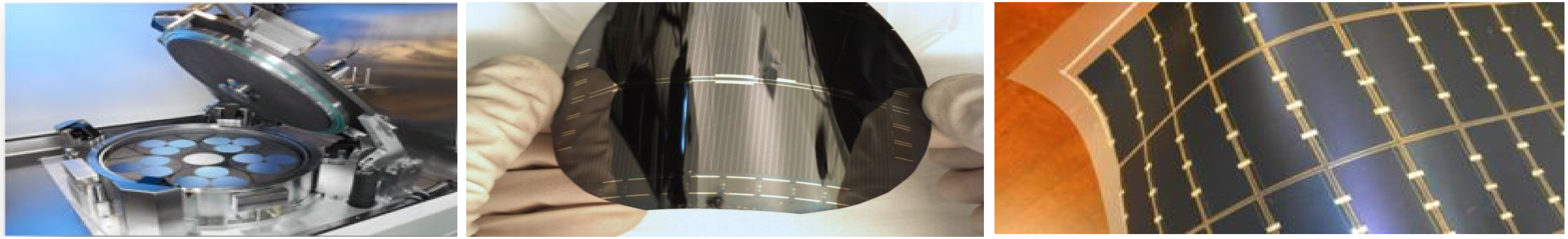

Space Power Workshop 2021

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Application of wavelength selective photonic structures (WSPS) to multijunction solar cells for radiation hardening

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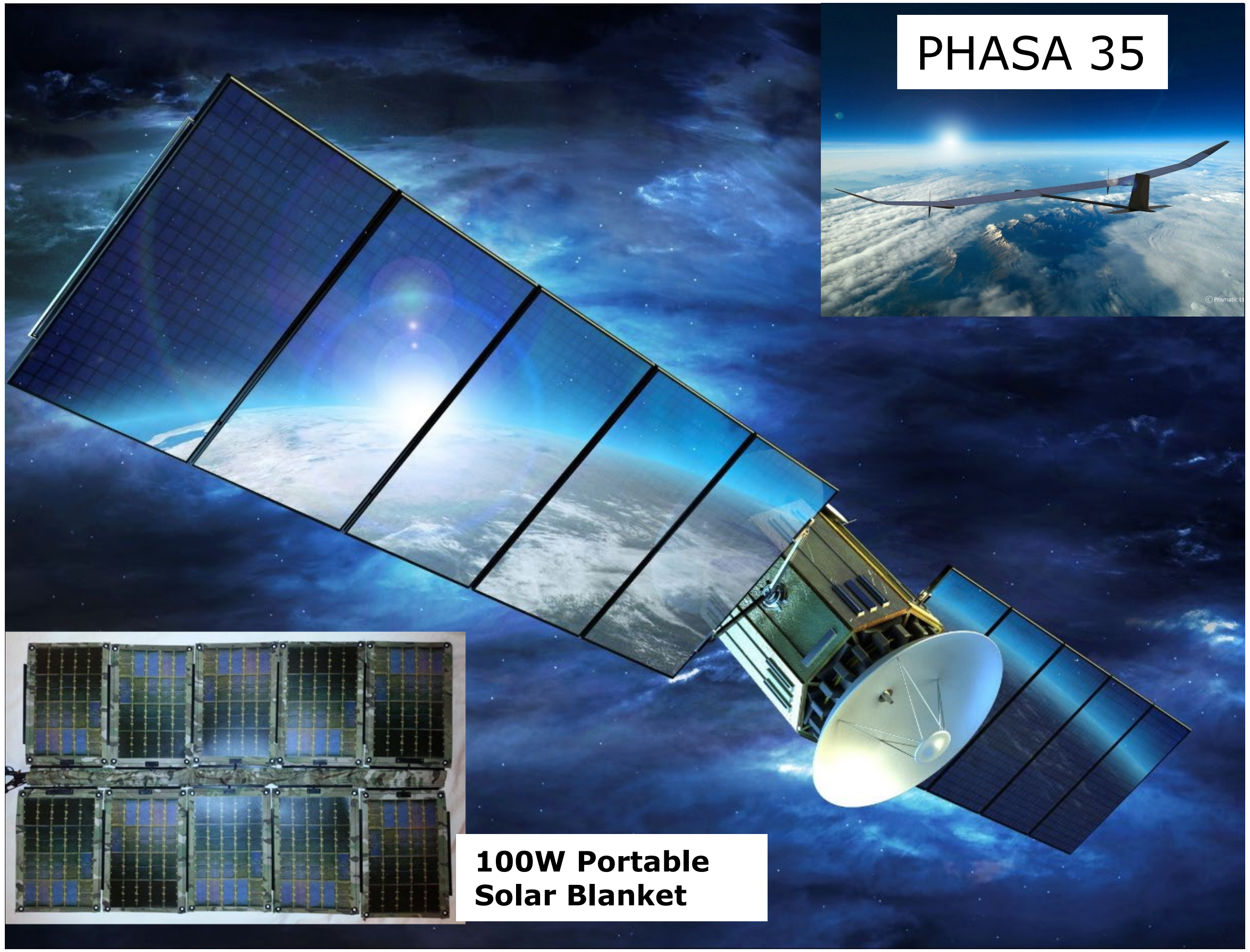
Rochester Institute of Technology, Rochester, NY USA

Outline

- **Introduction**
- Strategies for Radiation Tolerance improvement
- WSPS in multijunction cells
- Multijunction Solar cells with WSPS- Radiation Effects
- Conclusions

Motivation:
Space 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

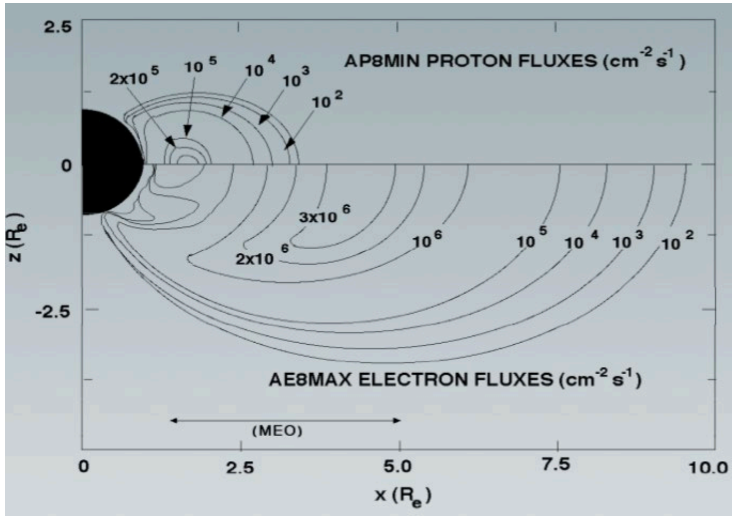
High Energy Radiation In Space

Van Allen Belts

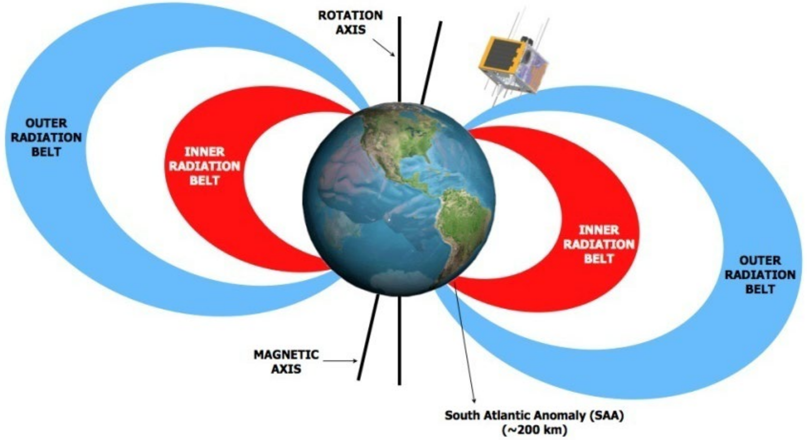
- Radiation trapped in Earth's magnetic field
- Peak 1+ MeV e^- flux of $3*10^6$ cm^{-2}s^{-1}

Solar winds

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



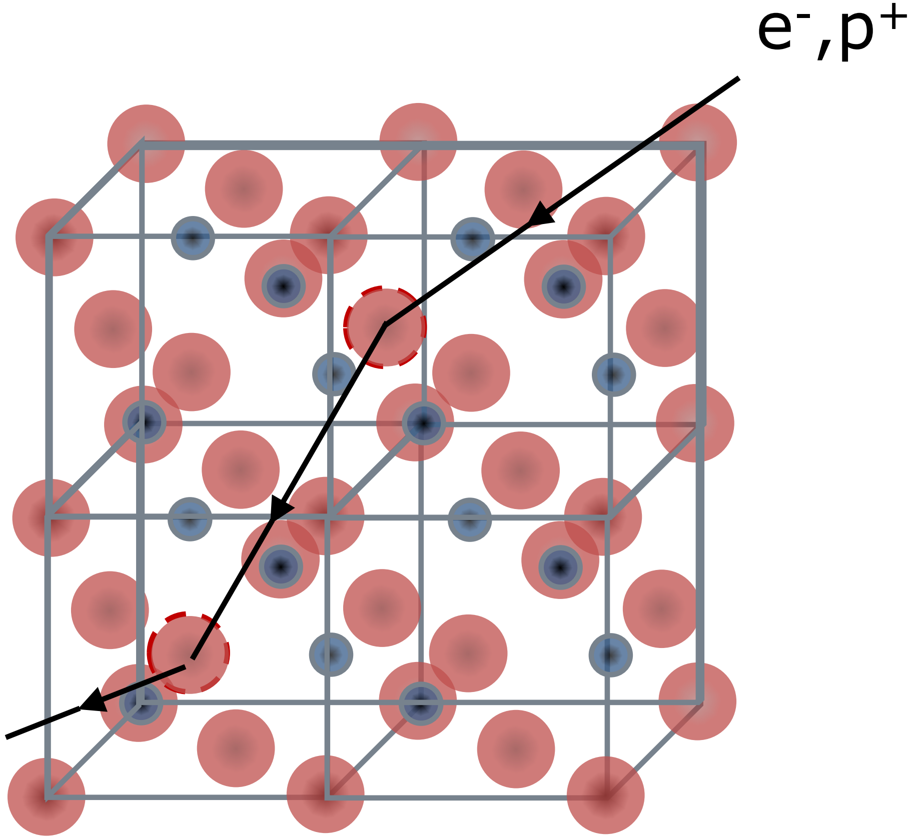
Mitigating In-Space Charging Effects NASA Technical Handbook



Radiation Damage in PV

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)**

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Strategies to increase EOL

1. Conventional optimization

☐ Doping gradients, disordered InGaP, EoL current matching

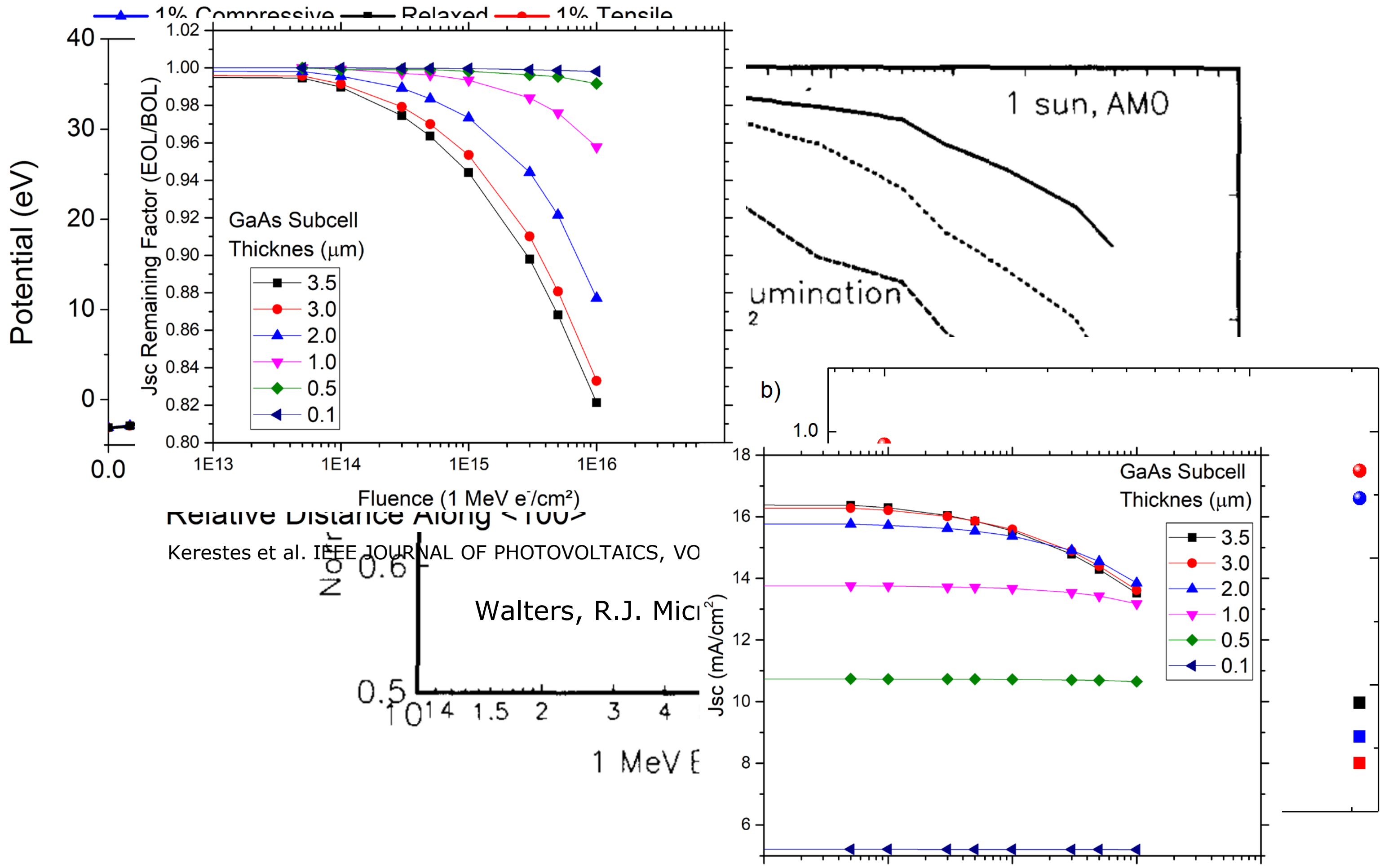
2. Use radiation Hard Materials

☐ InP was seen as candidate

☐ Difficult to integrate into 3J

3. Use strained nanostrucutres (QW, QD) to increase PKO E_A

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

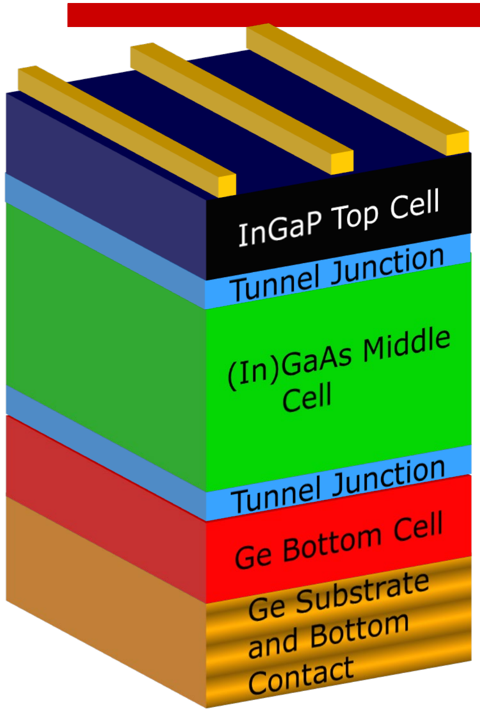


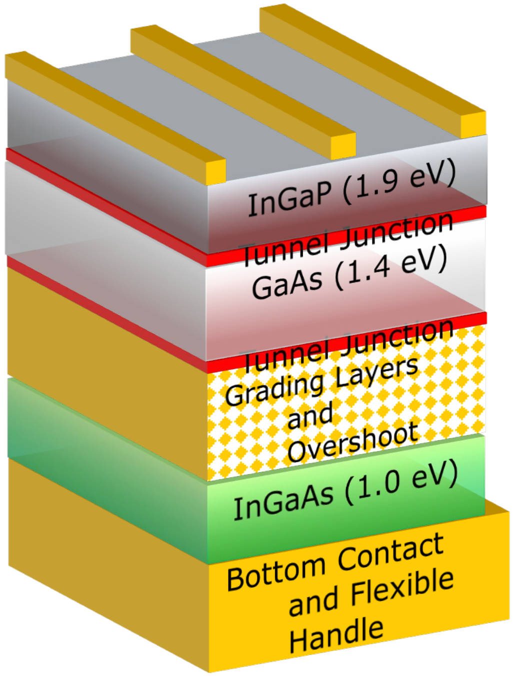
Kerestes et al. IEEE JOURNAL OF PHOTOVOLTAICS, VO

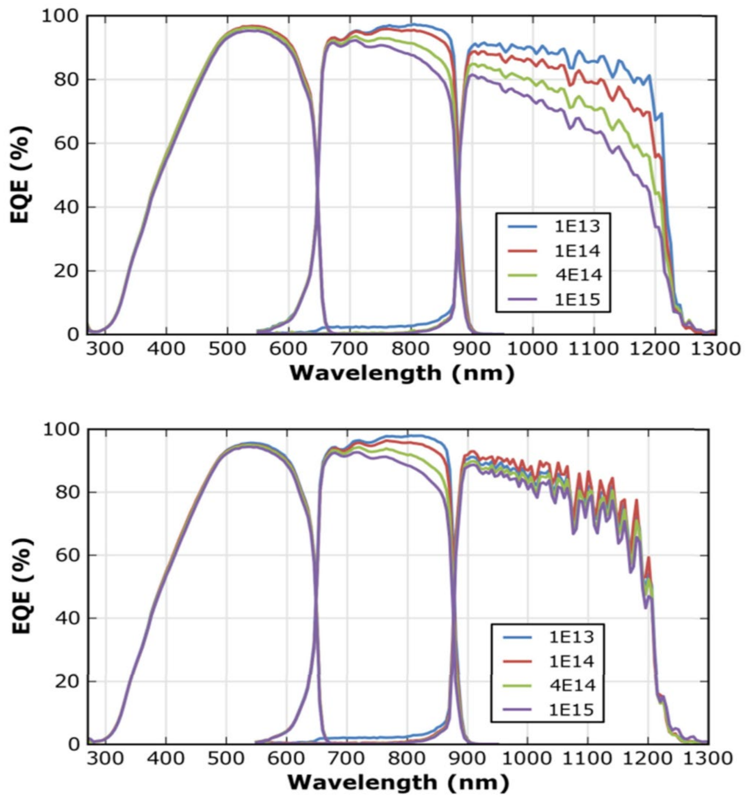
Walters, R.J. Mici

S. ... ***Solar Energy Materials and Solar Cells*, vol. 183, pp. 153-157, 2018.**

Current State-of-the-Art PV







Adams et al. In Proc. of 39th IEEE PVSC

- ☐ Upright: GaAs subcell current limiting at EoL
- ☐ IMM: Bottom, then middle cell current limiting

Outline

☐ Introduction

☐ Strategies for Radiation Tolerance improvement

☐ **WSPS in multijunction cells**

☐ Multijunction Solar cells with WSPS- Radiation Effects

☐ Conclusions

DBR DESIGN SPACE

TF Calc

Lattice matched to GaAs

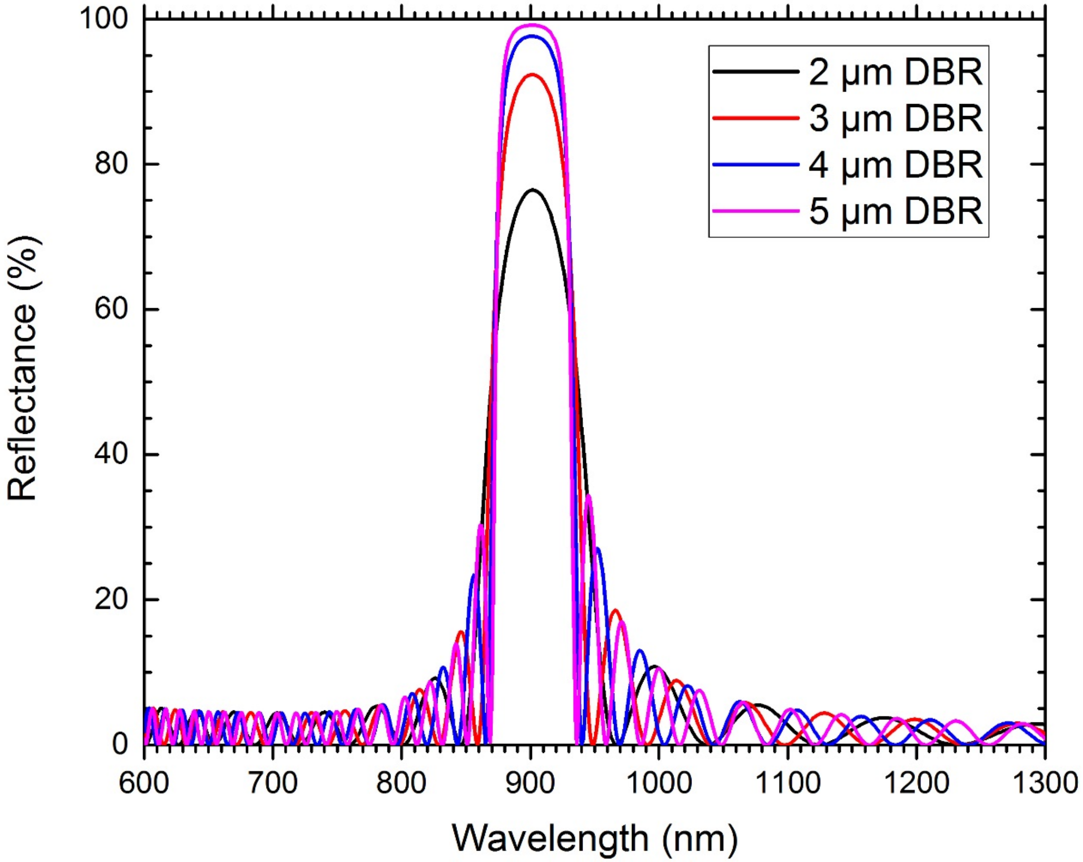
71.1 nm $In_{0.49}Ga_{0.51}P$

78.1 nm $In_{0.46}Al_{0.54}P$

MLD InGaP and InAlP materials were measured by Variable Angle Spectroscopic Ellipsometry (VASE) and complex index of refraction was extracted.

Matched pairs of alternating refractive index allow for strong reflectance peaks, DBRs

DBR target max %R at 900 nm



GaAs / DBR / GaAs environment

LONGPASS DBR DESIGN

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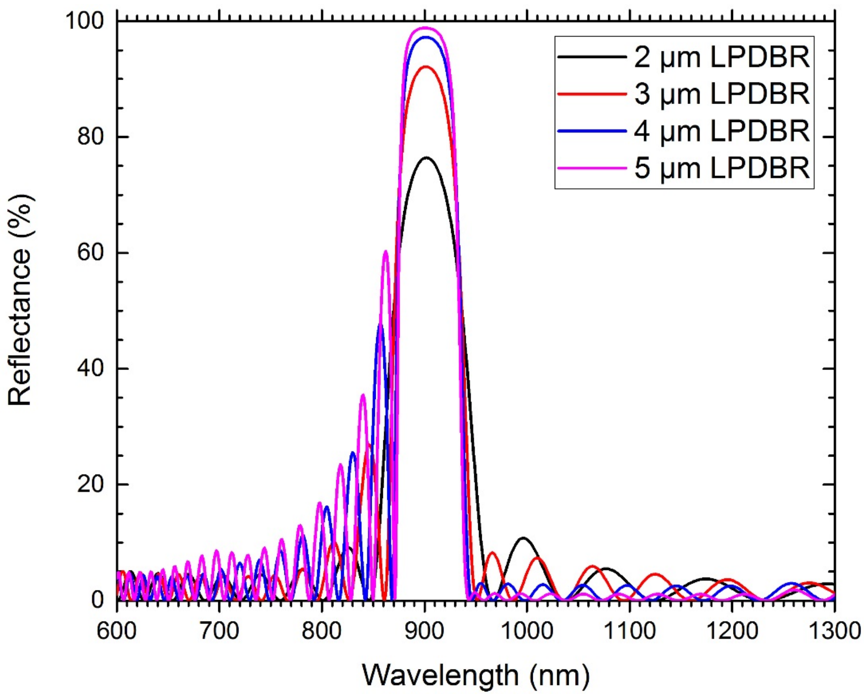
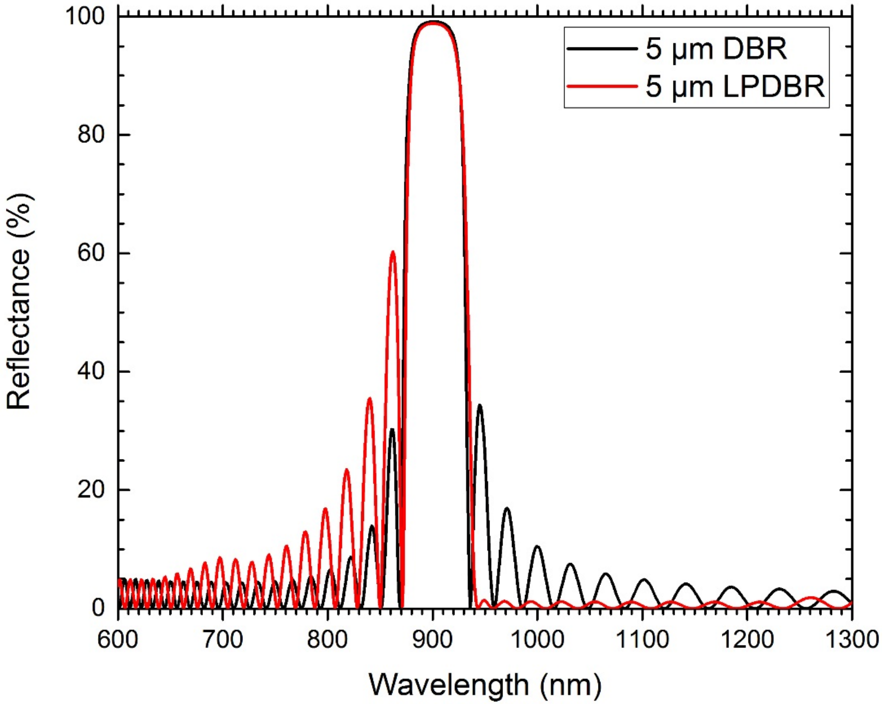
DBR target max %R at 900 nm, min %R from 950 nm to 1250 nm

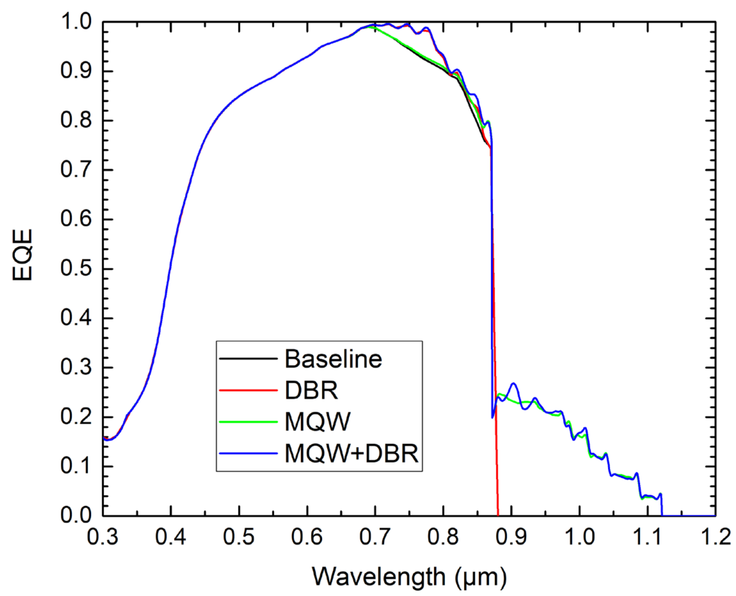


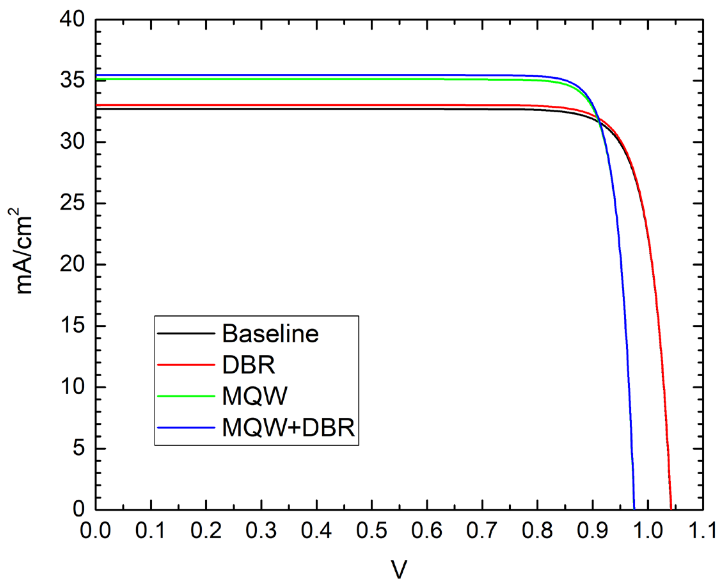


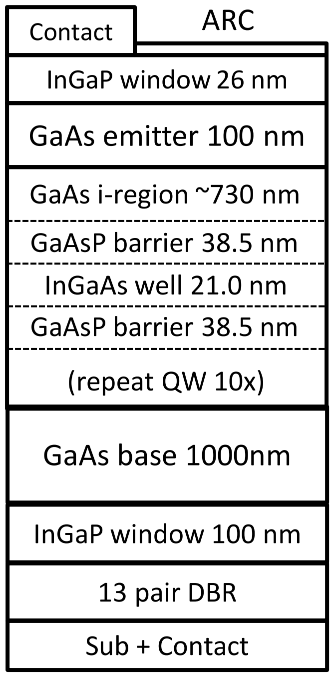
Target region of lower absorption near band edge of junction material, enable improved collection from a thinned device for improved radiation hardness.

Optimization yields “Lowpass DBR” design, significantly limiting reflective losses for lower junctions, increases reflection above bandgap for upper junctions.

Cell Simulations






Contact
ARC
InGaP window 26 nm
GaAs emitter 100 nm
GaAs i-region ~730 nm
GaAsP barrier 38.5 nm
InGaAs well 21.0 nm
GaAsP barrier 38.5 nm
(repeat QW 10x)
GaAs base 1000nm
InGaP window 100 nm
13 pair DBR
Sub + Contact

Sentaurus model using MQW absorption

QW is currently modeled as bulk material with QW absorption coefficient

DBR here is targeting sub-900nm

DBR adds 0.4 mA

10xQW add 2.5 mA

Together gain of ~3 mA

	baseline	dbr	mqw	mqw+dbr
Jsc	32.7	33.0	35.1	35.5
Voc	1.04	1.04	0.98	0.98
FF	85	85	87	87
AM0 Eff	21.2	21.4	22.0	22.2

GaAs Single junction cells

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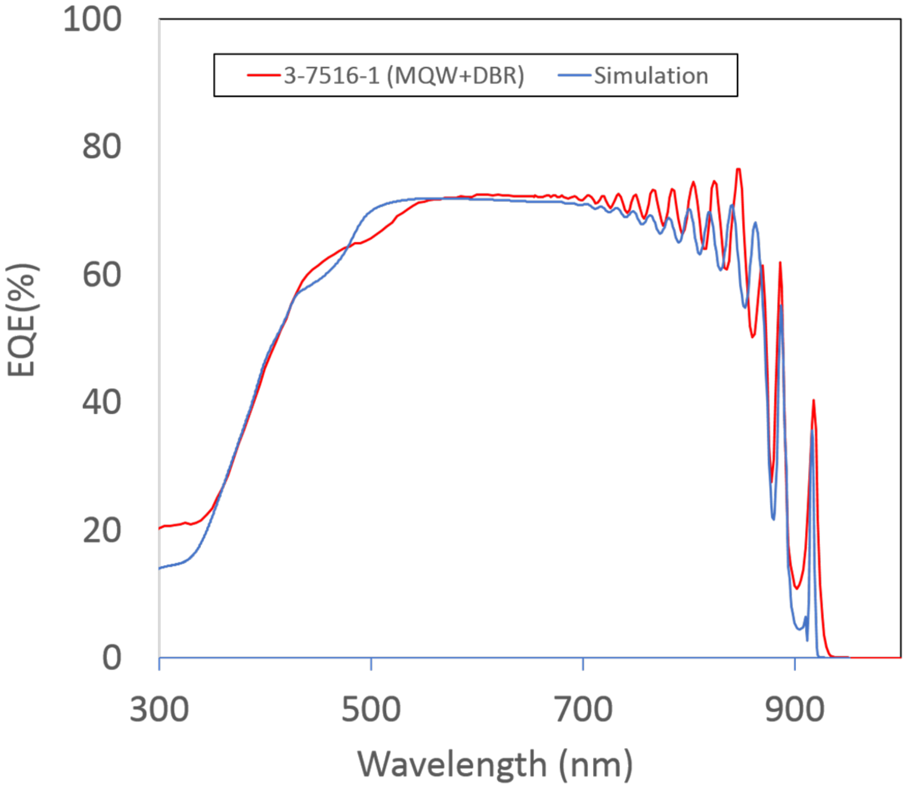
GaAs Single Junction ELO Cells with DBR and MQW

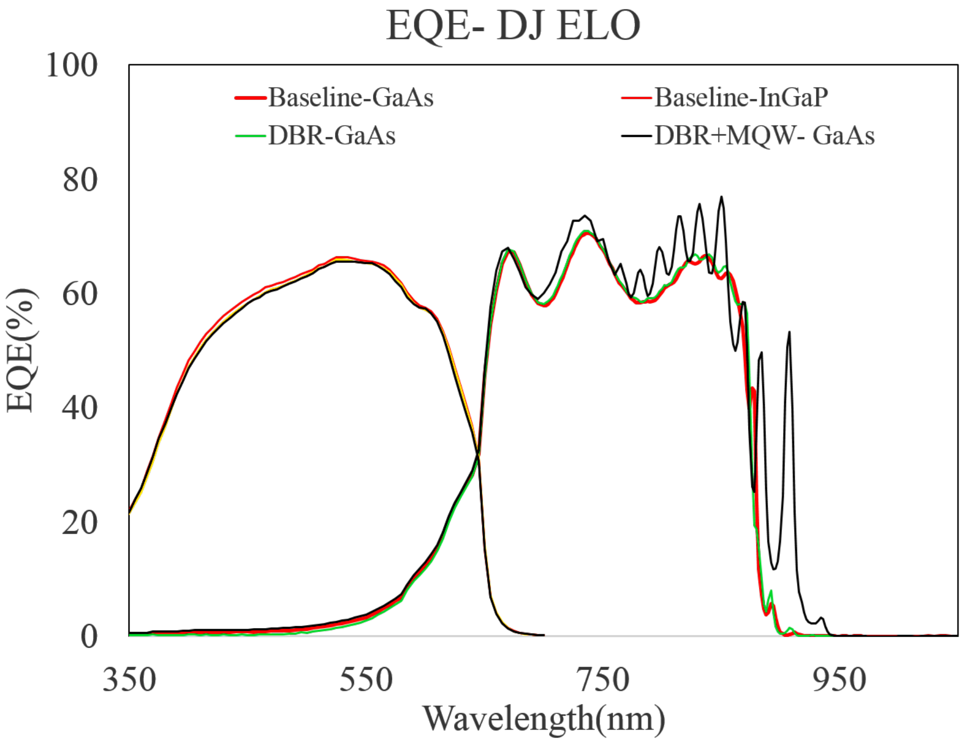


Measured and simulated EQE spectra for GaAs n-i-p structures with MQW in the i-region and DBR below the BSF layer.

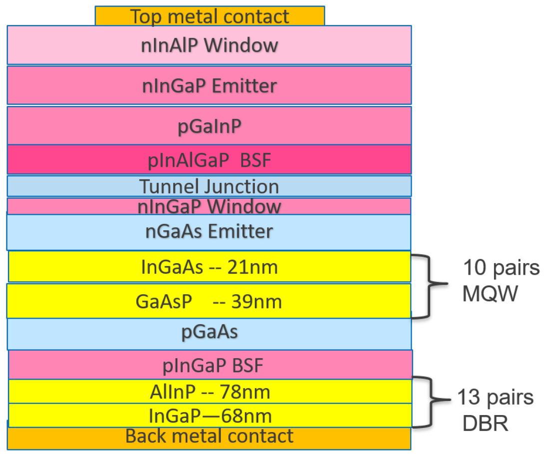
GaAs ELO Cells EQE Summary

GaAs SJ ELO cells (AM0)				
Run No.	**IV (Expt)**	**EQE (Expt)**	**EQE(Model)**	
7518	**25.34**	**26.07**	**25.63**	**DBR**
7515	**25.54**	**26.57**	**25.96**	**MQW**
7516	**26.06**	**26.48**	**26.13**	**MQW+DBR**

InGaP-GaAs DJ Solar cell



Dual Junction ELO Solar Cell Structure


Top metal contact
nInAlP Window
nInGaP Emitter
pGaInP
pInAlGaP BSF
Tunnel Junction
nInGaP Window
nGaAs Emitter
InGaAs -- 21nm
GaAsP -- 39nm
10 pairs MQW
pGaAs
pInGaP BSF
AlInP -- 78nm
InGaP—68nm
13 pairs DBR
Back metal contact

EQE Summary (No AR Coating)

InGaP-GaAs Dual Junction ELO		
AM0 - Jsc (mA/cm2)EQE-Data		
	InGaP	GaAs
Baseline	12.04	12.25
DBR	11.92	12.2
DBR+MQW	11.87	13.46

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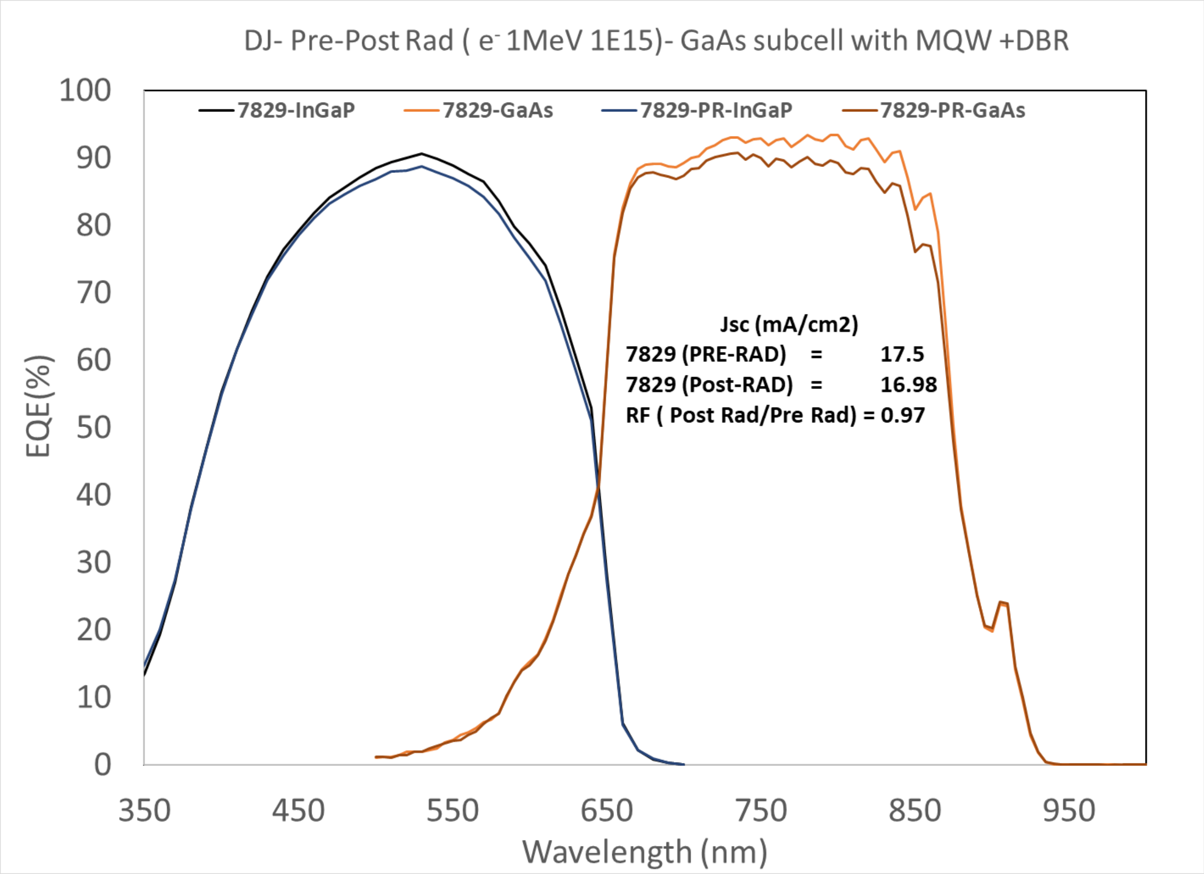
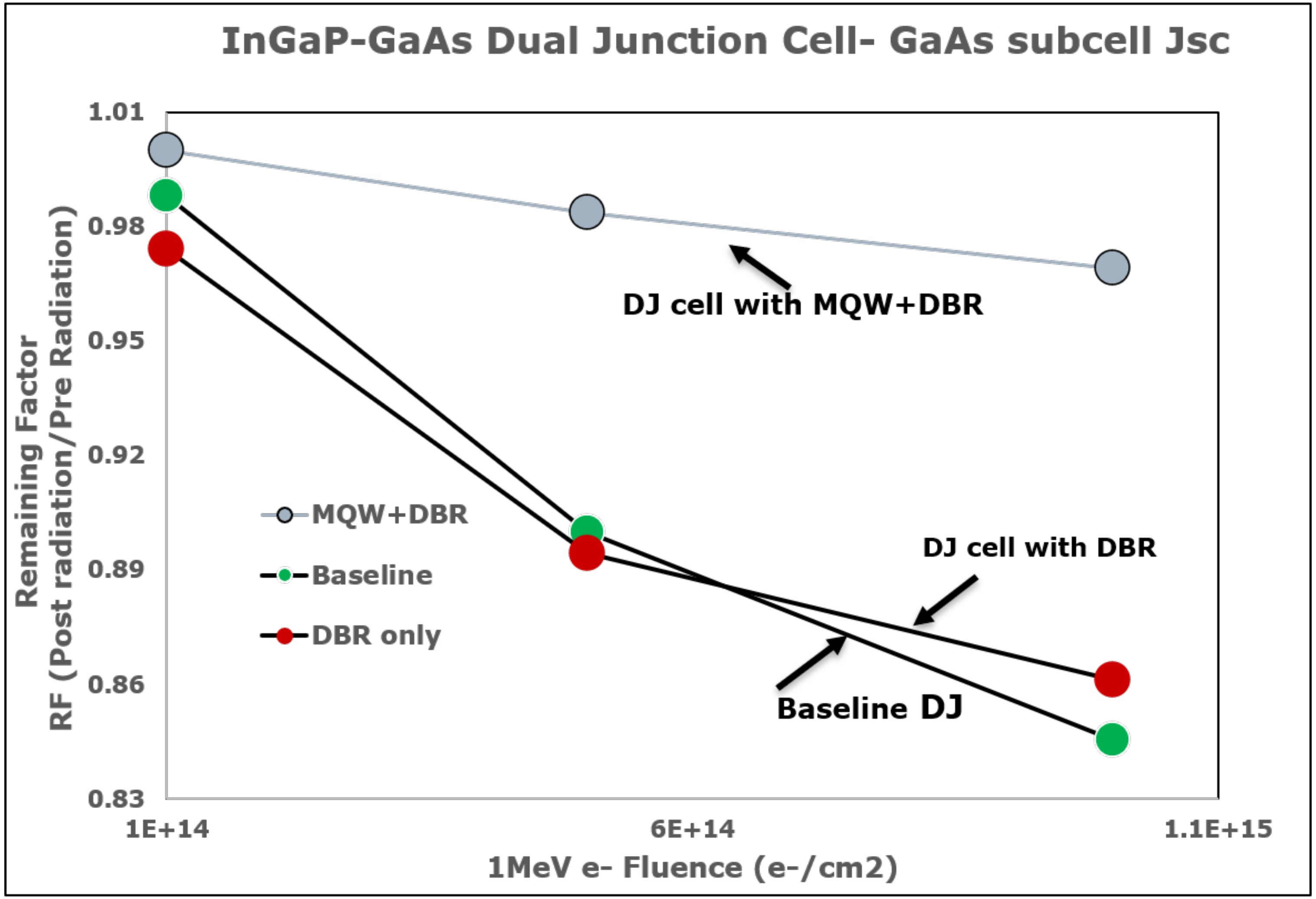
DJ with DBR and MQW- Pre/Post Rad 1MeV e^-



Jsc (mA/cm2)
7829 (PRE-RAD) = 17.5
7829 (Post-RAD) = 16.98
RF (Post Rad/Pre Rad) = 0.97

RF for J_{sc} from EQE= 0.97
for GaAs sub-cell – Rad 1E15 1MeV e^- [1]

DJ with DBR and MQW- Pre/Post Rad 1MeV e$^-$

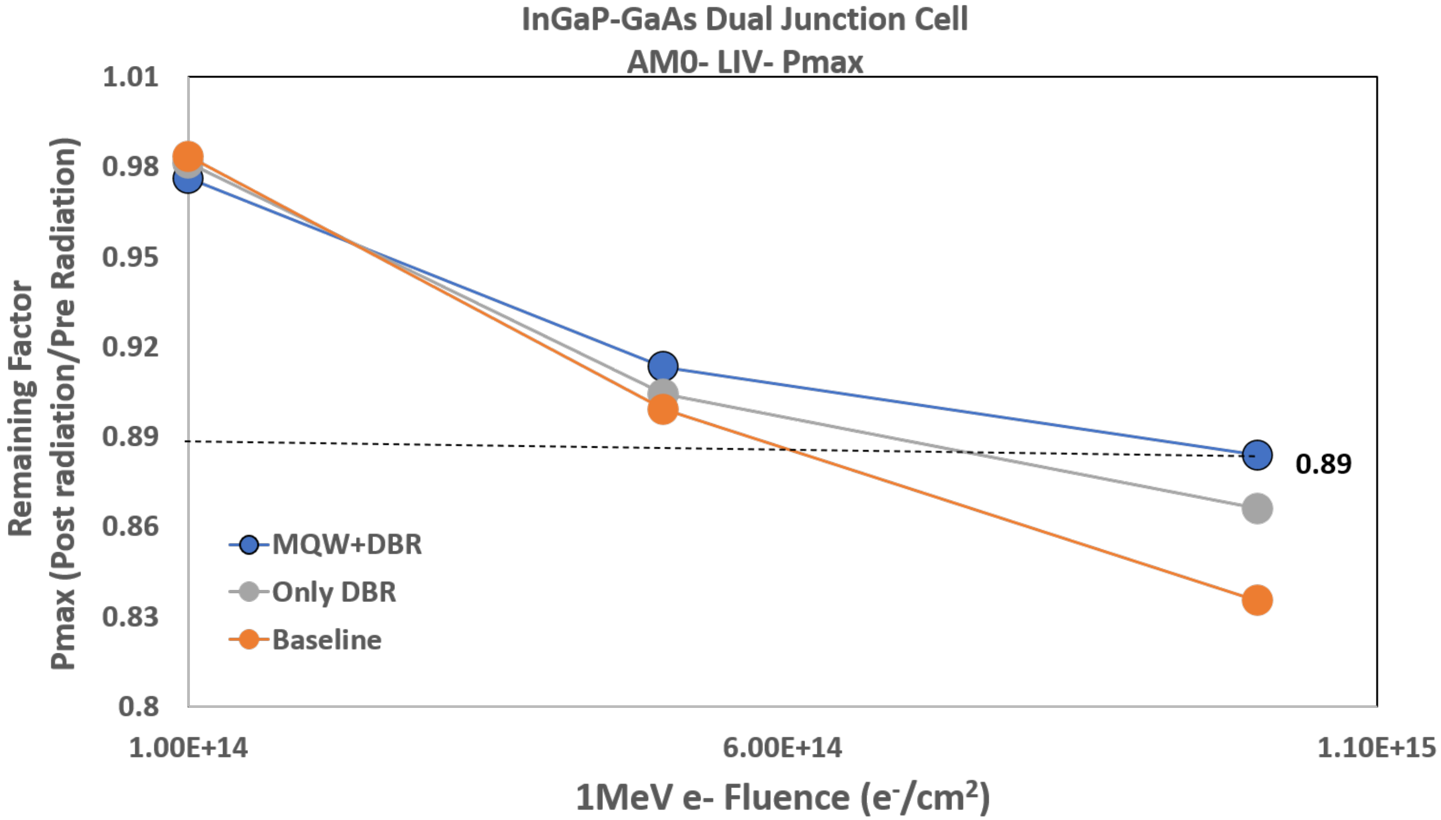


<u>Data from EQE (3-7829/30/31)</u>

DJ cells with MQW and DBR
Exhibited higher RF (>0.97)
Jsc values for GaAs subcell (n-i-p)

The DJ cells with no MQW and DBR have lower RF 0.85

DJ with DBR and MQW- Pre/Post Rad 1MeV e^-



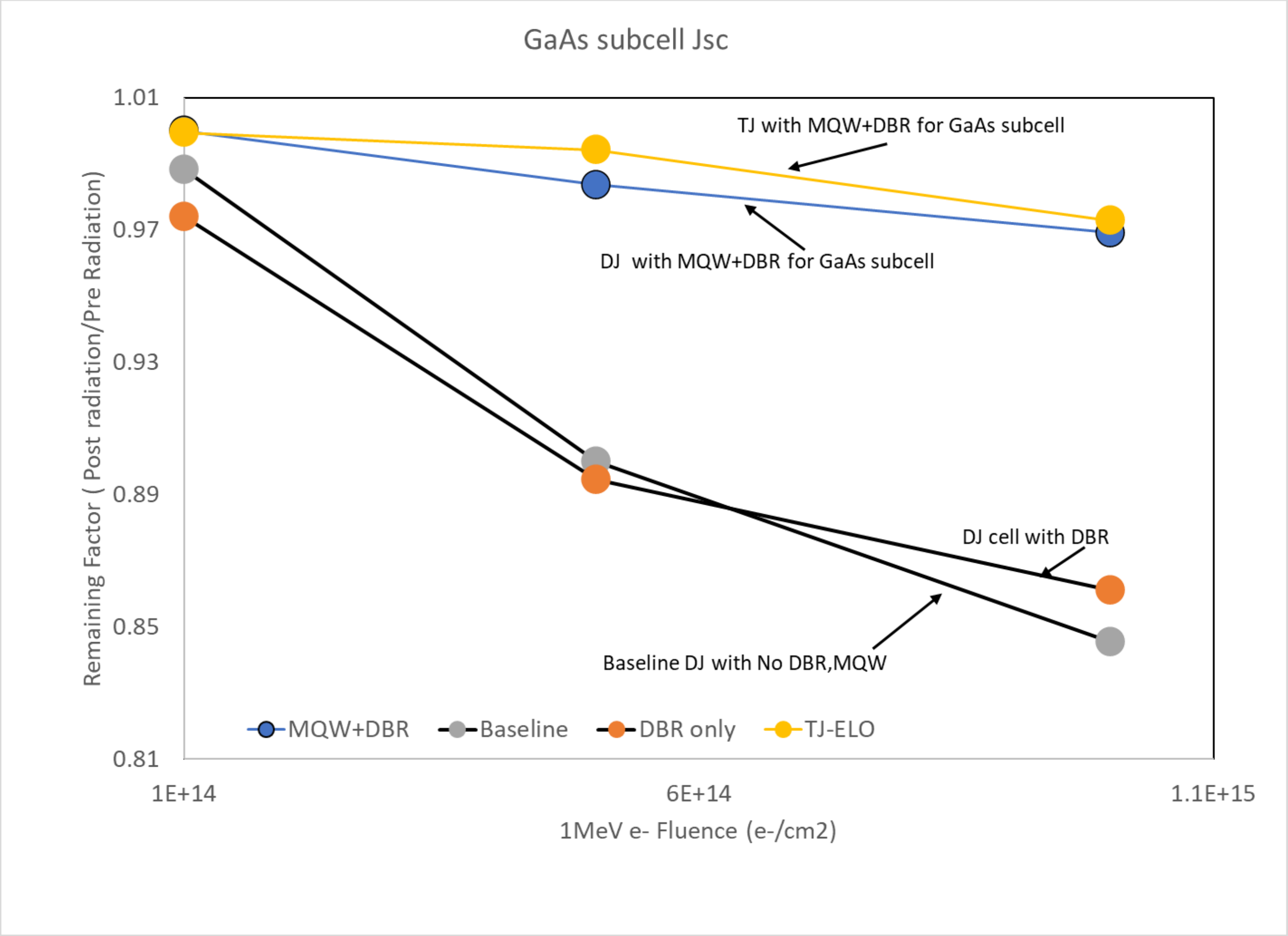
Data from AM0 LIV curves

DJ Cells with MQW+DBR exhibited RF for Pmax 0.89

DJ Cells with only DBR exhibited RF for Pmax 0.86

Baseline cells RF for Pmax of 0.83

IMM 3J ELO cells -Pre/Post Rad 1MeV e$^-$



<u>Data from EQE</u>

TJ and DJ cells with MQW and DBR
Exhibited higher RF (>0.97)
Jsc values for GaAs subcell (p-i-n)

MLD 3J IMM- GaAs subcell is standard
Structure X – RF -0.93

The DJ cells with no MQW and DBR
have lower RF 0.85

Temperature Behavior in ELO devices with WSPS

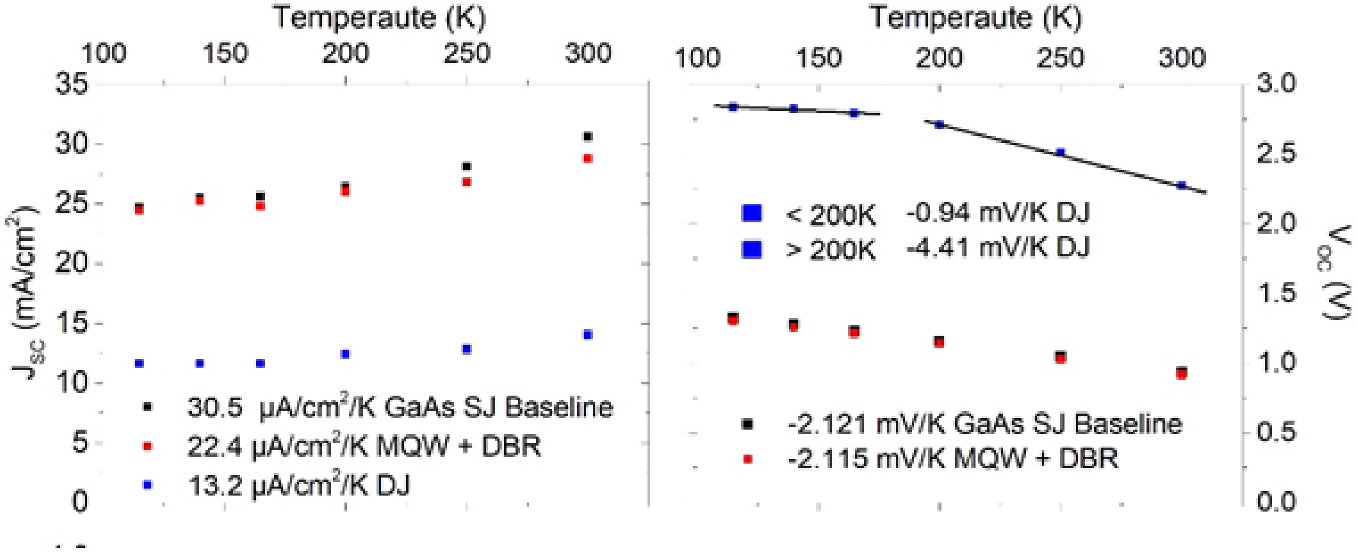
Temperature coefficients ranging from 115K to 300K were performed for single-junction GaAs control, GaAs solar cell with MQW and DBR, and a GaInP/GaAs dual-junction in a TS Space Solar Simulator using a cryogenic system. The system was calibrated under the AM0 spectrum.

GaAs single-junctions (with and without WSPS)

- The baseline and MQW/DBR devices result in similar dV_{OC}/dT and dJ_{SC}/dT , so adding MQW does not degrade temperature behavior.
- Efficiency increases at low temperatures for both baseline and MQW/DBR devices.

InGaP/GaAs Dual-junction solar cell

- Our work: dV_{OC}/dT = -4.41 mV/K
- The high temp (> 200K), dV_{OC}/dT is in agreement with values from conventional high-V_{OC} InGaP/GaAs tandem devices, based on literature. Small change in dV_{OC}/dT for low temp (< 200K) is observed.
- Steady efficiency in DJ across a wide range of temperatures



Conclusions

InGaP-GaAs DJ structures with GaAs n-i-p configuration showed improved radiation performance
When DBR and MQW were integrated with bottom GaAs cell.

DJ Solar cells- RF Pmax value was measured as 0.89

TJ cells with DBR and MQW in GaAs subcell have shown RF Isc as 0.93
Which is higher than the baseline cell value of 0.84.

The baseline and MQW/DBR devices result in similar dV_{OC}/dT and dJ_{SC}/dT values

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MicroLink Team

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