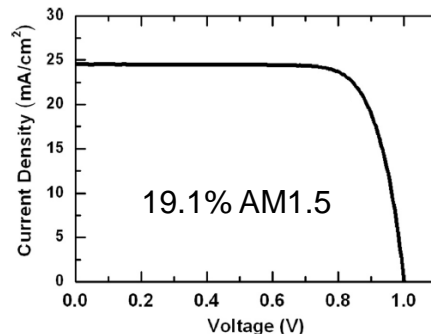
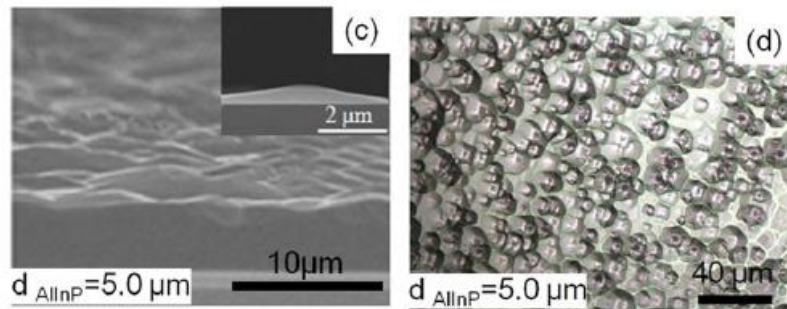
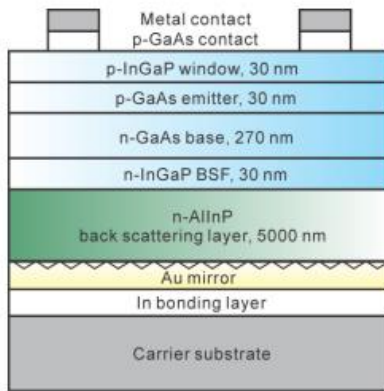


Watanabe, K. et al. *Euro. PV Solar Ener. Conf.* (2015): 181

## Ultra-thin GaAs: growth of textured InAlP







## Back-side texture

### - Advantages

No additional parasitic absorption in ARC compared to conventional cell

### - Disadvantages

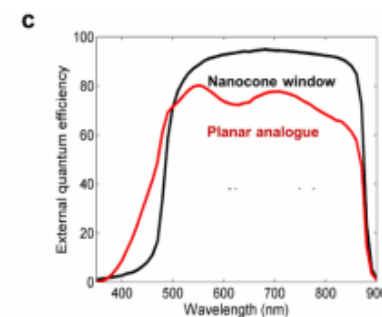
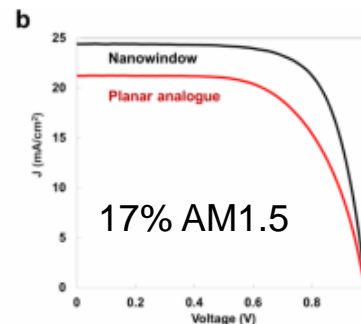
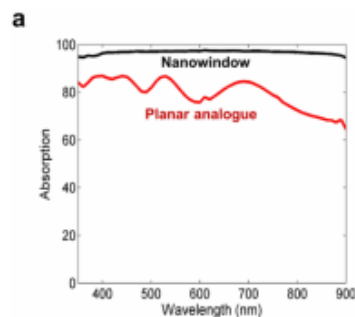
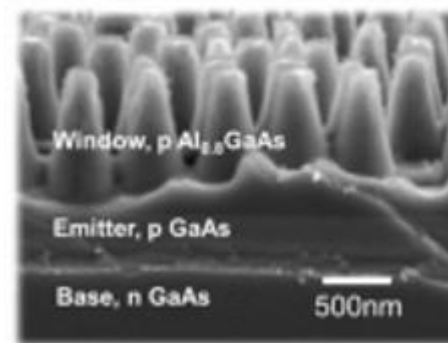
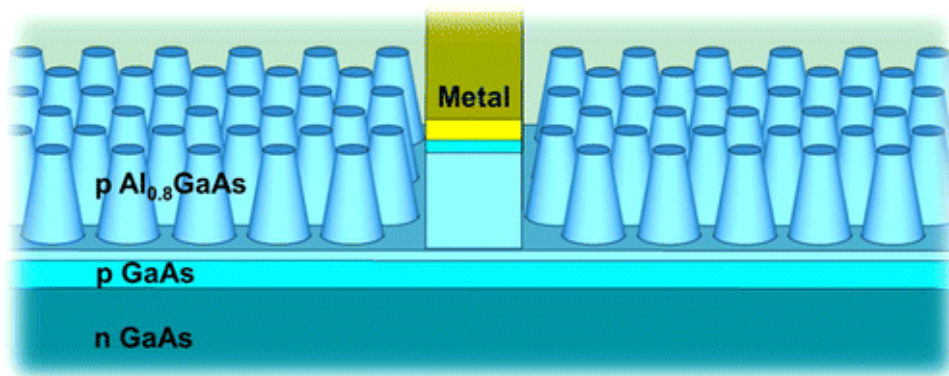
Fabrication complexity (substrate removal)

Here, inverted growth of AlInP transparent scattering layer resulted in 'textured' surface

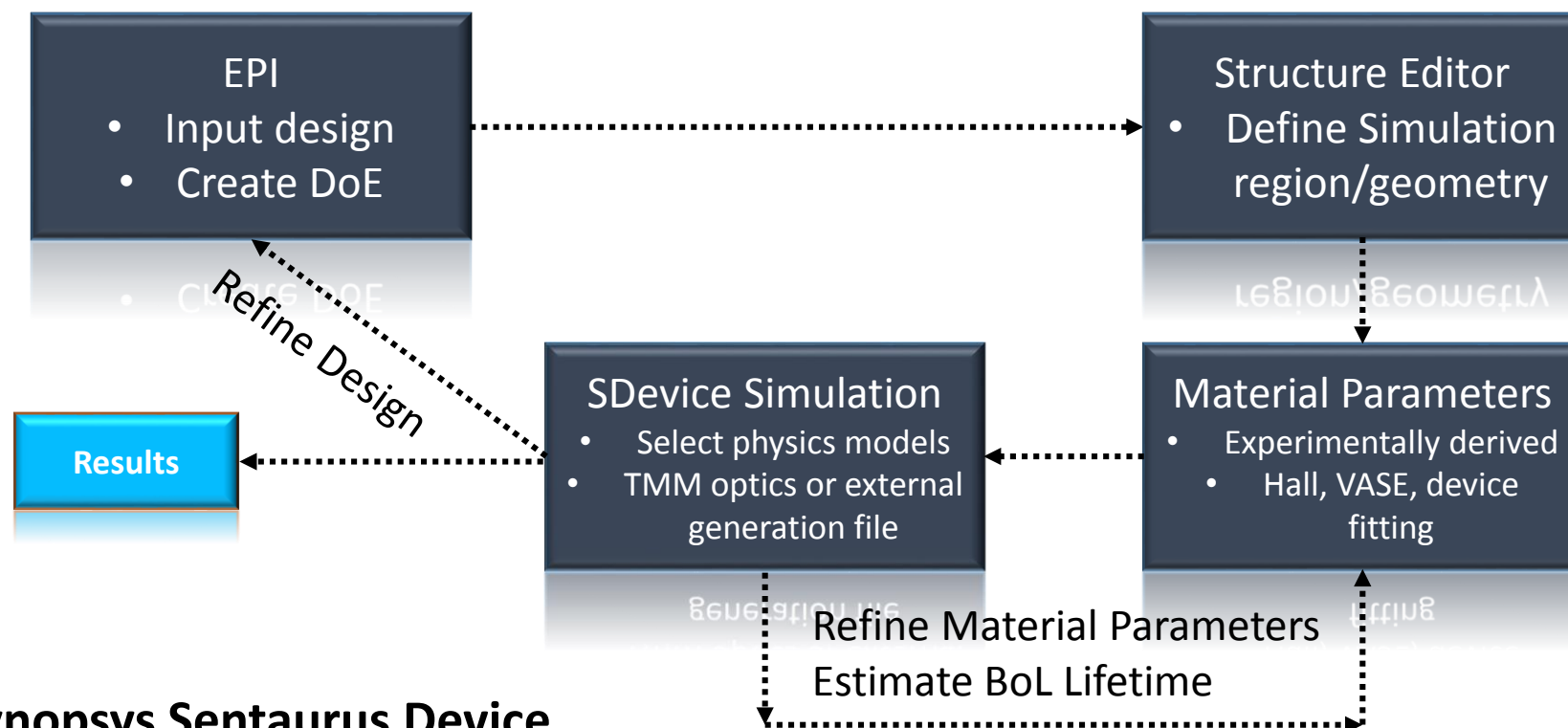
GaAs cell only 300 nm thick

W. Yang *et al.*, "Ultra-thin GaAs single-junction solar cells integrated with a reflective back scattering layer," *Journal of Applied Physics*, vol. 115, no. 20, p. 203105, May 2014.

- Frontside texturing
  - Advantages
    - Omni-directional ARC
  - Disadvantages
    - Parasitic Absorption of short wavelengths
    - Top cell sensitivity in multijunction design
- Here, the front  $\text{Al}_{0.8}\text{GaAs}$  window was nanostructured with cones
- Very thin cells possible, though the authors chose a  $3.3\ \mu\text{m}$  cell thickness



D. Liang, Y. Kang, Y. Huo, Y. Chen, Y. Cui, and J. S. Harris, "High-Efficiency Nanostructured Window GaAs Solar Cells," *Nano Lett.*, vol. 13, no. 10, pp. 4850–4856, Oct. 2013.



## • Synopsys Sentaurus Device

Description: Iterative solver for the Boltzmann and Poisson equations capable of simulating electrical characteristics of semiconductor devices

Used for: Simulating performance of solar cells with light trapping structures via inputting RSoft absorption results

Assumes:

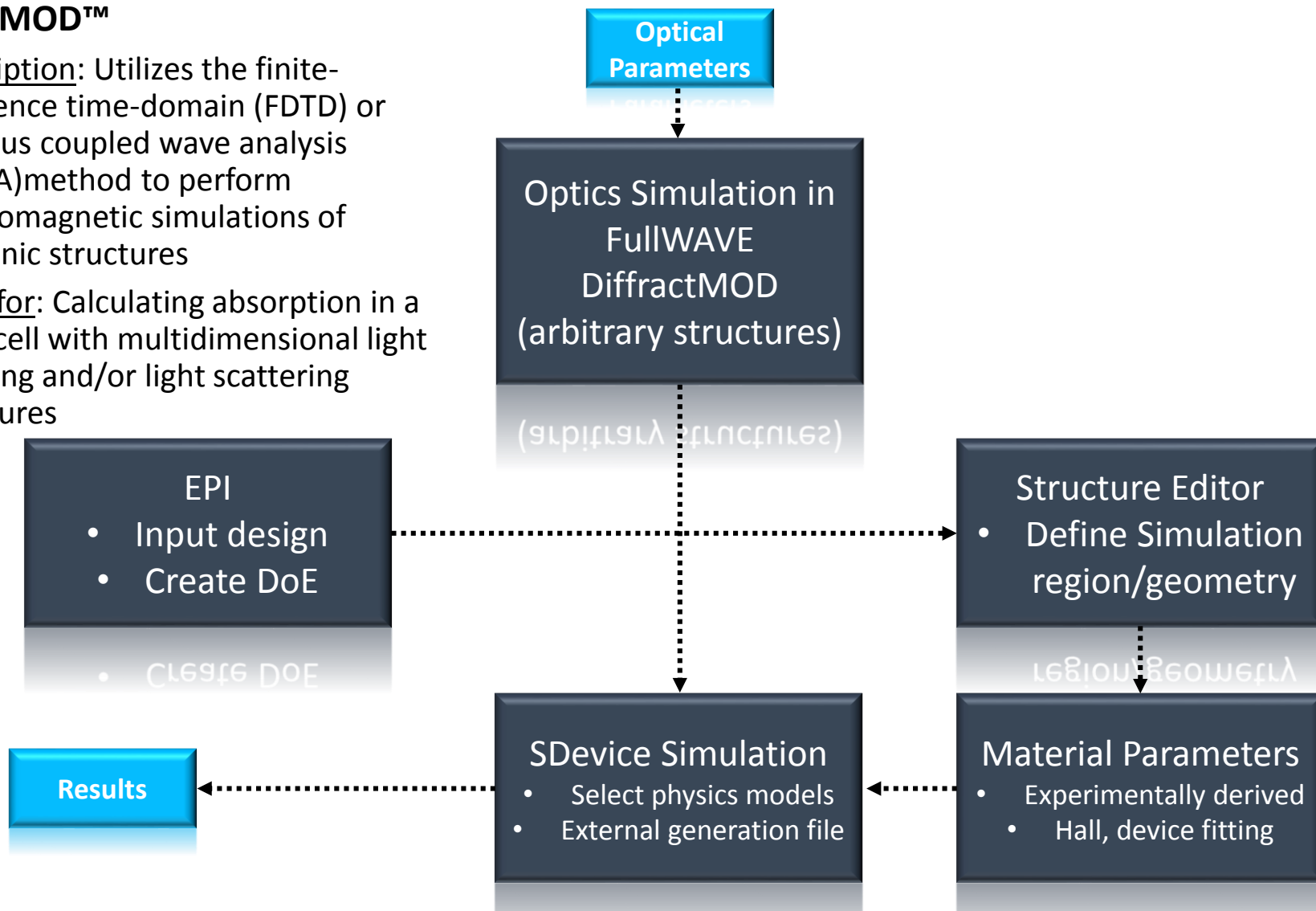
- InGaP/GaAs interface recombination velocity is low
- Empirical mobility/doping relationships (low compensation)

## Simulation Flow

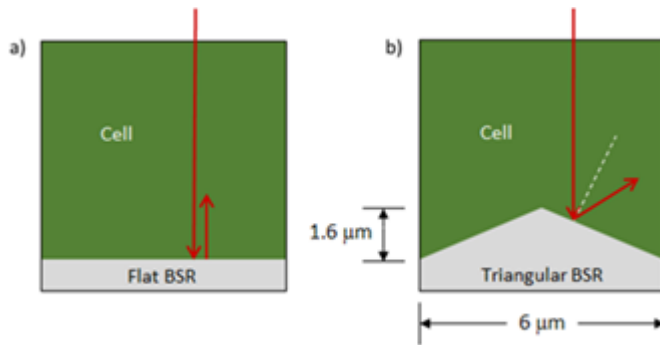
### • Synopsys RSoft FullWAVE™ & DiffractMOD™

Description: Utilizes the finite-difference time-domain (FDTD) or rigorous coupled wave analysis (RCWA) method to perform electromagnetic simulations of photonic structures

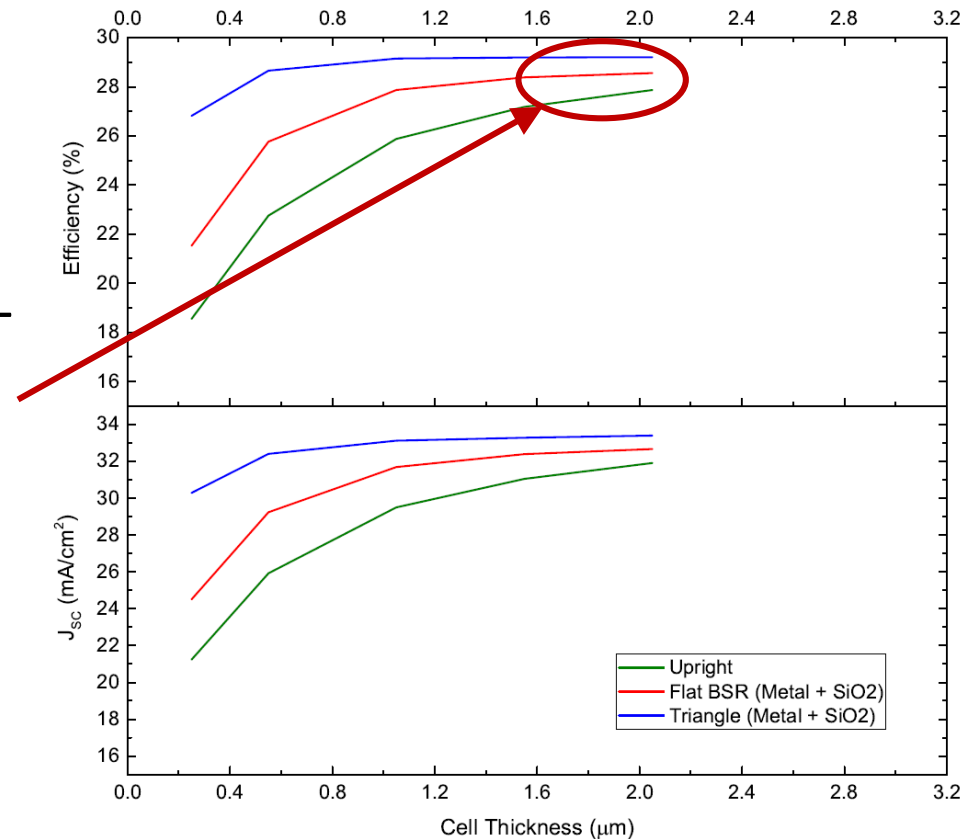
Used for: Calculating absorption in a solar cell with multidimensional light trapping and/or light scattering structures





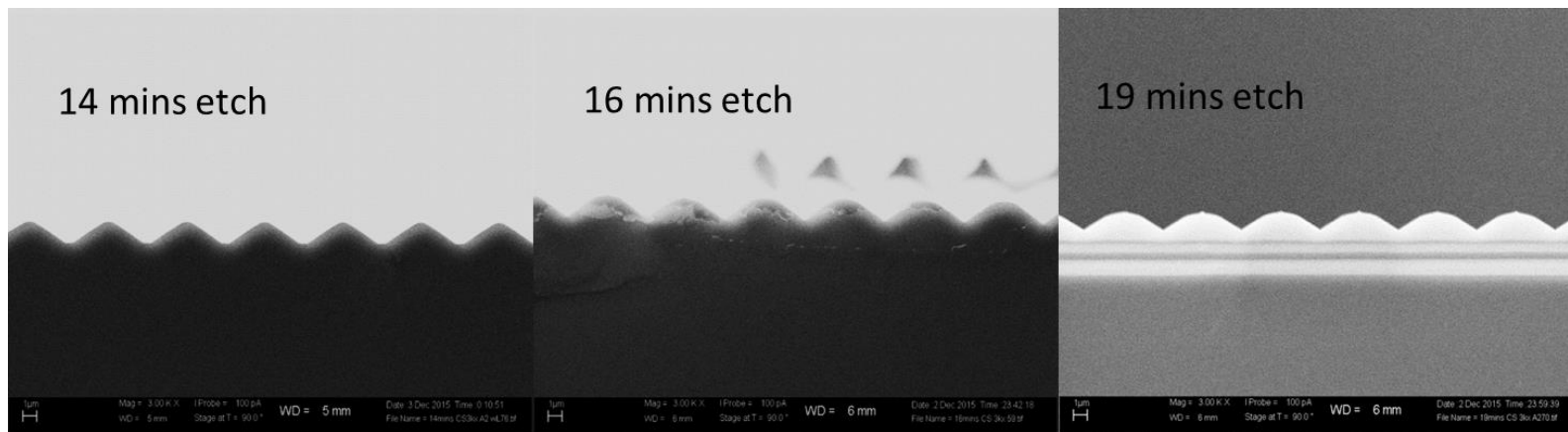
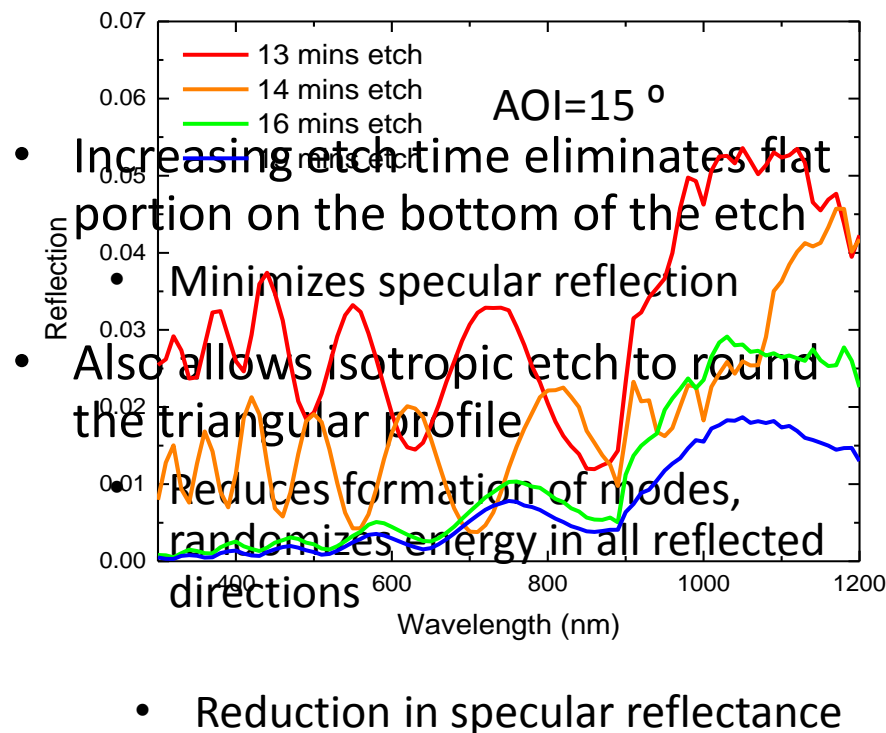
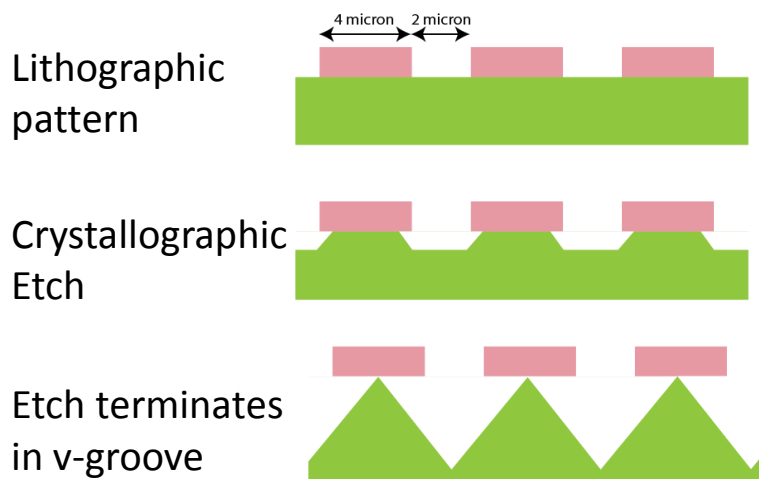


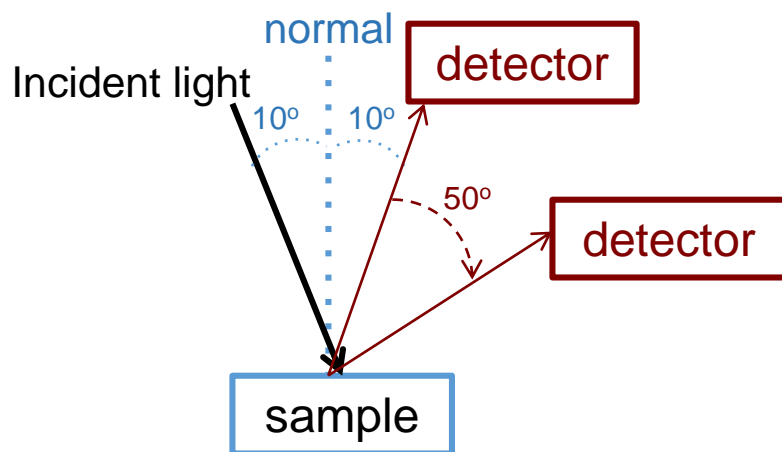
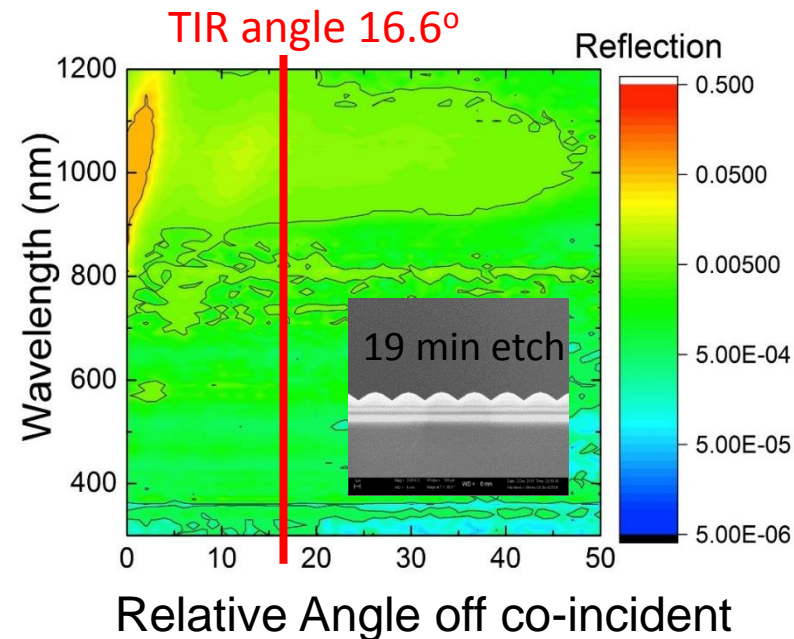
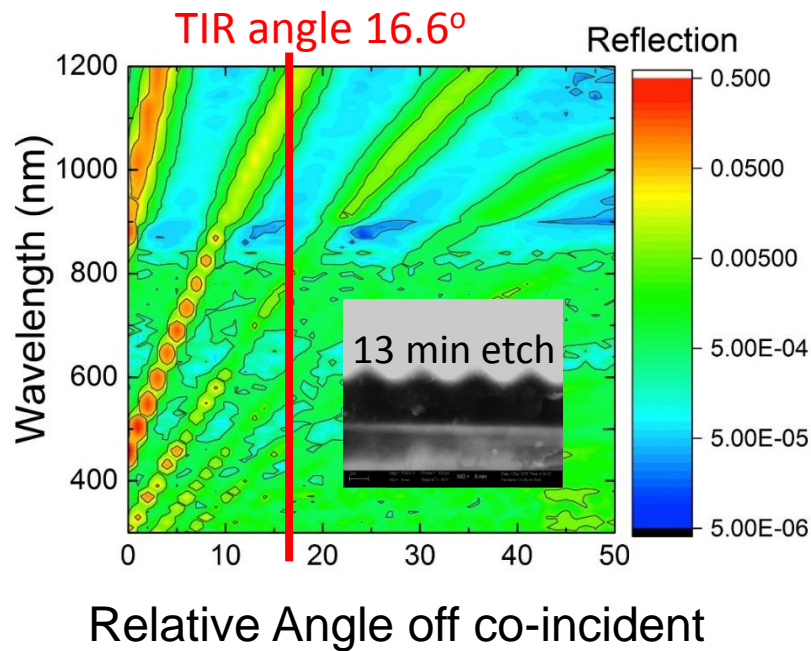
- Physics-based model of a back-side textured GaAs cell
- No photon recycling (emulate space environment)
- Textured cell maintains efficiency lead at 2  $\mu\text{m}$
- Thinner cells are more radiation tolerant



**Without photon recycling, textured BSR is preferable for OPL enhancement**

- 1:1:75  $\text{NH}_4\text{OH} : \text{H}_2\text{O}_2 : \text{H}_2\text{O}$
- Pitch = 1.6  $\mu\text{m}$
- Period = 6  $\mu\text{m}$

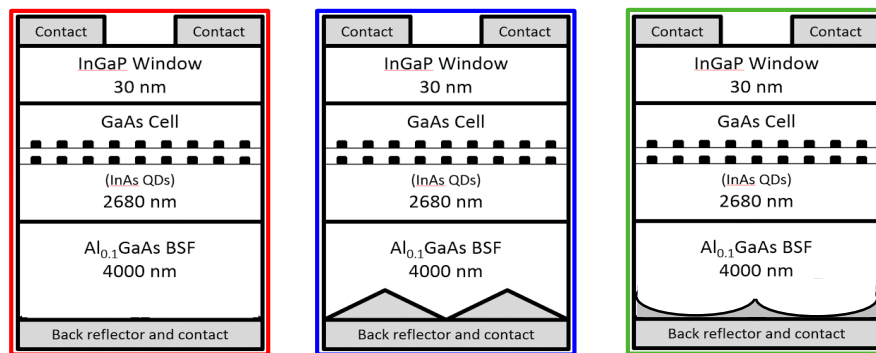




- Angle of incident light is 10°
- Detector angle varied by 50°, increment of 1°
- Reflection intensity in 19 mins etch shows less effect of diffraction grating than 13 mins etch

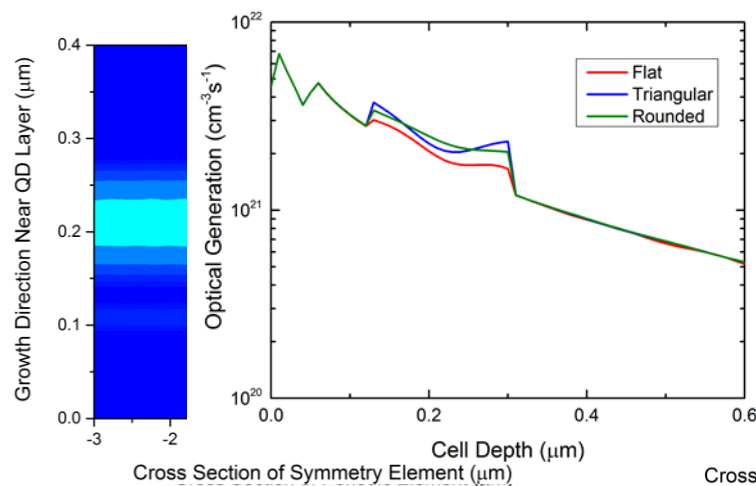
Percent of light totally-internally-reflected  
15.4% for 13 mins vs. 39.7% for 19 mins

- 1047 nm near QD absorption peak
- Flat < Triangular < Rounded
- Patterns mitigate destructive interference

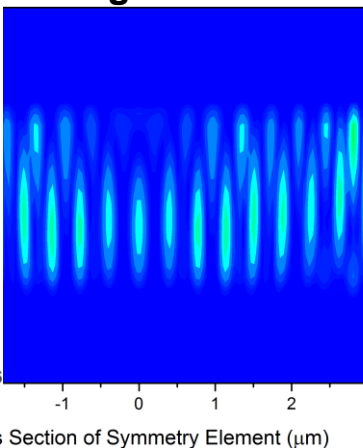


- RSoft FullWAVE™
  - Electric Field
  - Power Absorbed in QD region
  - AM1.5 optical generation
    - Integrated for all wavelengths
    - Rounded has better absorption for sum of entire spectrum, not just 1040 nm
- Generation curve imported into Sentaurus Device™
  - Simulated AM1.5 illuminated J-V curve
  - Pattern improves  $J_{SC}$  20.0 → 22.2 mA/cm<sup>2</sup>
  - Efficiency increase from 15.4% → 17.1%

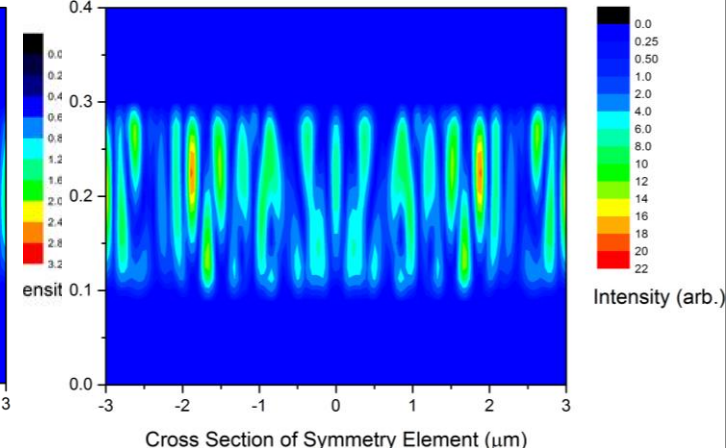
Power absorbed in QD region  
Intensity of electric field in bulk



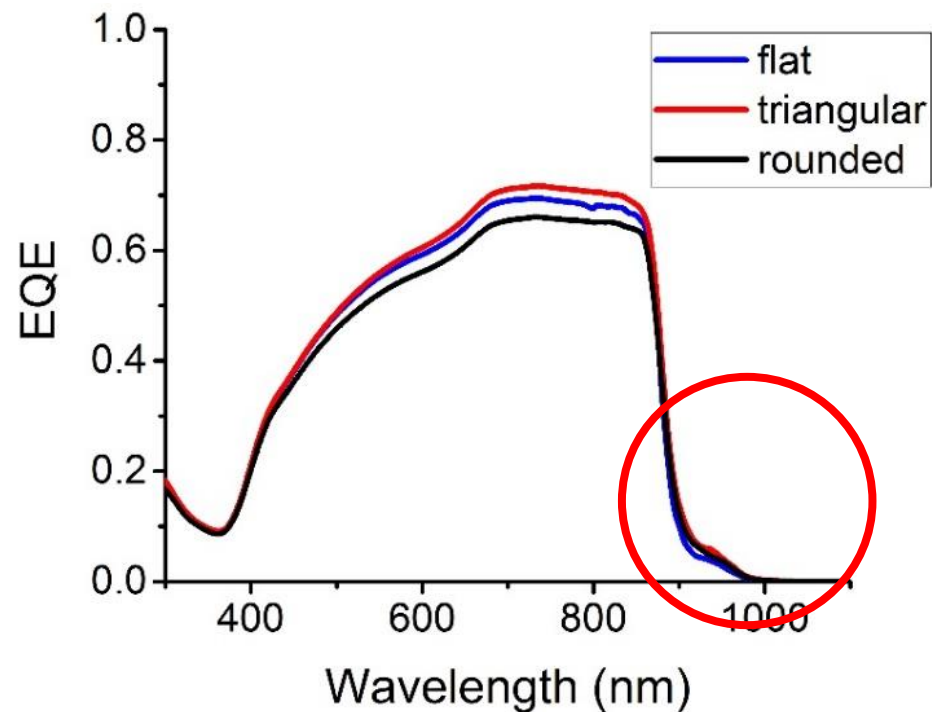
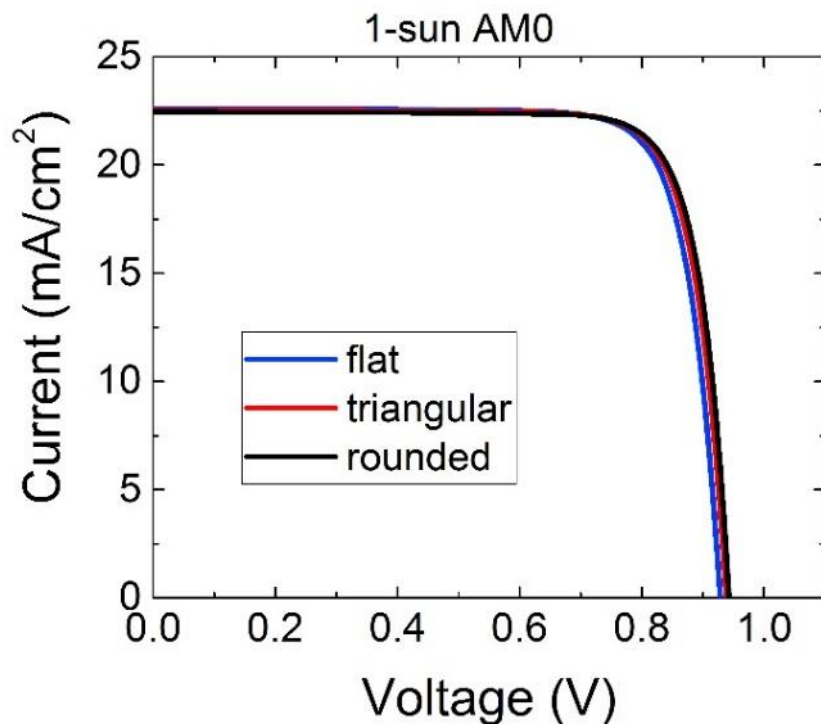
Triangular BSR



Rounded BSR





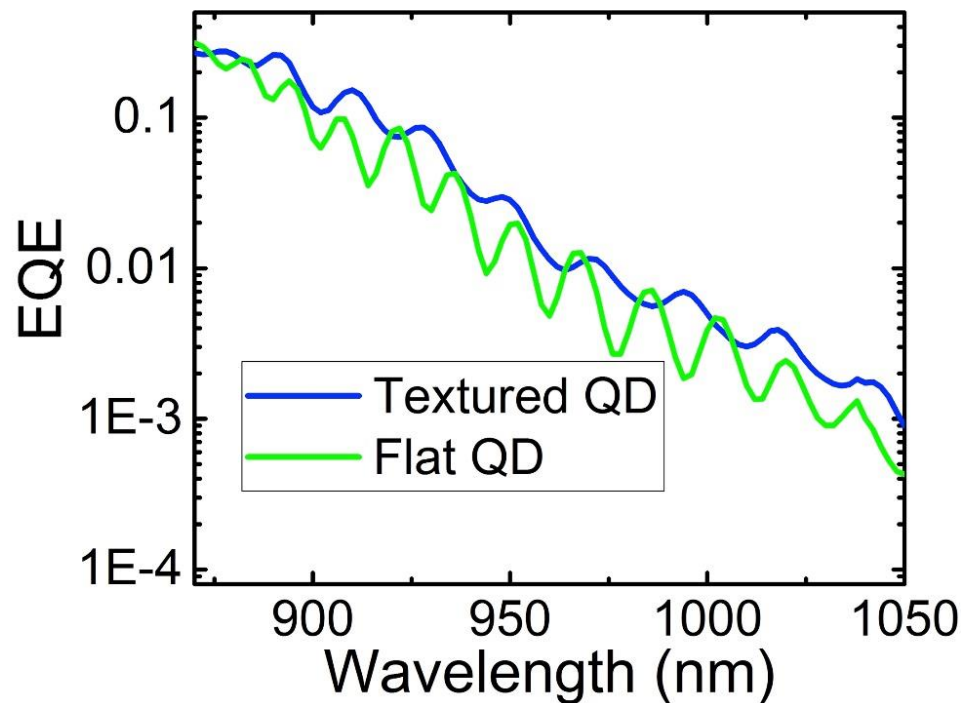


- Almost 80% EQE in bulk of devices

1-sun AM0	$J_{sc}$ (mA/cm <sup>2</sup> ) Avg (St. Dev)	$V_{oc}$ (V)	FF (%)	Eff (%)
Flat	22.49 (0.26)	0.93	77	11.86
Triangle	22.44 (0.09)	0.94	80	12.38
Rounded	22.36 (0.08)	0.94	81	12.49

- $J_{sc}$  QD enhancement masked by cross-wafer variability
- $V_{oc}$  trend with BSR texture

- Weak Absorber test vehicle for measuring OPL Enhancement



	Sub-880 nm Int QE (mA/cm <sup>2</sup> )	Optical Path Length
No BSR (prior experiment)	0.26	1
Flat	0.43	2 (assumed)
Triangle	0.53	2.46
Rounded	0.60	2.79

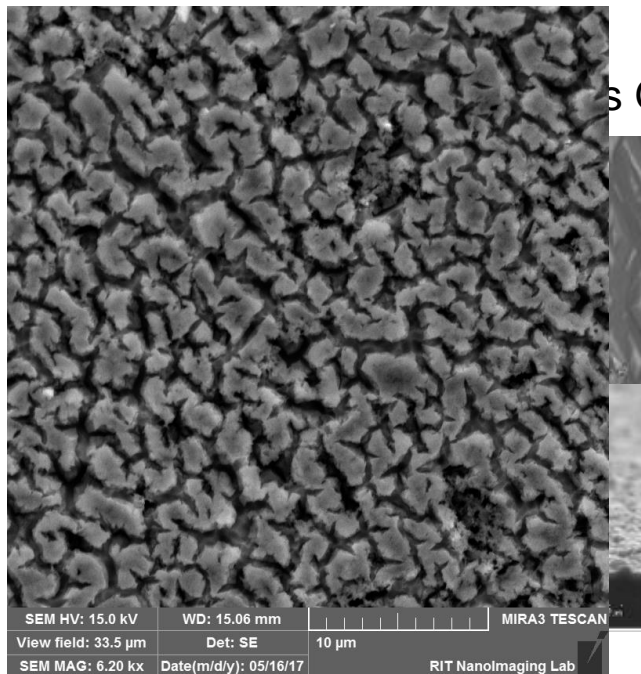
flat → triangular: 23% increase

flat → rounded: 40% increase

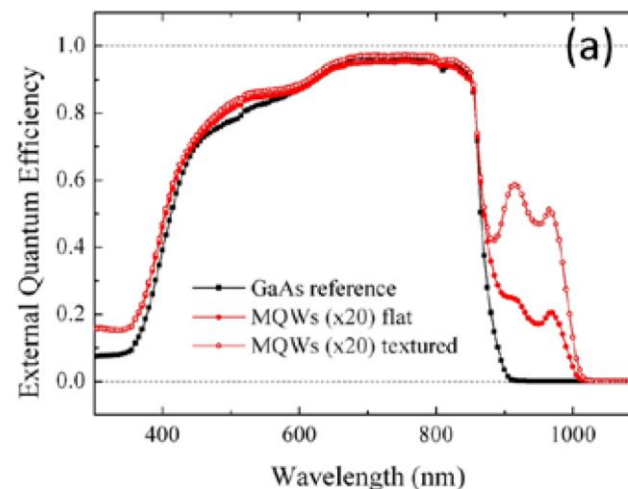
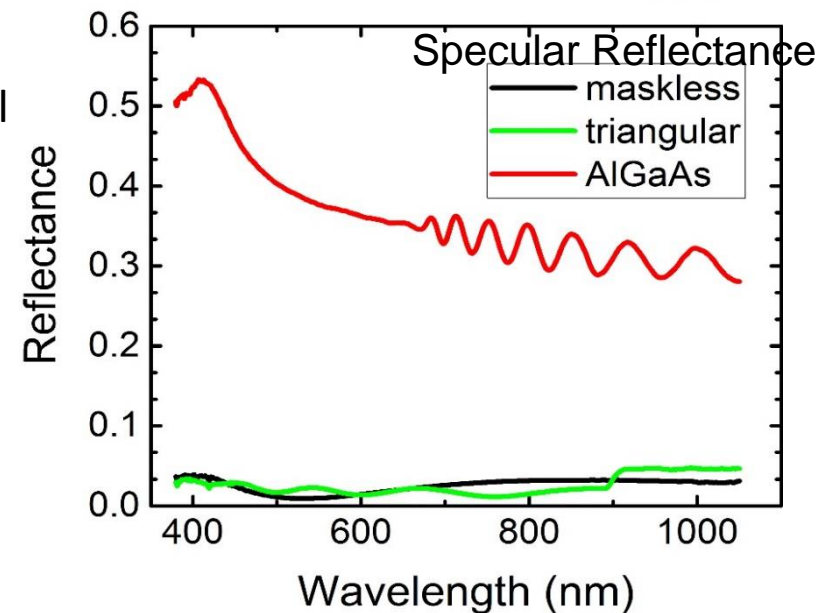
2-dimensional variation texture necessary for optical path length to approach Lambertian limit of  $4n^2$

Maskless texturing by crystallographic etch:  
GaAs etched for 25 minutes in:  
1:4:80  $\text{NH}_4\text{OH}:\text{H}_2\text{O}_2:\text{H}_2\text{O}$  at  $5^\circ\text{C}$

RMS Roughness: 58 nm



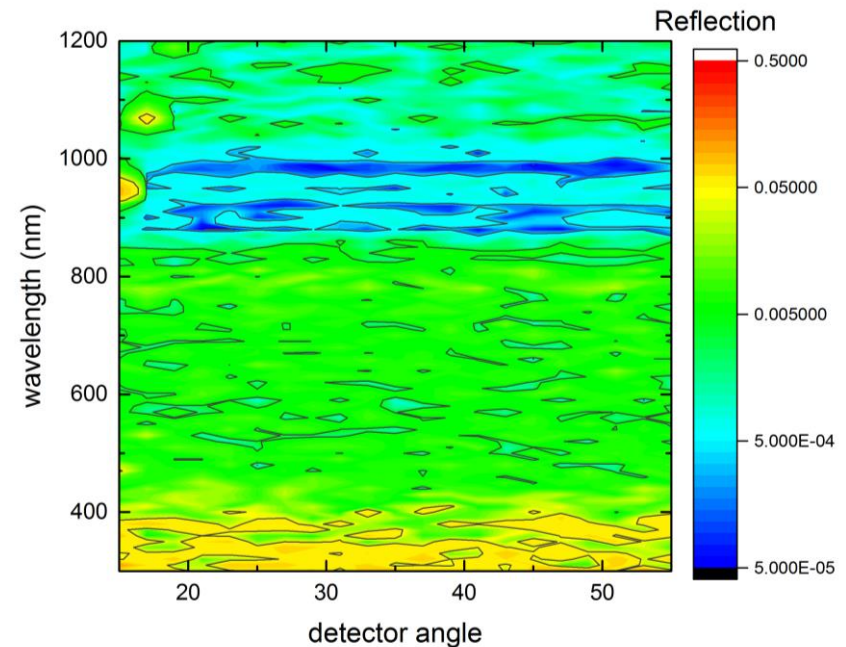
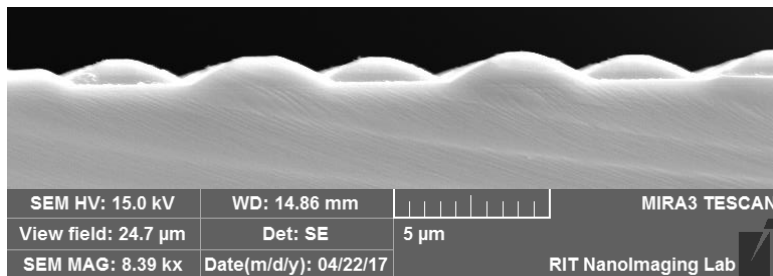
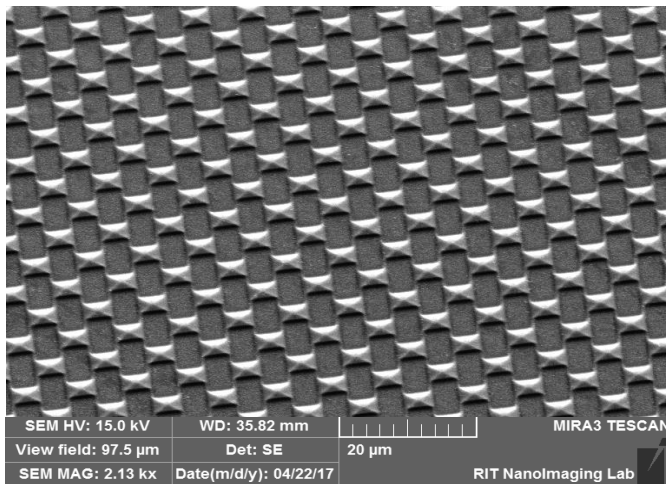
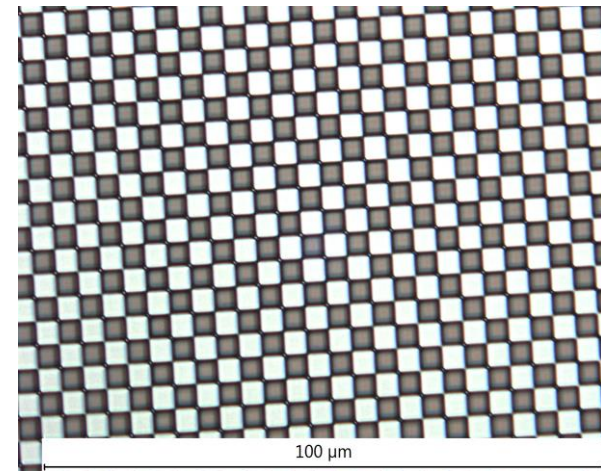
as GaAs texture: 3.5 effective optical path length



Watanabe, K. et al. *Euro. PV Solar Ener. Conf.* (2015): 181

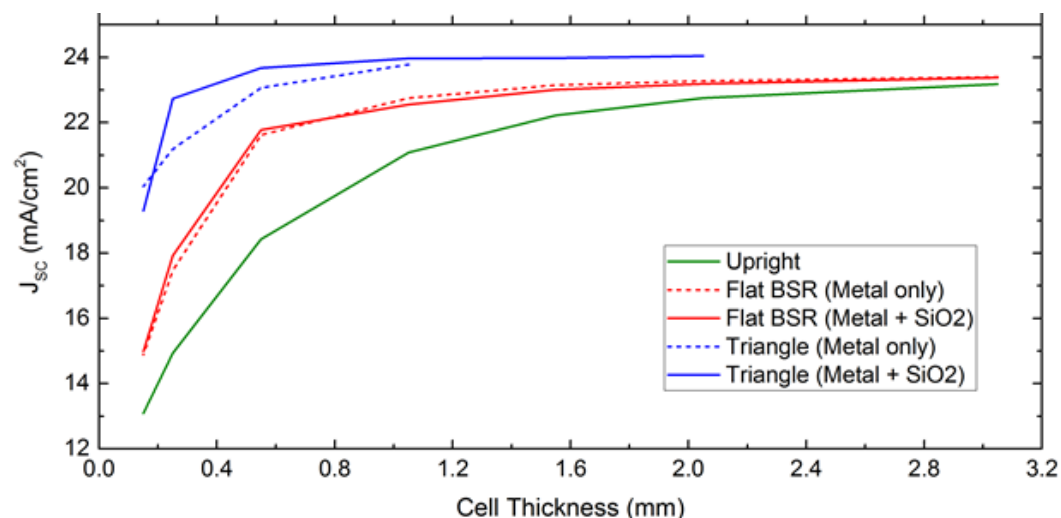
- Direct-write laser lithography
- 4  $\mu\text{m}$  x 4  $\mu\text{m}$  checkerboard
- 1:1:75  $\text{NH}_4\text{OH} : \text{H}_2\text{O}_2 : \text{H}_2\text{O}$
- 1  $\mu\text{m}$  height features

Photoresist pattern

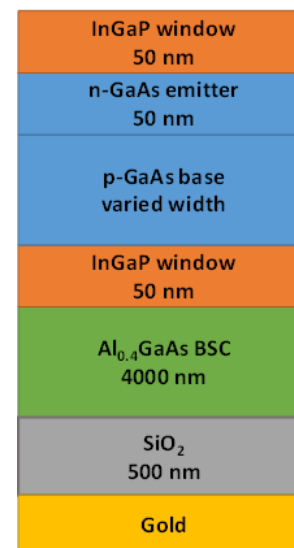
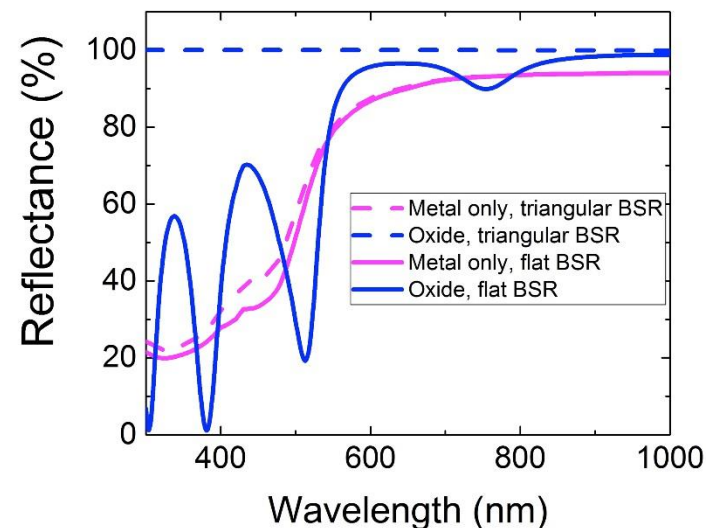




- Necessary to increase BSR reflectivity
- Transfer matrix method via TFCalc™
  - 500 nm SiO<sub>2</sub>
  - Oxide significantly enhances reflectivity for textured BSR



- Synopsys® RSoft FullWAVE™ electromagnetic simulations
- Synopsys® Sentaurus™ TCAD device simulation



- Significant increase for thin cells with textured BSR

- I. Background and Introduction to Multijunction Solar Cells
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- IV. Bandgap/Absorption Engineering & work at RIT

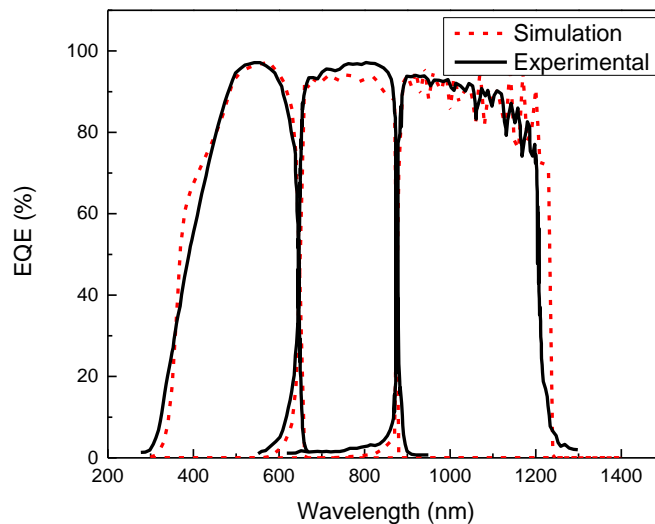
- Simulation of radiation damage
  - Modify material parameters to match reduction in minority carrier lifetime
  - Reduce dopant concentration to simulate carrier removal

Damage Coefficient

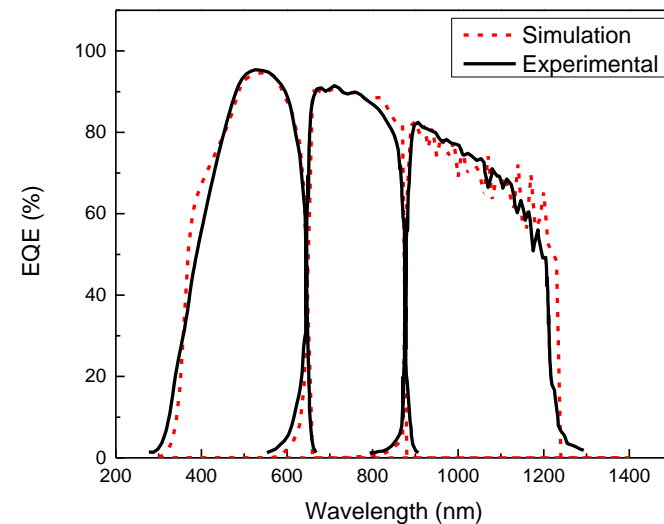
Flux

$$\frac{1}{L_{\phi}^2} = \frac{1}{L_0^2} + K_L \phi$$

**e<sup>-</sup> radiation: 1e13**

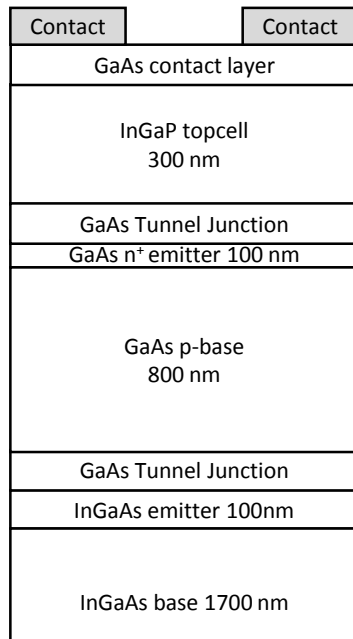


**e<sup>-</sup> radiation: 1e15**

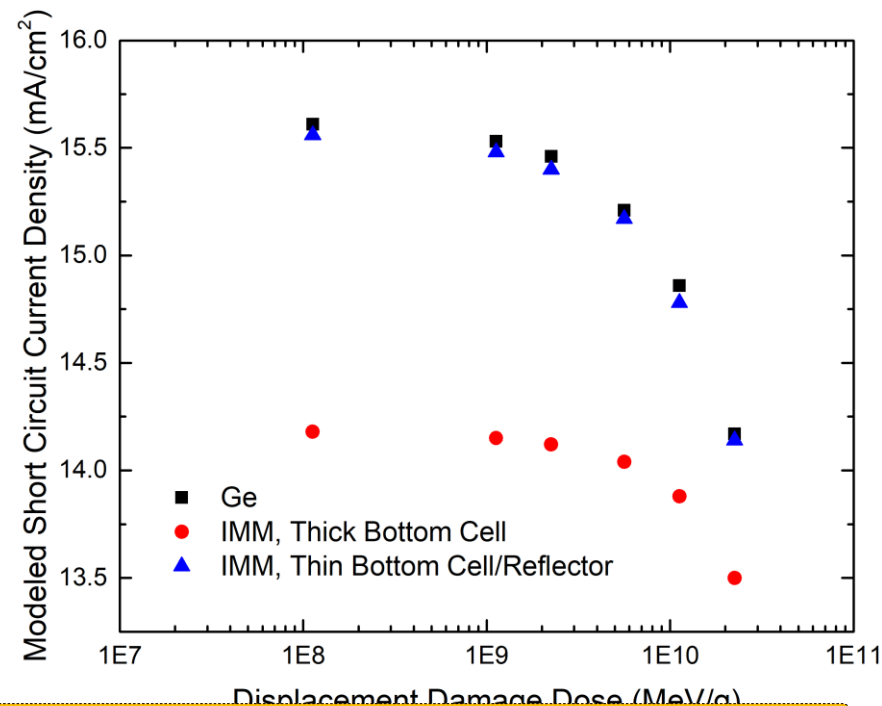
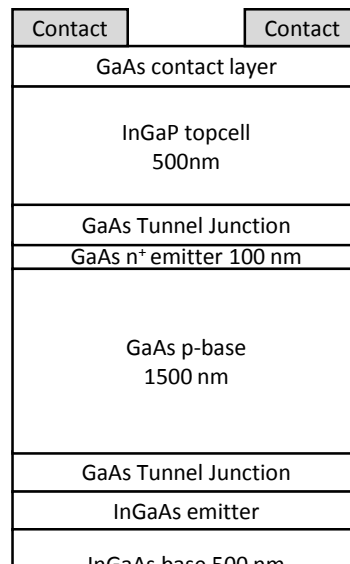


- Thinning InGaAs subcell drastically enhances radiation tolerance allowing for thickening of Middle Junction and higher EoL  $J_{SC}$ .

[Non-reflective Back Contact]



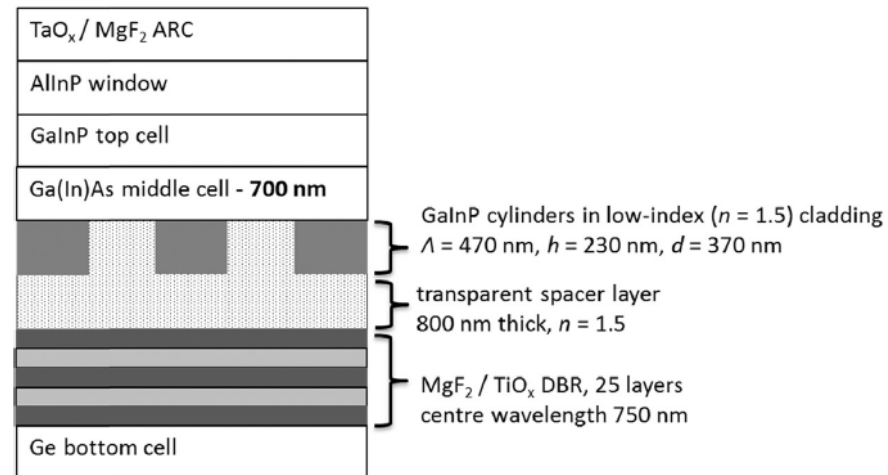
[Reflective Back Contact]



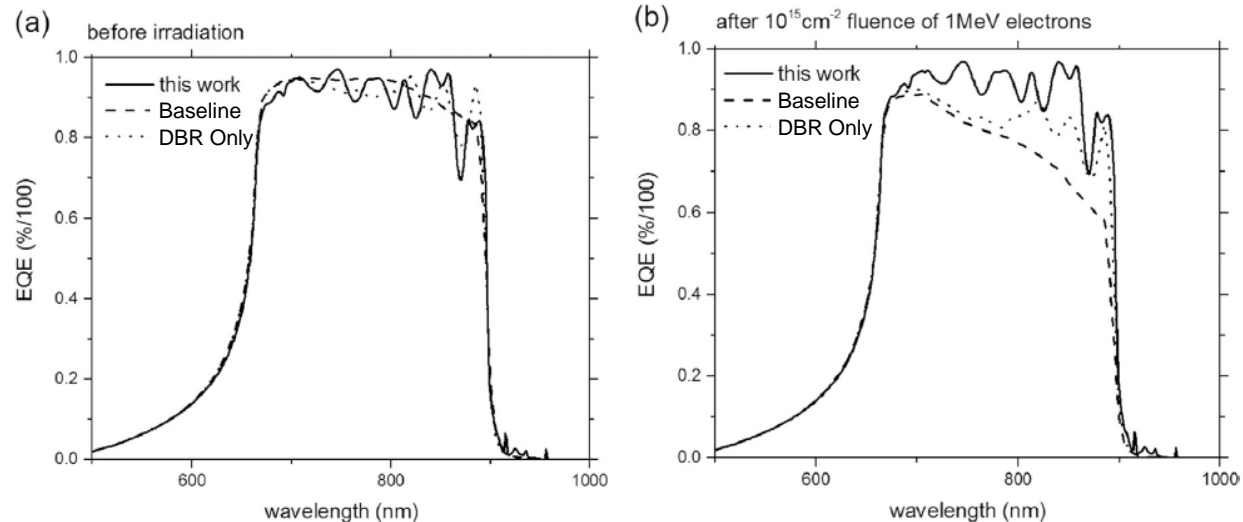
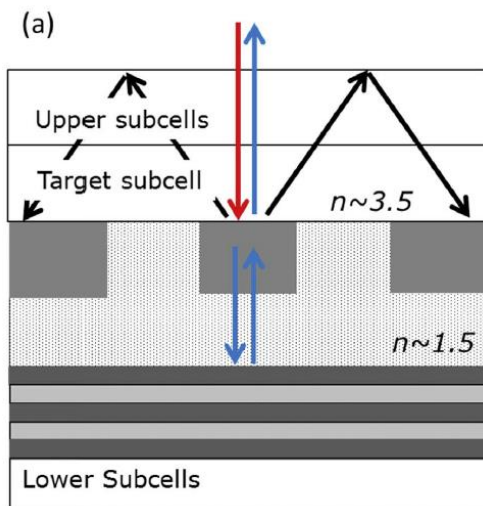
**EoL Performance limited by GaAs subcell in upright and BSR enhanced IMM**



- Diffraction grating + Transparent Spacer + DBR
  - Enhance current in GaAs subcell
  - Radiation harden the GaAs subcell by thinning (700 nm)

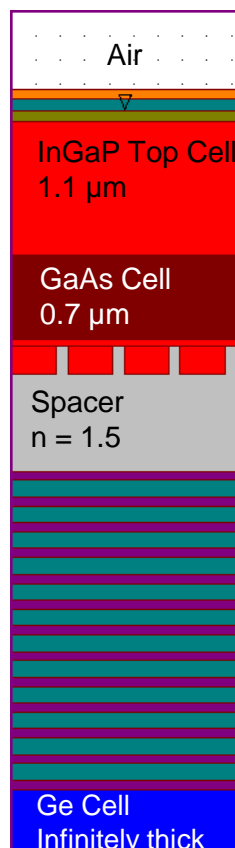


## Light trajectory



A. Mellor, N. P. Hylton, S. A. Maier, and N. Ekins-Daukes, "Interstitial light-trapping design for multi-junction solar cells," *Solar Energy Materials and Solar Cells*, vol. 159, pp. 212–218, Jan. 2017.

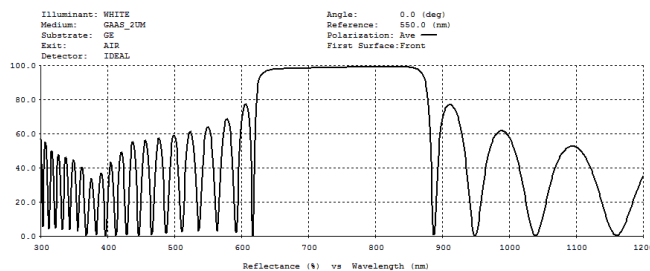
- Simulation using Rsoft and Sentaurus



MgF<sub>2</sub>/ZnS ARC

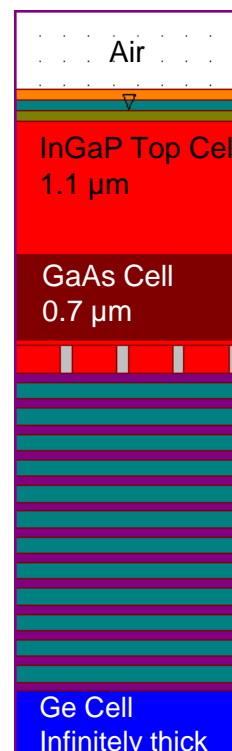
InGaP window  
InGaP Grating

MgF<sub>2</sub>/TiOx  
25 Layer DBR

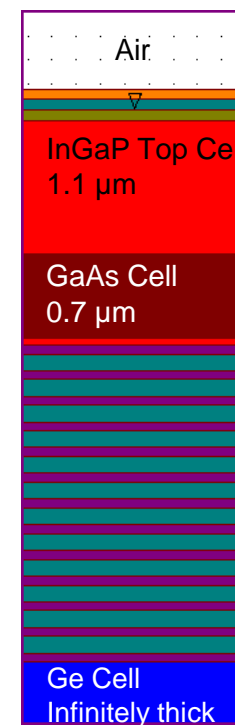


**Gra+Sp+DBR**  
(Grating + Spacer +  
DBR)

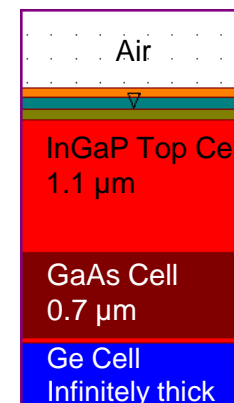
DBR reflection



**Gra+DBR**  
(Grating +  
DBR)

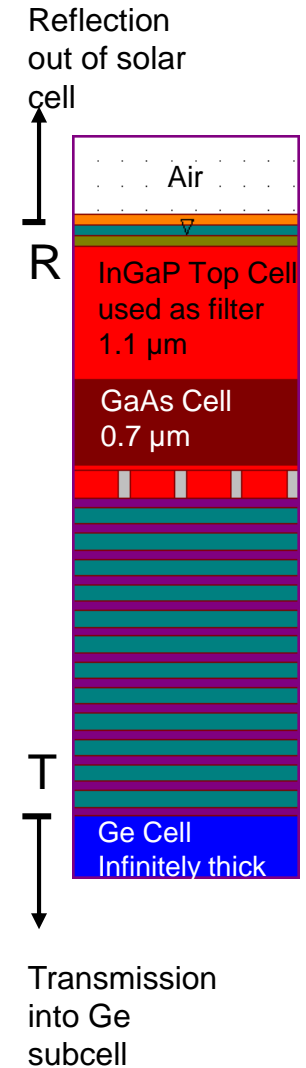
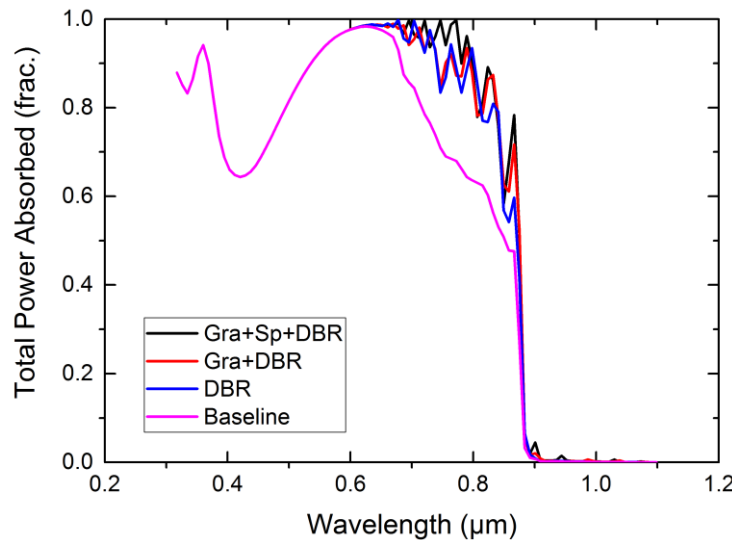
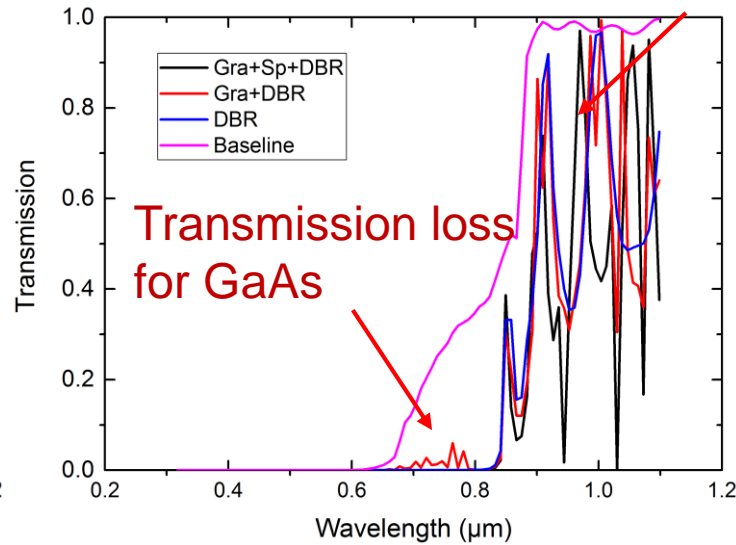
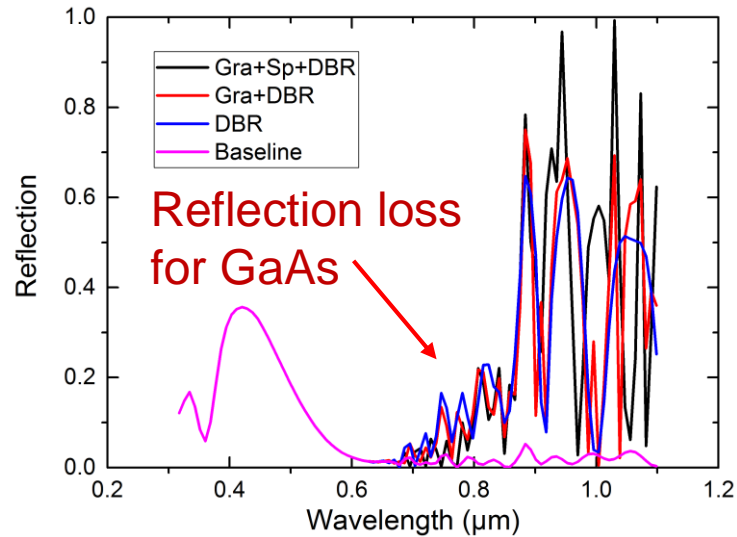


**DBR only**

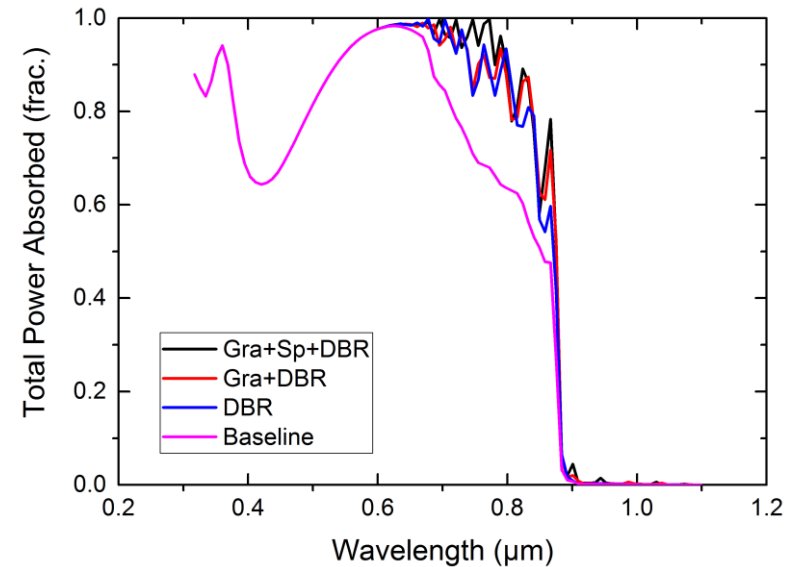
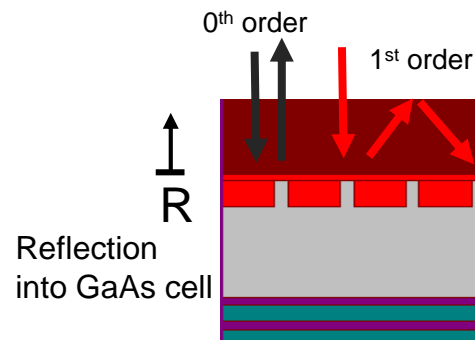


**Baseline**

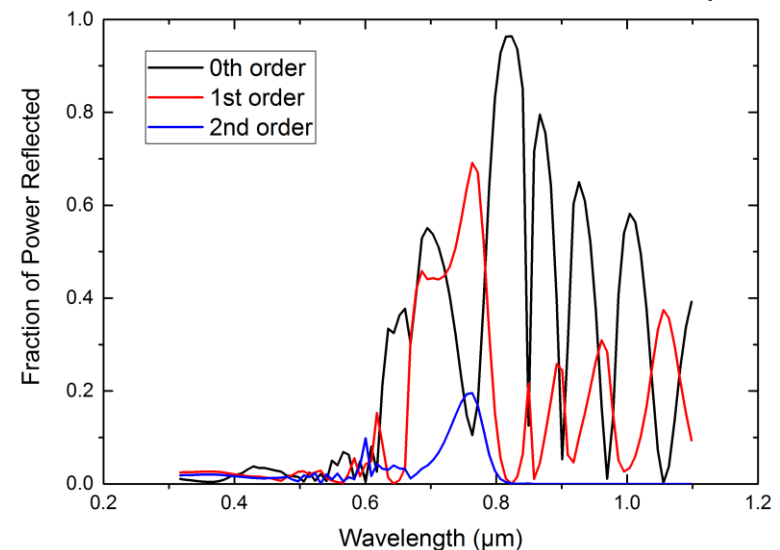
Wavelengths not transmitted into Ge



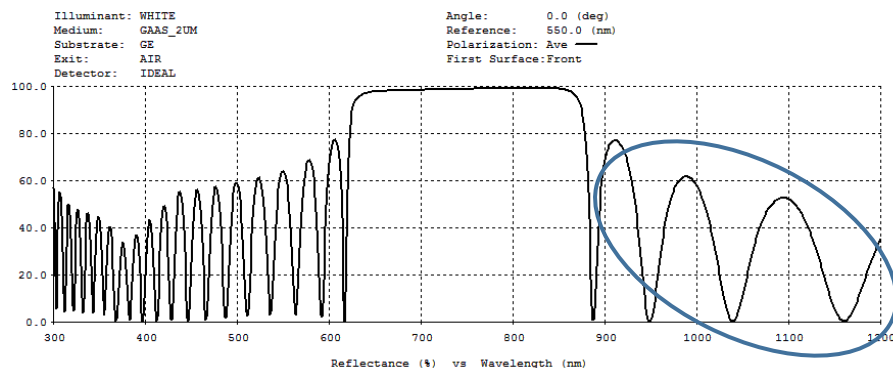
- Grating + Spacer + DBR has highest absorption for wavelengths absorbed in GaAs base
- Without spacer layer, oblique angles can transmit through DBR
- Without grating, 0.7  $\mu\text{m}$  GaAs cell is not thick enough to absorb all light
  - light reflects off DBR and escapes through the front surface
- Some loss of light transmitted into bottom subcell
- Current grating structure scatters most at  $\sim 760 \mu\text{m}$ 
  - 1<sup>st</sup> order diffraction angle is  $\sim 28^\circ$



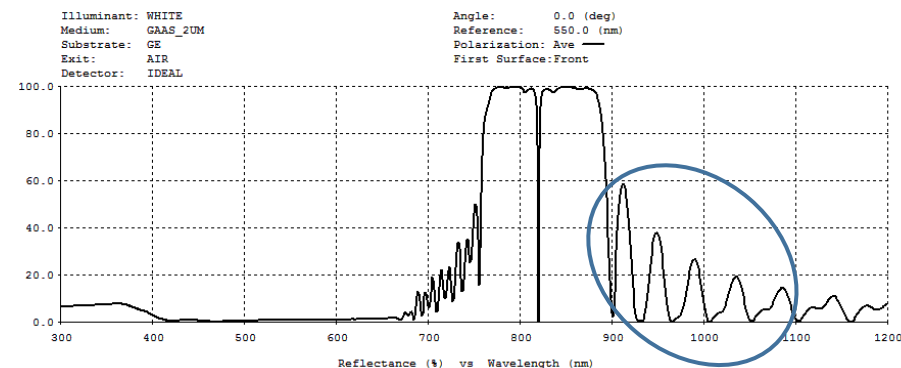
Reflection vs diffraction order of Gra+Sp+DBR







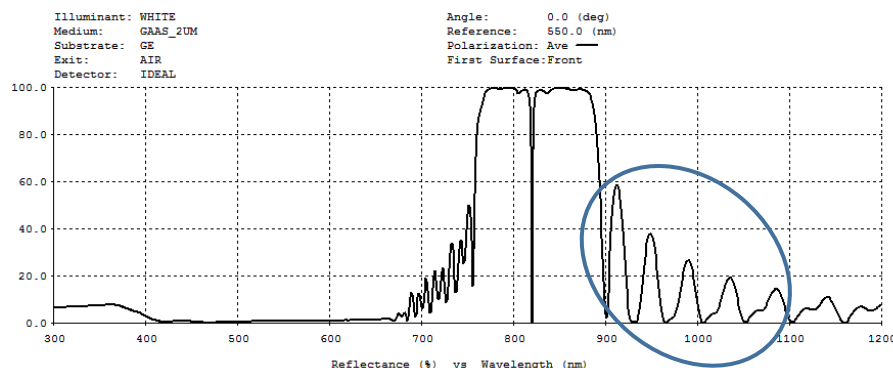
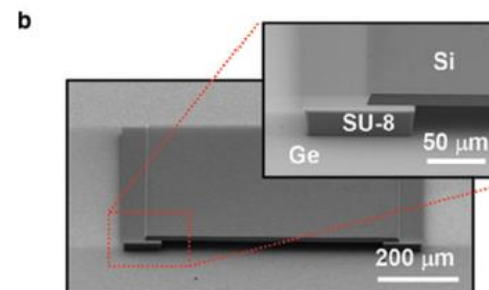
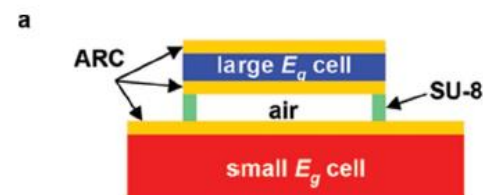
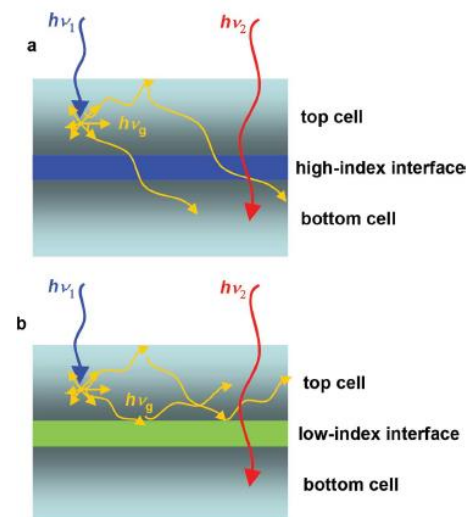
MgF<sub>2</sub>/TiO<sub>x</sub> DBR



AlAs/AlGaAs DBR

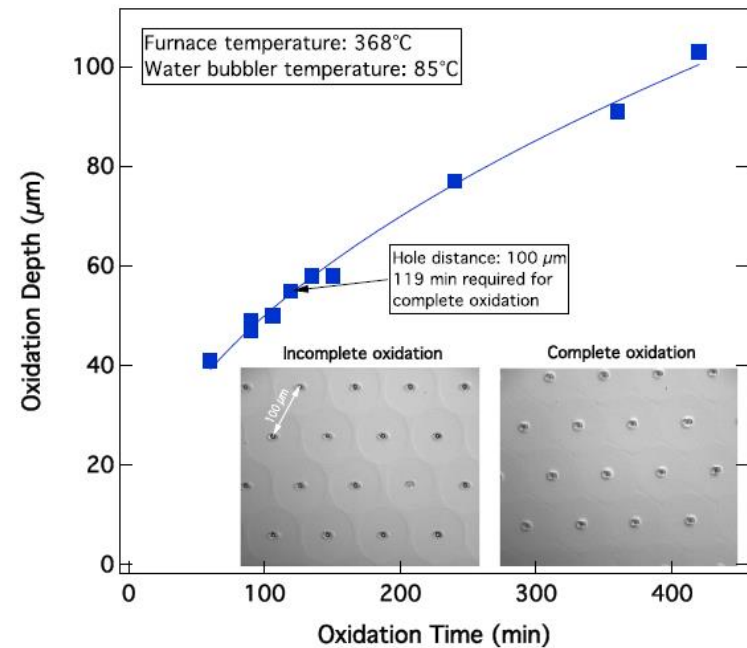
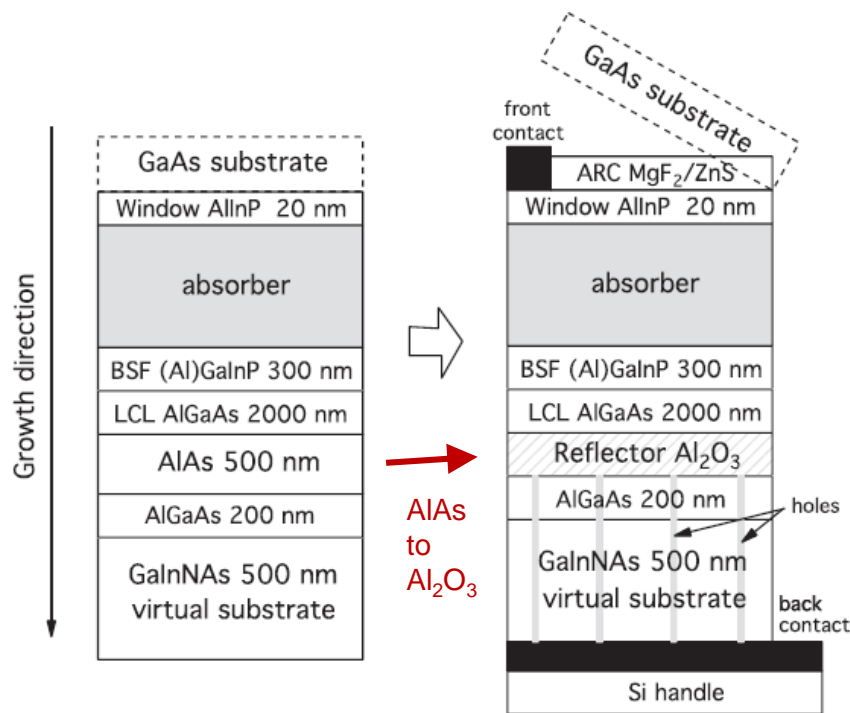
- Can be accomplished with dielectric or semiconductor DBR
- Leads to reduction in light to bottom cell
  - May be incompatible with current-matched IMM.

- Transparent spacer can also help with photon recycling or OPL enhancement in each sub-cell
- Transparent spacer can also be an air gap
- Separate bottom cell ARC can reduce impedance to bottom cell

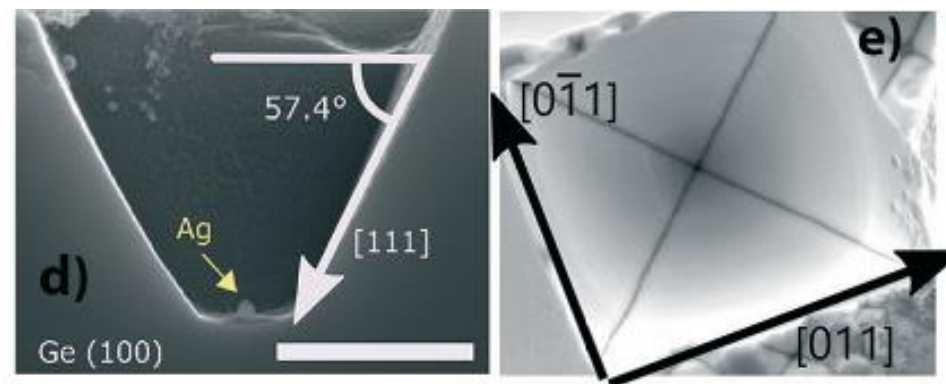
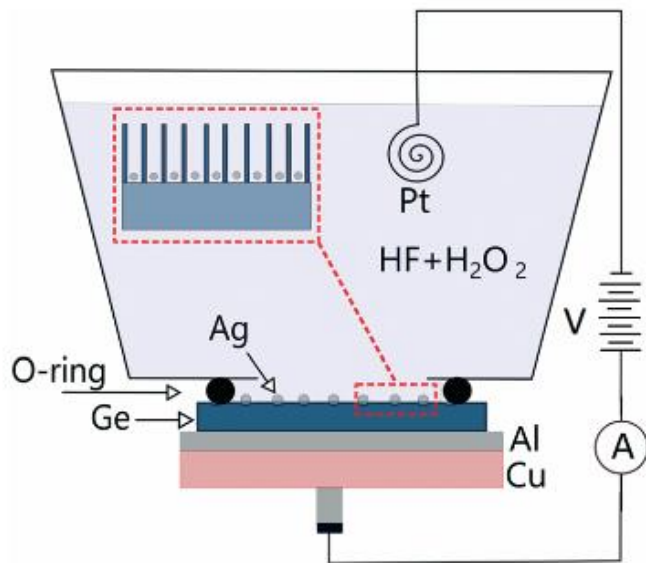


X. Sheng *et al.*, "Device Architectures for Enhanced Photon Recycling in Thin-Film Multijunction Solar Cells," *Adv. Energy Mater.*, vol. 5, no. 1, p. n/a-n/a, Jan. 2015.

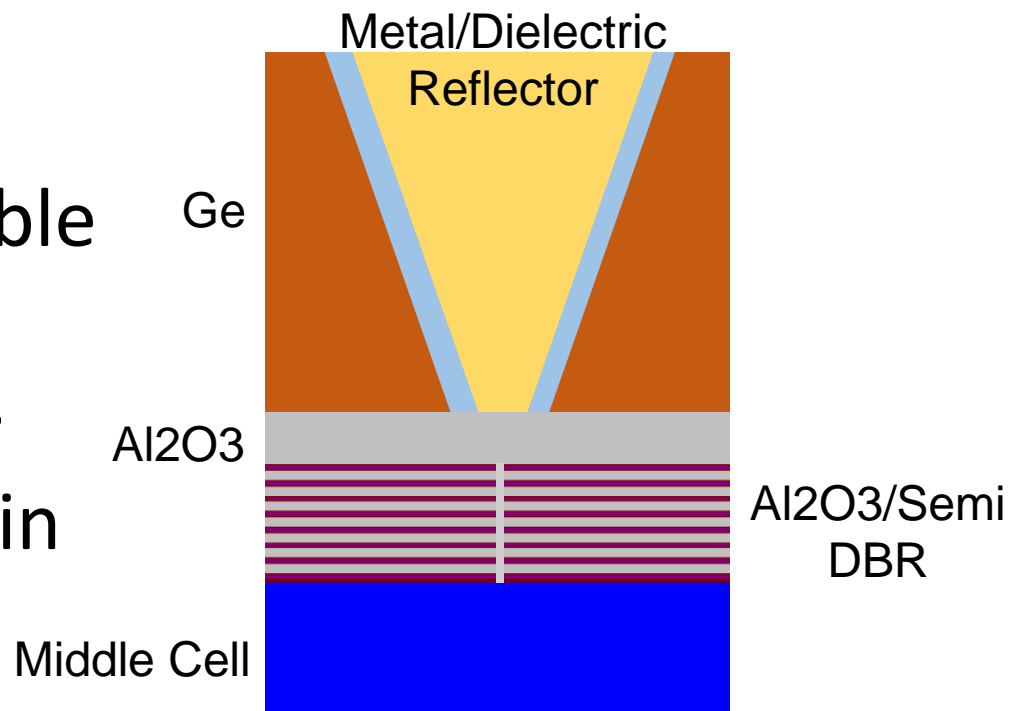
Transparent spacer can be implemented via buried  $\text{Al}_2\text{O}_3$  layer formed by lateral oxidation of AlAs



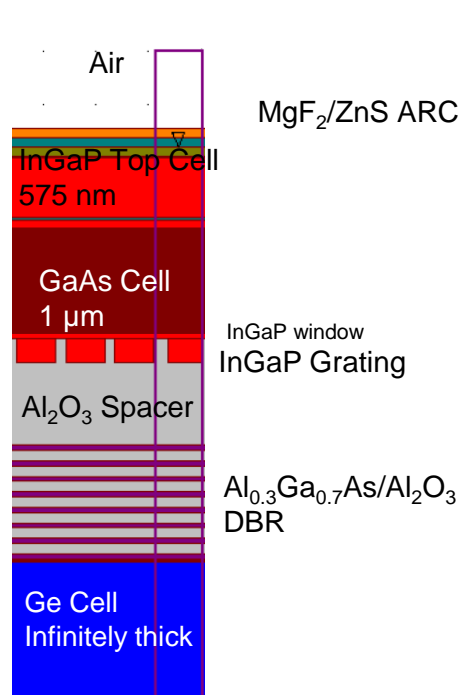
Garcia et al., "Back reflectors based on buried  $\text{Al}_2\text{O}_3$  for enhancement of photon recycling in monolithic, on-substrate III-V solar cells," *Appl. Phys. Lett.*, vol. 105, no. 13, p. 133507, Sep. 2014.



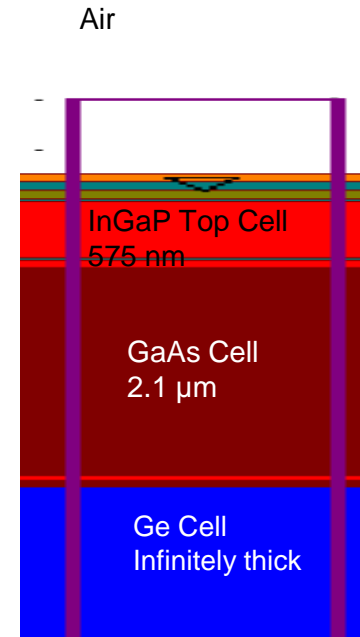
- Tapered etch pits possible via Anodic MAC etch
- Metal/Dielectric mirror could minimize  $J_{SC}$  loss in Ge.



- Attempt to reproduce work in “Interstitial light-trapping design for multi-junction solar cells” by Mellor et al.



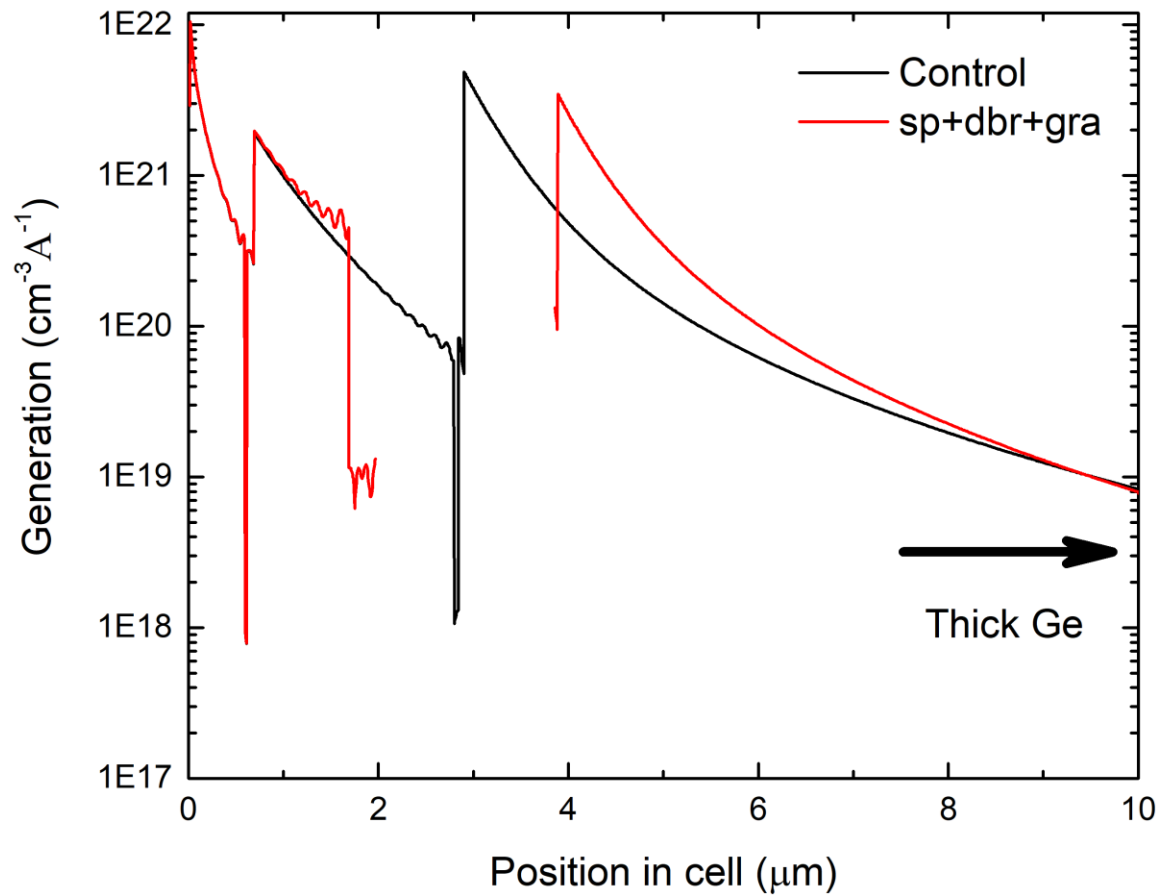
**Gra+Sp+DBR**  
(Grating + Spacer +  
DBR)

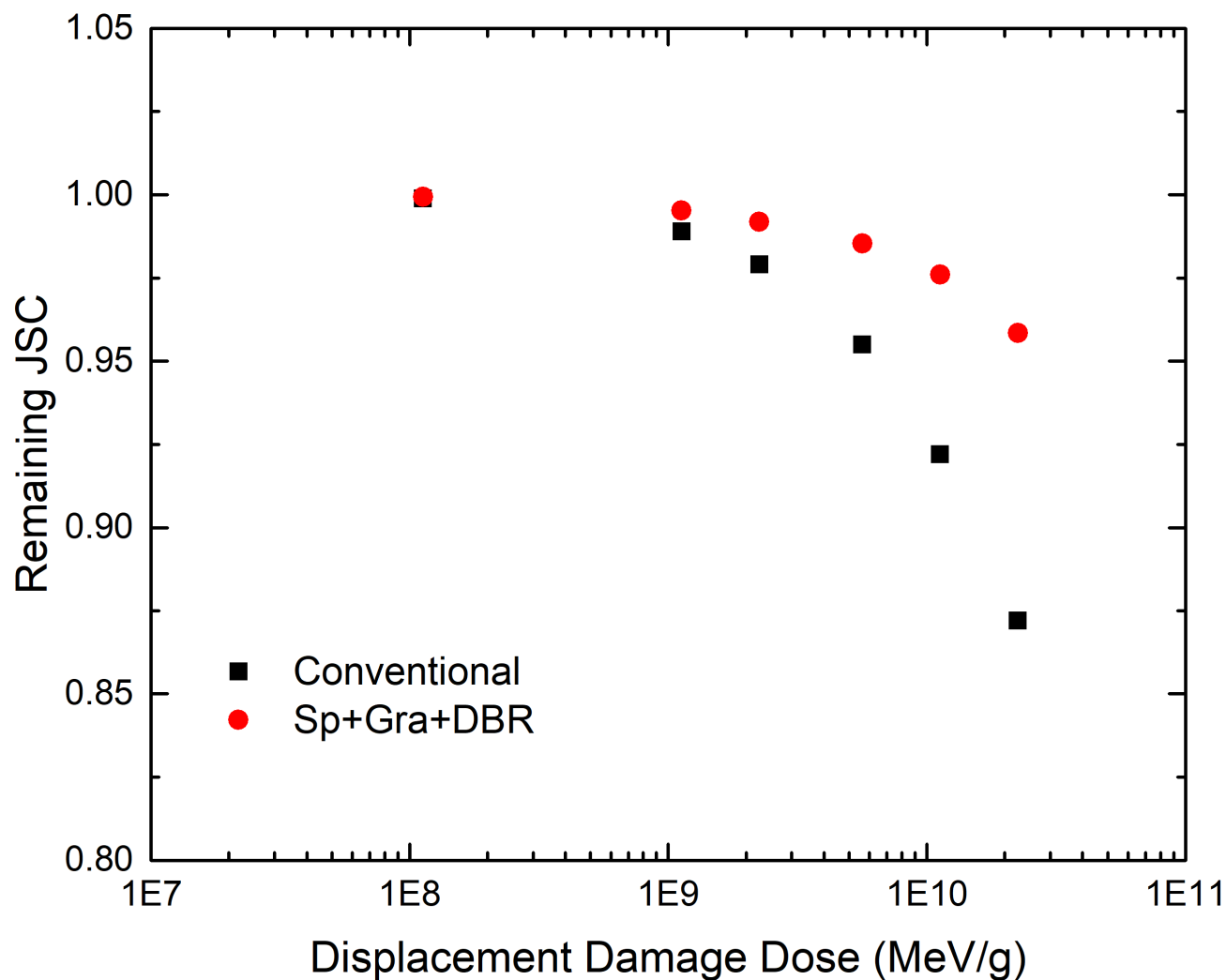


**Baseline**



# 3J Generation vs Position /w & w/o Grating

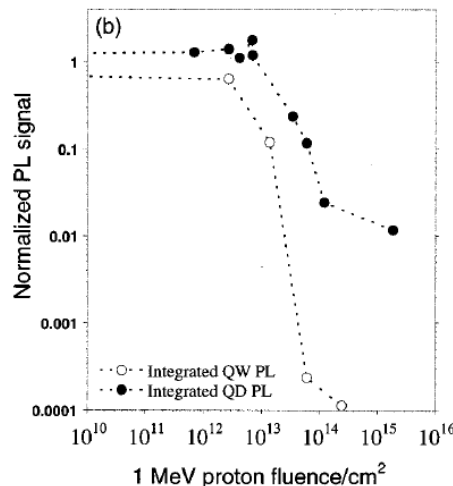
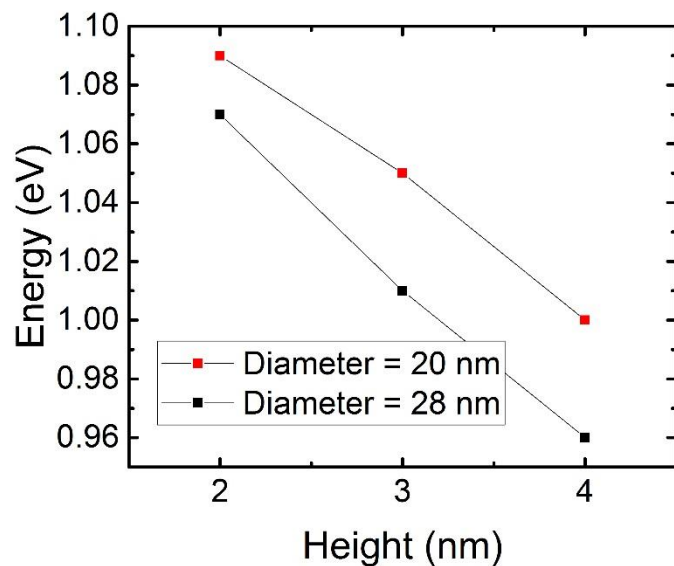
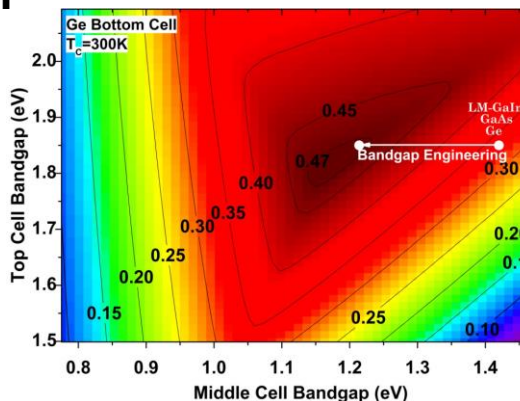




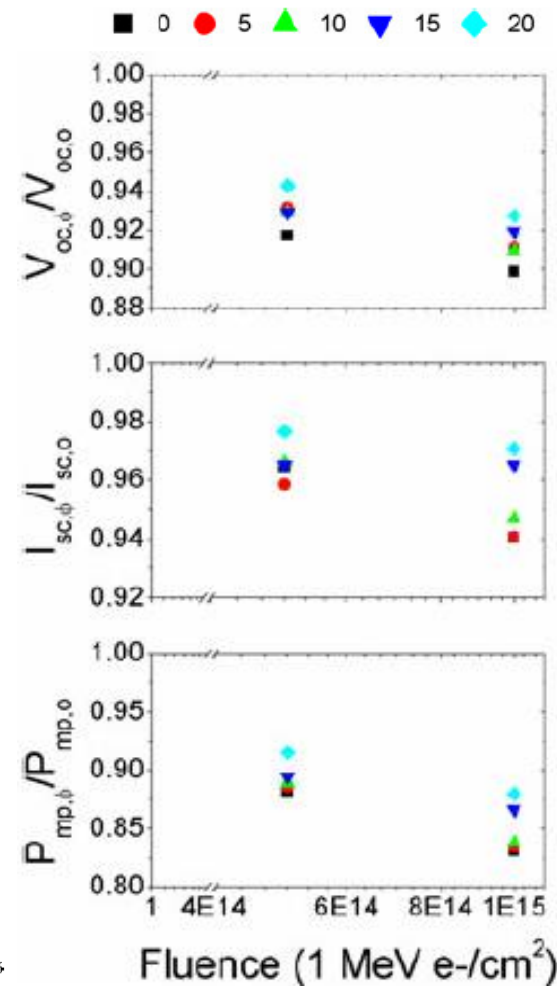
- I. Background and Introduction to Multijunction Solar Cells
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How it applies to radiation hard environments
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End of life (EOL) current matching
- IV. Bandgap/Absorption Engineering & work at RIT

## Nanostructures in photovoltaics: Quantum Dots and Quantum Wells

- Bandgap engineering
  - QDs smaller effective bandgap
- Radiation tolerance
  - QDs more resilient



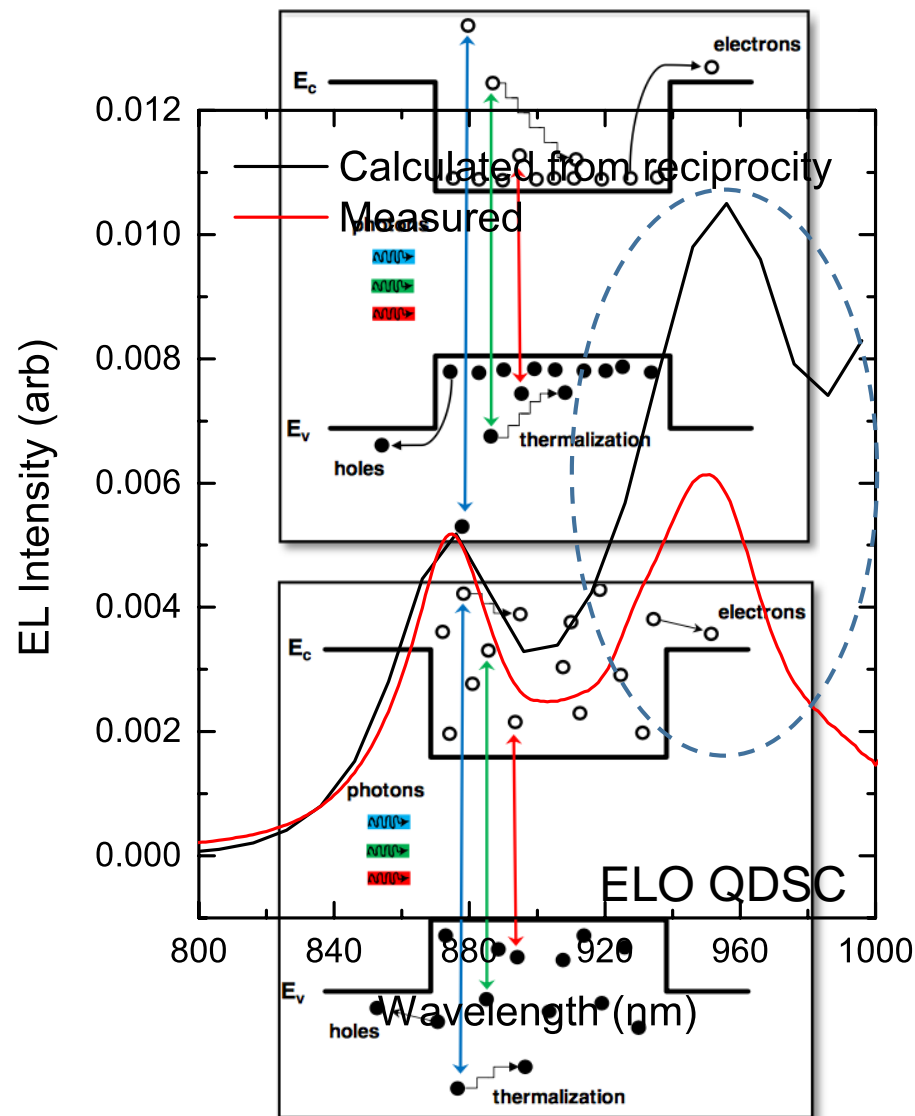
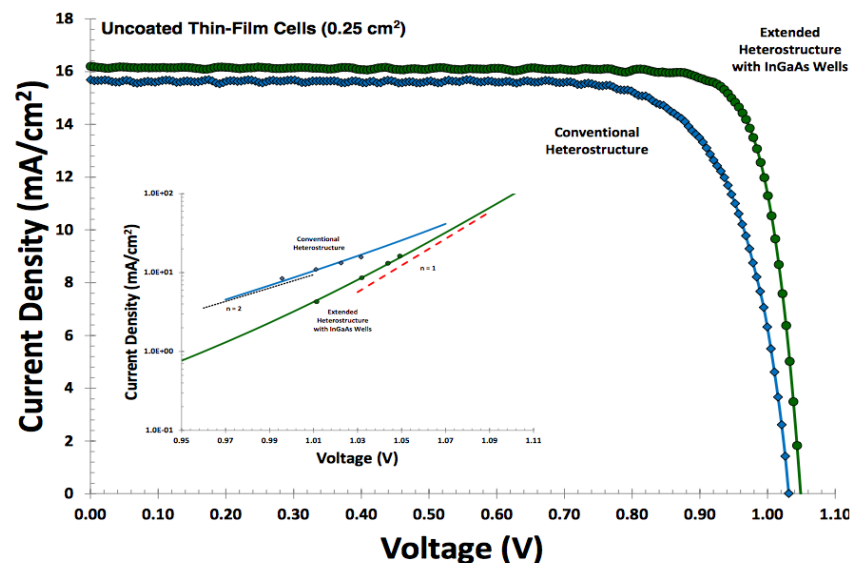
Leon, R., et al. *Appl Phys Lett* 76 (2000): 2074



Kerestes, C., et al. *IEEE J. Photovolt* 4.1 (2014):224-232

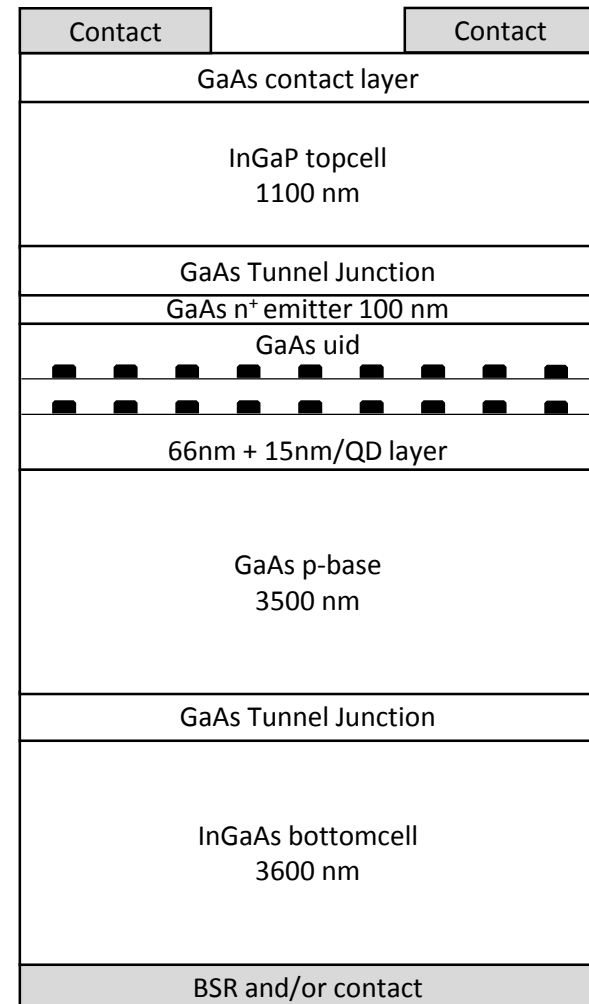
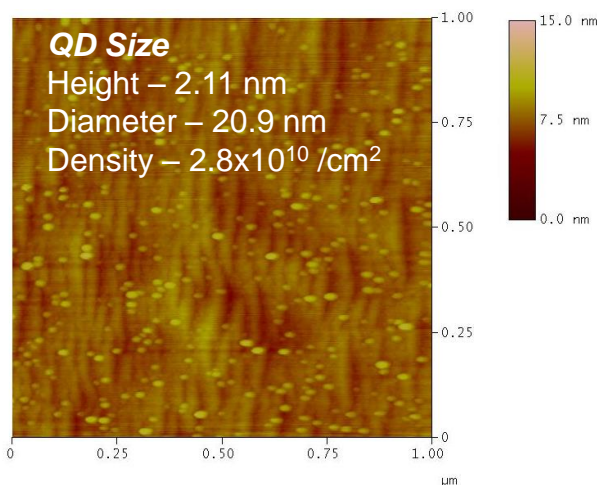
- Goal is suppression of nonradiative and radiative recombination in the QW/QD.
- Dark current contribution from nanostructures can be managed if measured EL is weaker than EL predicted from EQE and Reciprocity relationship
  - Suggests hot carrier collection

$$\phi_{EL,i}(J_{EL}) = \phi_{EQE,i} \cdot \phi_{BB} \left[ \exp \left( \frac{qV_i(J_{EL})}{kT} \right) - 1 \right]$$

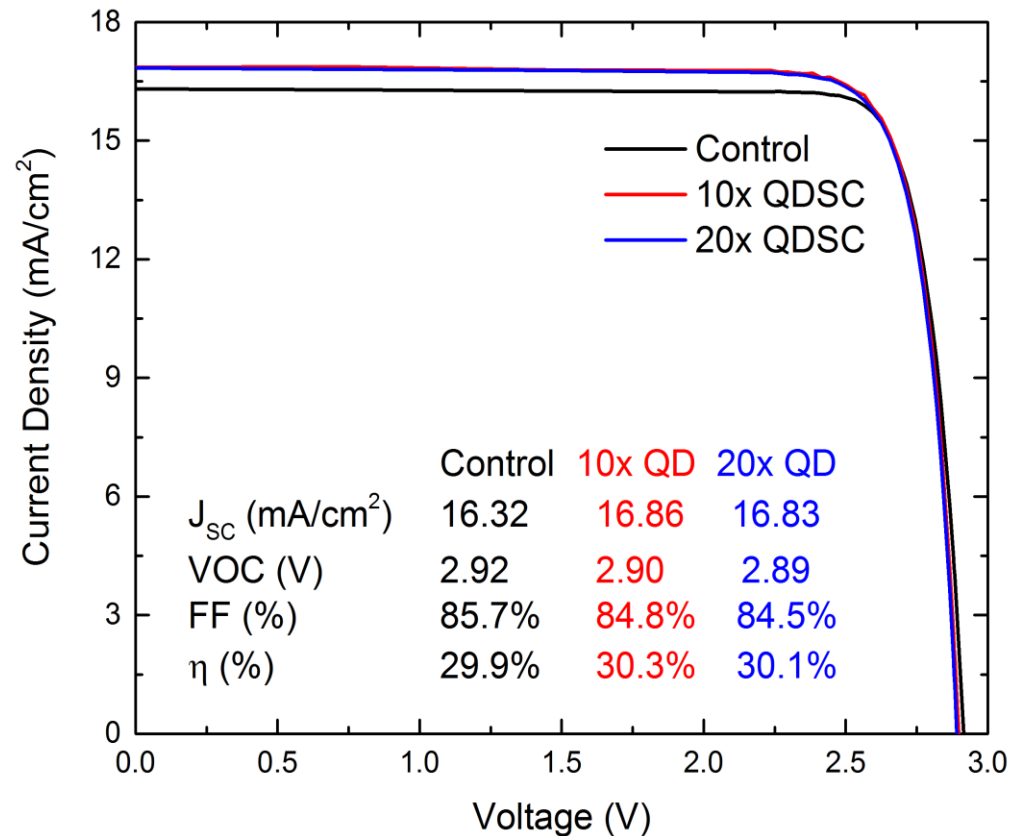


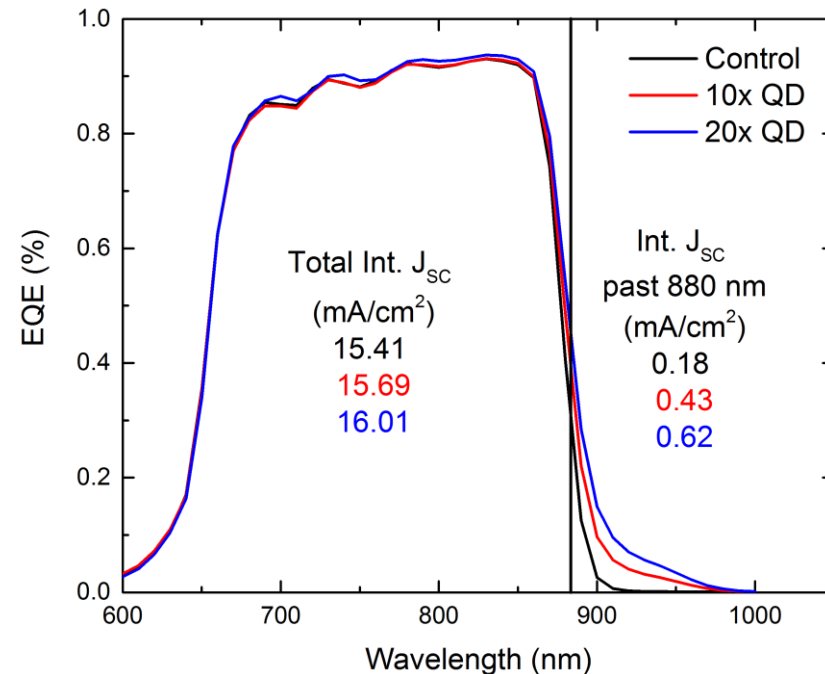
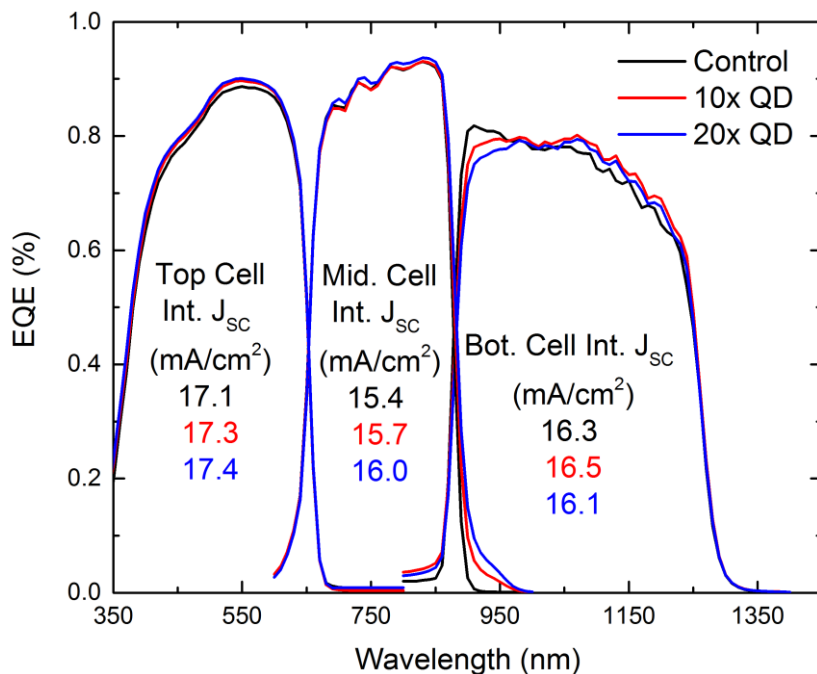


- ELO layer and top cell grown at Microlink
- GaAs middle cell grown at RIT on Aixtron 3x2" close coupled showerhead MOCVD
- Metamorphic buffer and bottom cell grown at Microlink

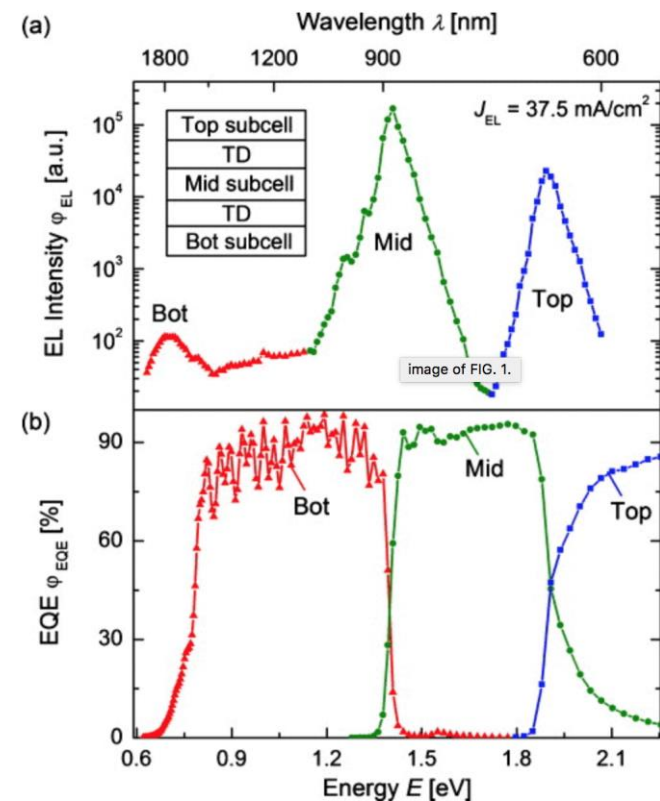
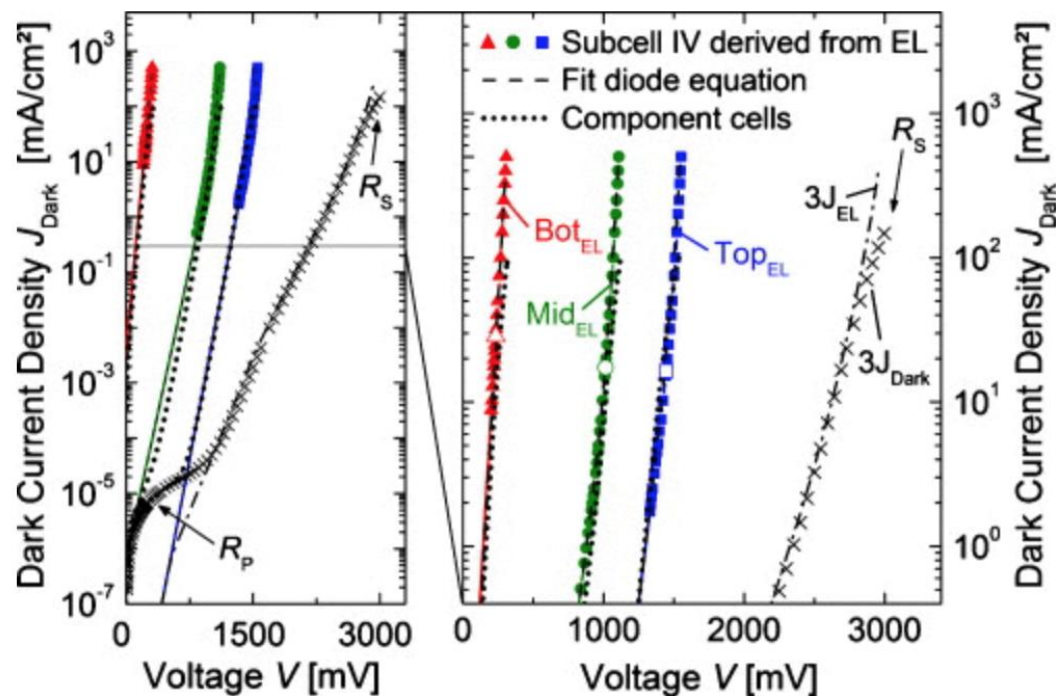


- Demonstration of improved current matching via QD incorporation
- **2.24% efficiency increase** (relative) with addition of 20x QDs
- **Only 30meV loss in  $V_{oc}$**  with addition of 20x QD layers
- Increase in  $J_{sc}$  corresponds with increase in integrated sub-bandgap spectral response

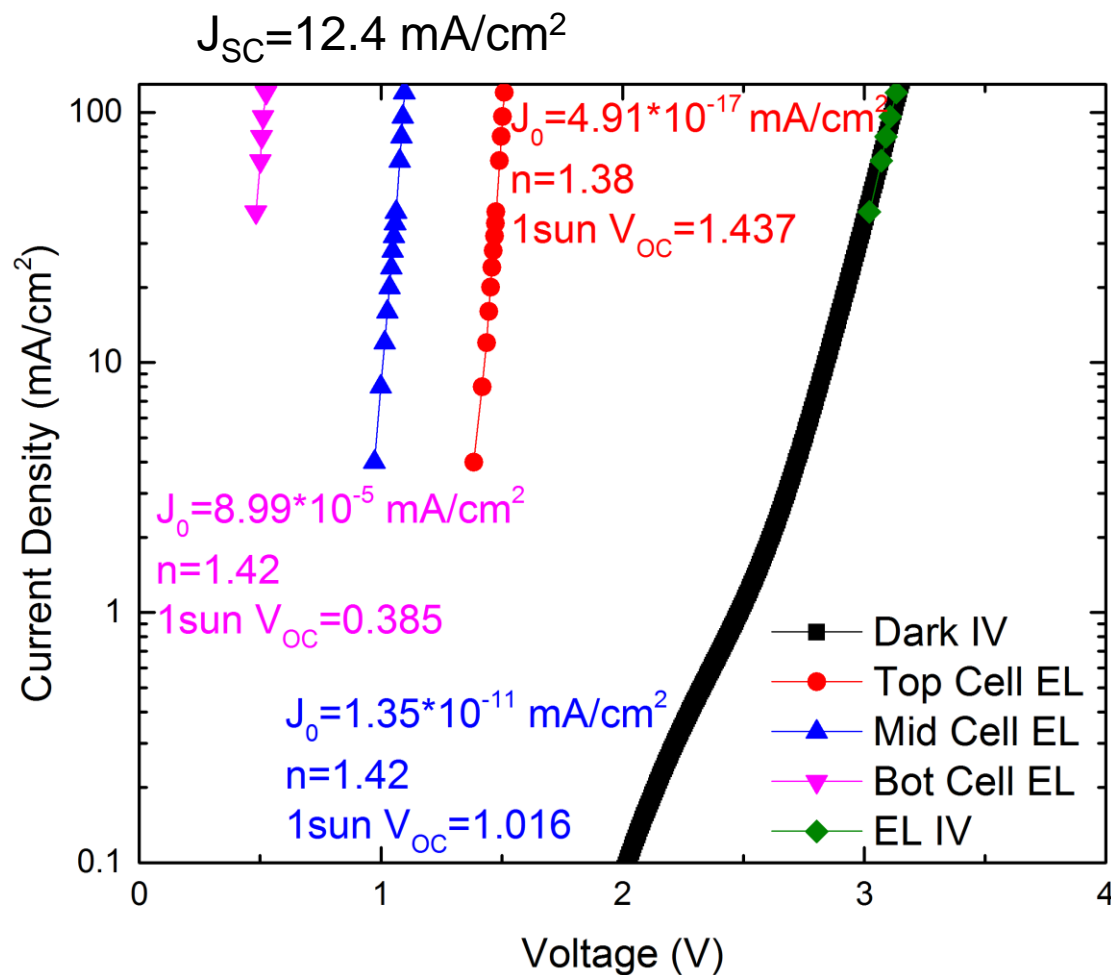




- Linear increase in current with QD superlattice repeat
- Uncertain response from QD wavelengths (>1000nm), lost due to noise in MJ-EQE measurement
  - Possible QDs were fully diffused into InGaAs wells



$$V_i(J_{EL}) = \frac{kT}{q} \ln [\phi_{EL,i}(J_{EL})] + \frac{E}{q} - 2 \frac{kT}{q} \ln(E) - \frac{kT}{q} \ln(\phi_{EQE,i}) - \frac{kT}{q} \ln(C) = V_i^*(J_{EL}) - \delta V$$



$$W_{OC} = E_g - V_{OC}$$

$$V_{OC,EL} = 2.84 \text{ V}$$

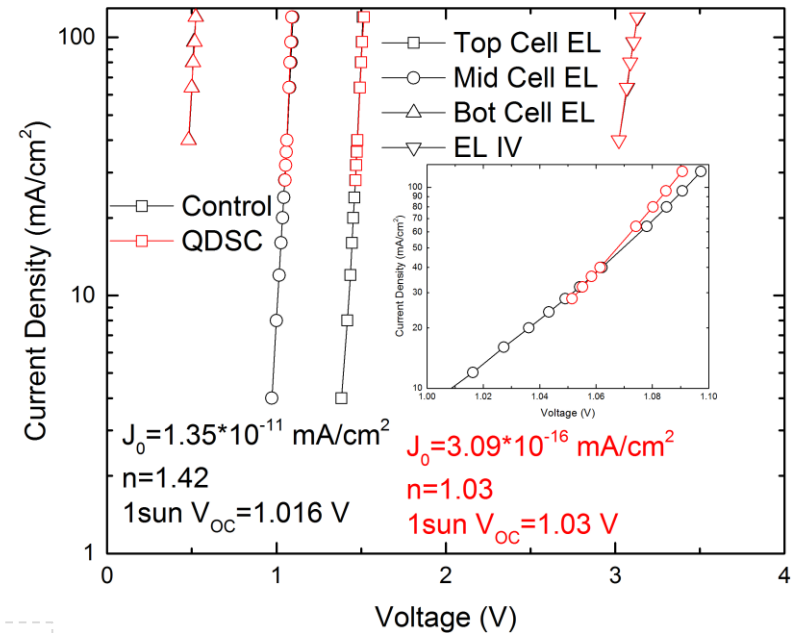
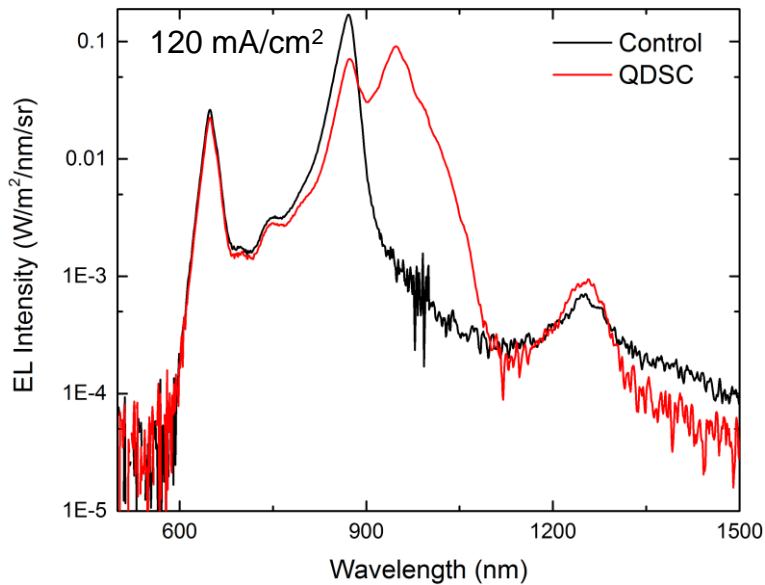
$$V_{OC,Meas} = 2.83 \text{ V}$$

$$W_{OC,top} = 0.477 \text{ V}$$

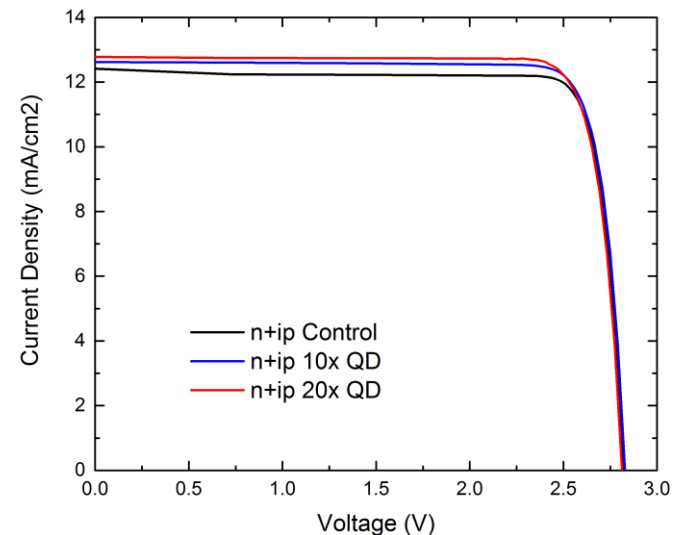
$$W_{OC,mid} = 0.413 \text{ V}$$

$$W_{OC,bot} = 0.608 \text{ V}$$

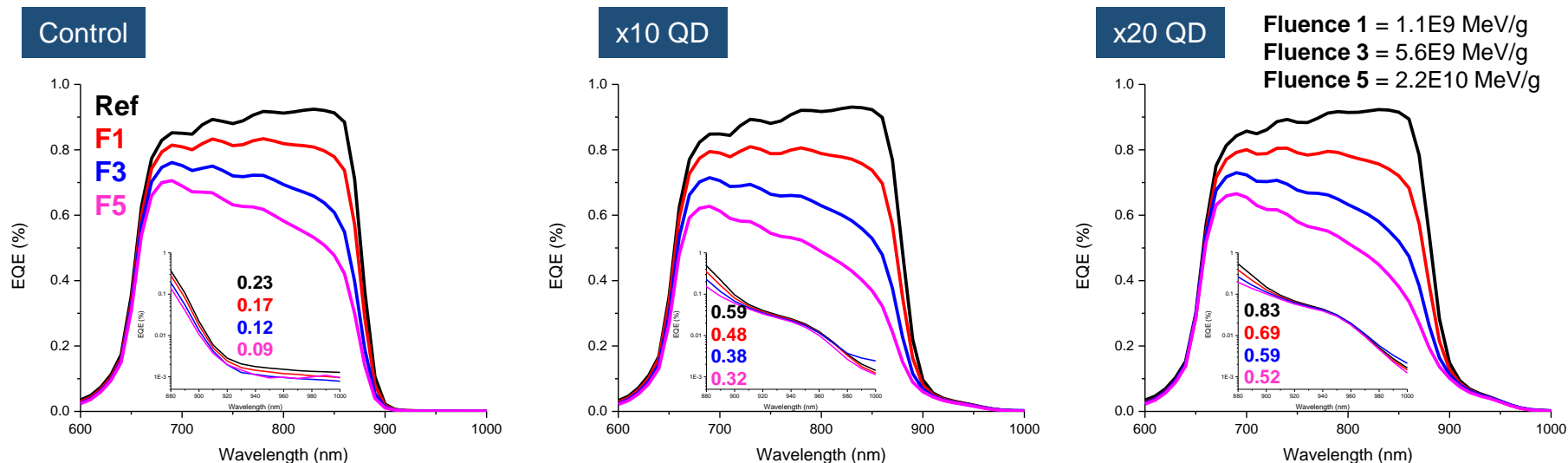




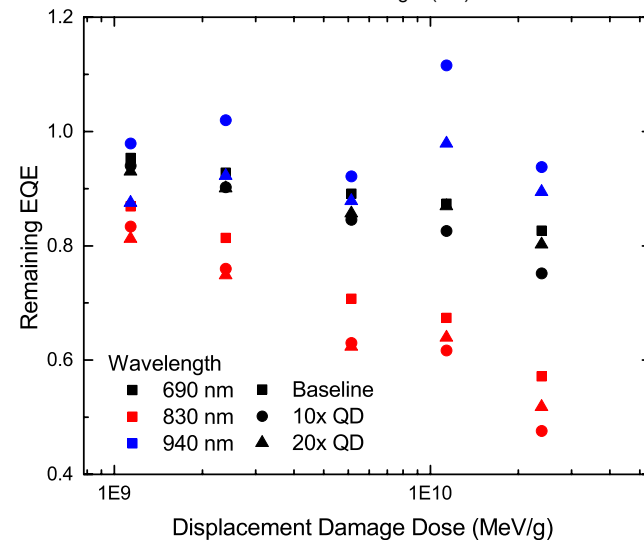
- Fit shows  $n=1.03$  for QDSC vs  $n=1.42$  for Control
- Similar  $V_{OC}$  to control at 1 sun.
  - Potential gains at lower illumination due to ideality factor indicating suppression of nonradiative recombination at low bias.
  - At high bias currents, control cell shows higher radiative recombination meaning higher  $J_{02}$  term but lower  $J_{01}$  term for control cell.
- QDSC shows improved radiative efficiency ( $\eta_{ext} \sim 1.5\%$  vs.  $3\%$ )



- Quantum efficiency degradation as a function of fluence for the GaAs middle cell. Degradation most severe near the band edge of the sub-cell (base degradation).

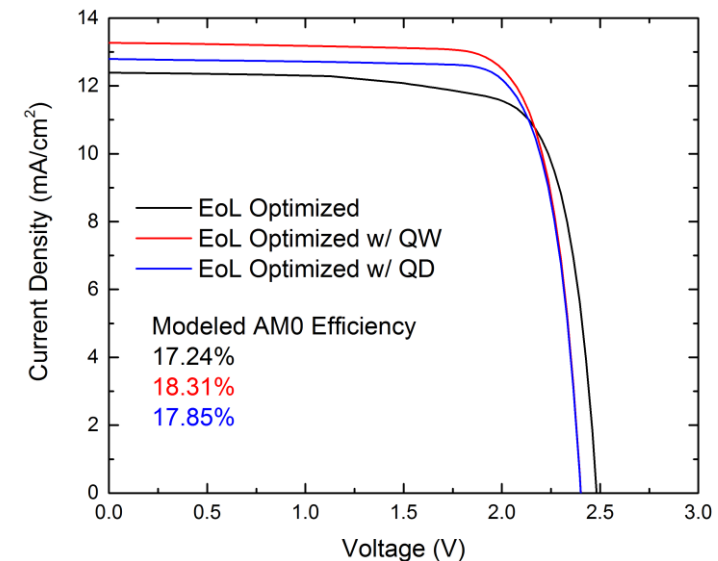
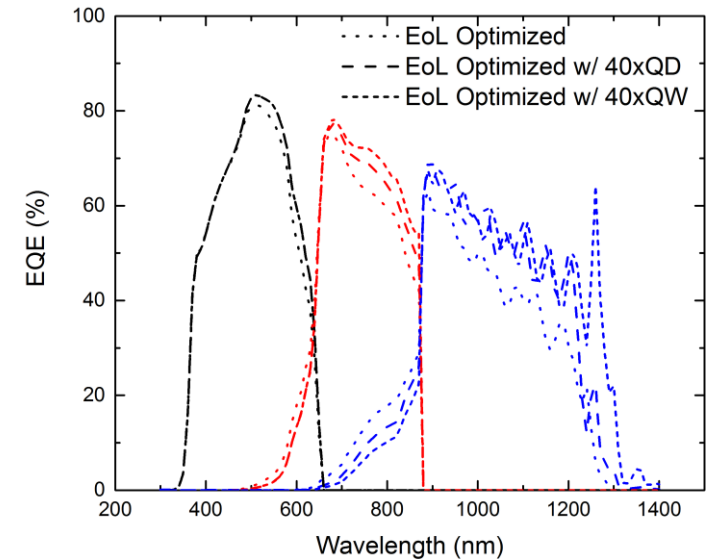


- $J_{SC}$  is 69% remaining for control, and drops to 60% and 65% with 10x and 20x QD respectively
  - Base was sensitive at 3 $\mu$ m
  - QDs could degrade material grown afterwards
- QD wavelengths (940nm) retain ~100% remaining factor up to 2.2x10<sup>10</sup> MeV/g

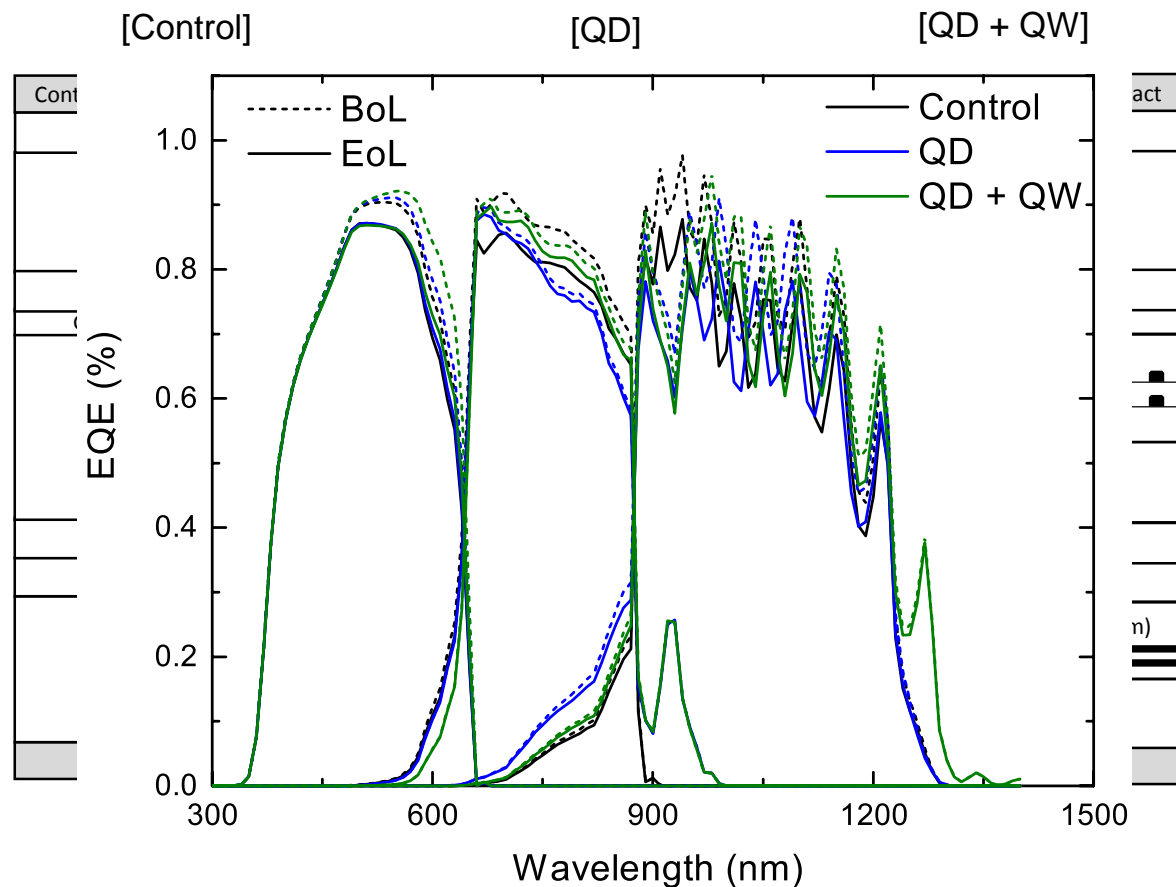


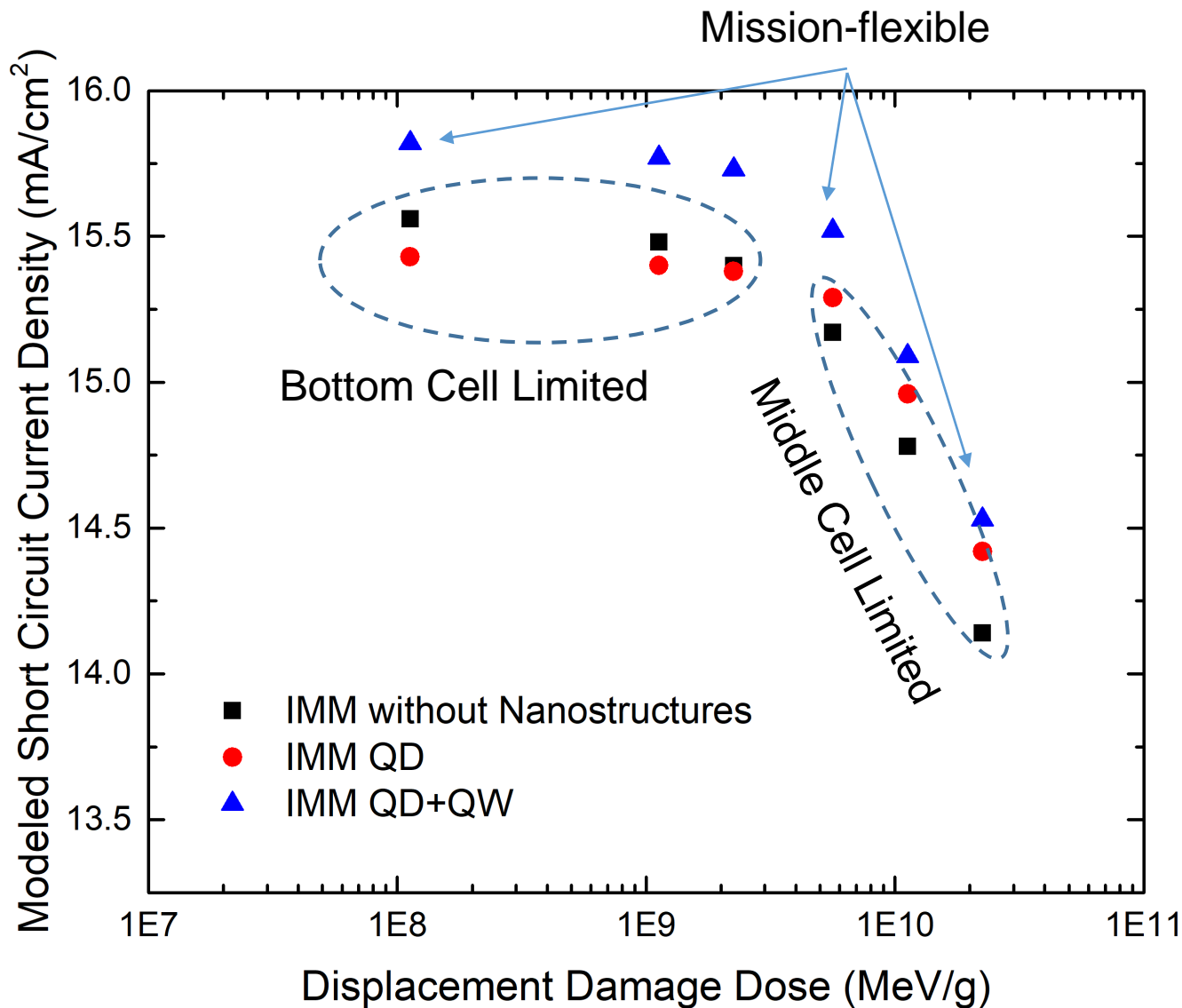
- Simulation results for QD- and QW-enhanced bottom InGaAs subcell show improved EOL ( $1 \times 10^{15}$  1MeV  $e^-/\text{cm}^2$ ) efficiency at AM0

[Control]	[QD-enhanced]	[QW-enhanced]
Contact	Contact	Contact
GaAs contact layer	GaAs contact layer	GaAs contact layer
InGaP topcell 300 nm	InGaP topcell 400 nm	InGaP topcell 400 nm
GaAs Tunnel Junction	GaAs Tunnel Junction	GaAs Tunnel Junction
GaAs $n^+$ emitter 100 nm	GaAs $n^+$ emitter 100 nm	GaAs $n^+$ emitter 100 nm
GaAs p-base 900 nm	GaAs p-base 1100 nm	GaAs p-base 1200 nm
GaAs Tunnel Junction	GaAs Tunnel Junction	GaAs Tunnel Junction
InGaAs emitter 100nm	InGaAs emitter	InGaAs emitter
InGaAs base 1750 nm	InGaAs uid + 40xQD (600nm) InGaAs base 1100 nm	InGaAs uid + 40xQW (600nm) InGaAs base 1100 nm
Contact	Contact	Contact



- Including InAs/GaAs QDs in GaAs subcell resulted in little change in  $V_{OC}$ .
- Potential to extend current enhancement to bottom subcells.
- Designs optimized for  $D^3$  of  $10^{10}$  MeV/g







- Back surface texturing in 1J devices can increase OPL
- IMM with QD/QW superlattice minimal  $V_{oc}$  degradation and absolute increase in efficiency
- QDs show clear current enhancement in MC at EOL for 1MeV electron exposure
- New cell designs using textures and QW have been simulated in Sentaurus TCAD for maximized EOL

## Funding Acknowledgments

