Optimized triple-junction solar cells using inverted metamorphic approach

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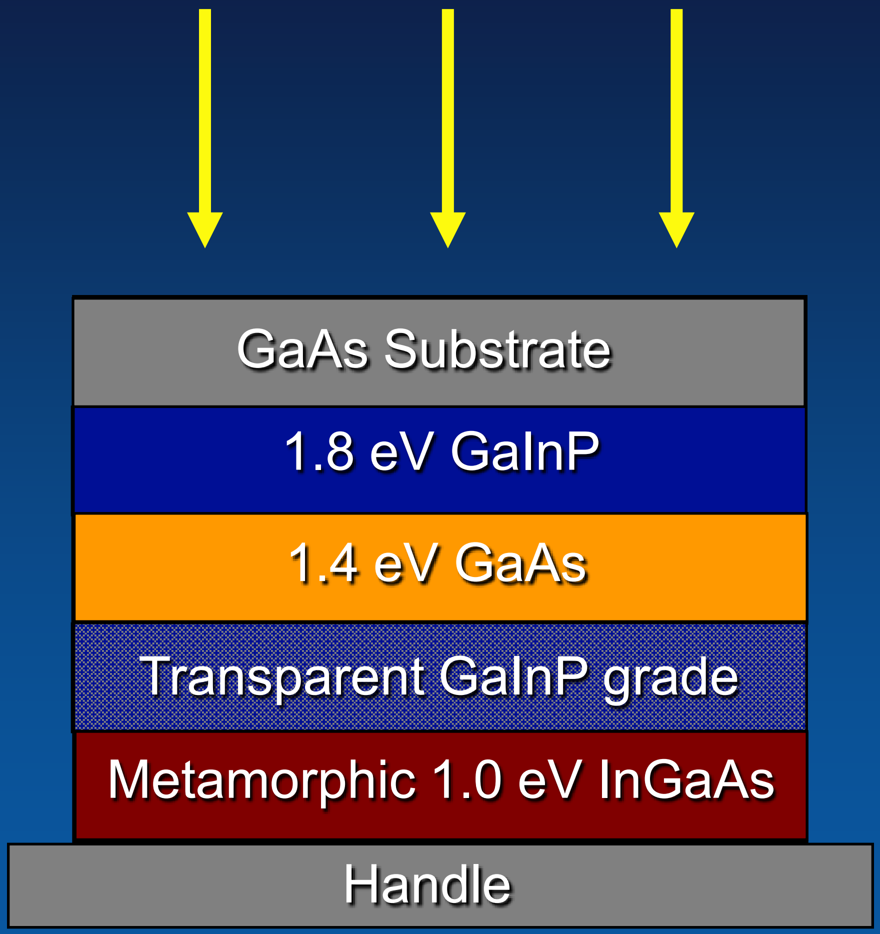
Outline

- Inverted design
- Modelling to optimize efficiency
- World record efficiency achieved
- Effects of temperature and concentration

Inverted Design

- OMVPE growth on GaAs
- Lattice-matched grown first
- Metamorphic grown last
- Mounted on Si or glass
- Substrate removed

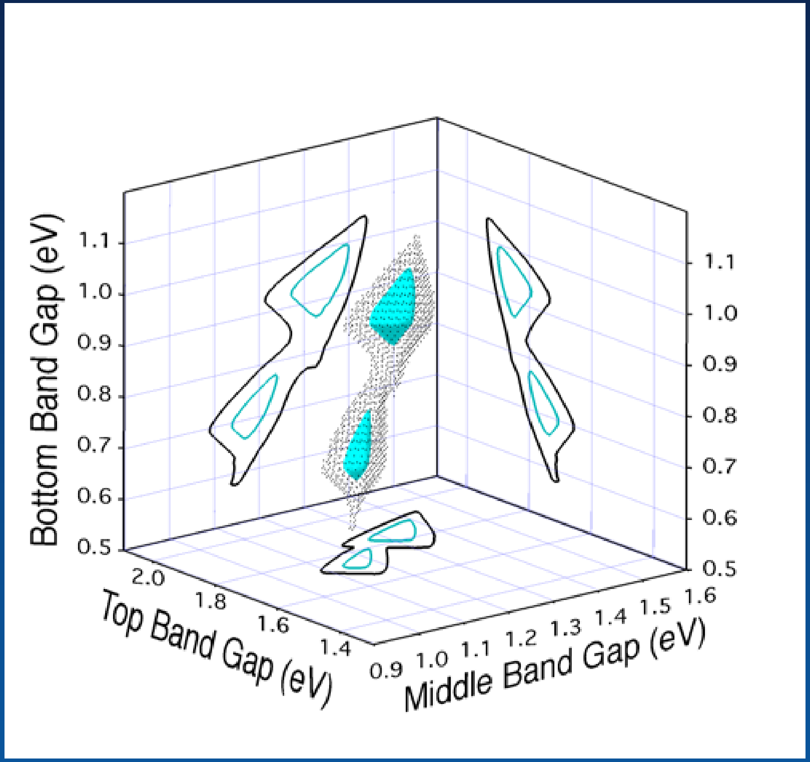


Introduced by Mark Wanlass, 2005

Advantages of Inverted Design

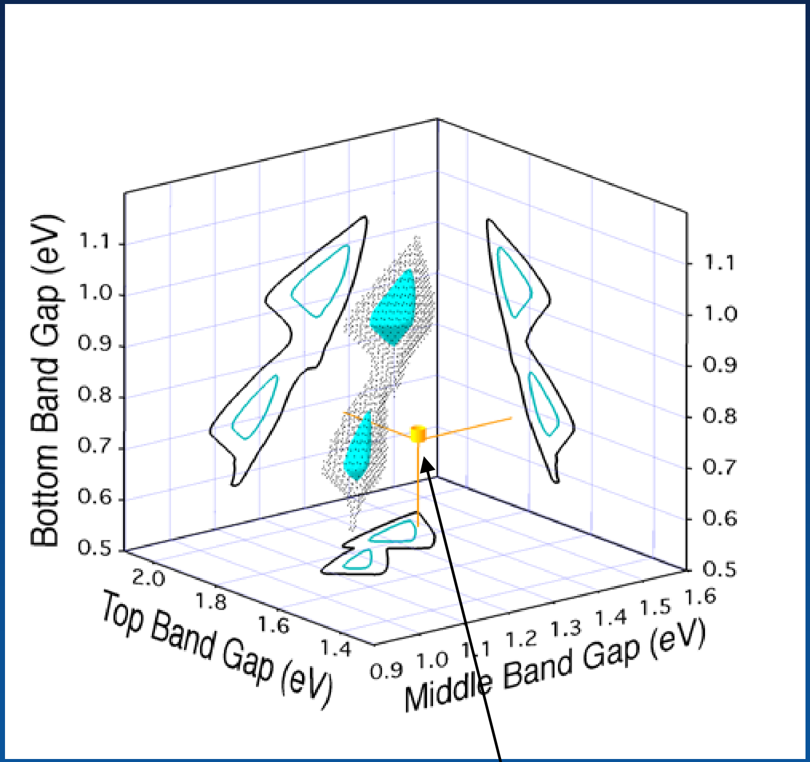
- Monolithic - one growth process
- Thin device – handle properties dominate
  - weight
  - heat removal
  - mechanical robustness
  - flexible
  - cheap (reuse substrate)
- Efficient
  - more band gap choices
  - top junction (most power producing) is lattice-matched
- Requires good metamorphic growth
  - minimize defects
  - transparent buffers

Model for 3 Junction Efficiency



- Iso-efficiency with shadow contours
- Thinned junctions
- 300K, 500 suns
- Direct spectrum
- Semi-empirical (GaAs-like)
- 52% (blue)
- 51% (black)
- Two maxima due to water absorption in terrestrial spectrum

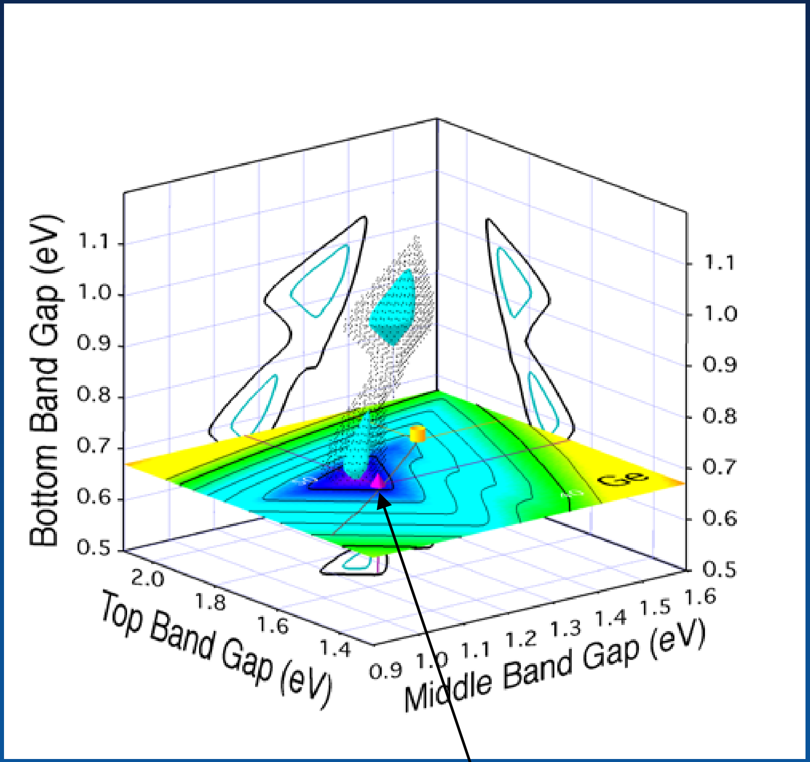
Model for 3 Junction Efficiency



Lattice-matched on Ge

- Lattice-matched not optimized

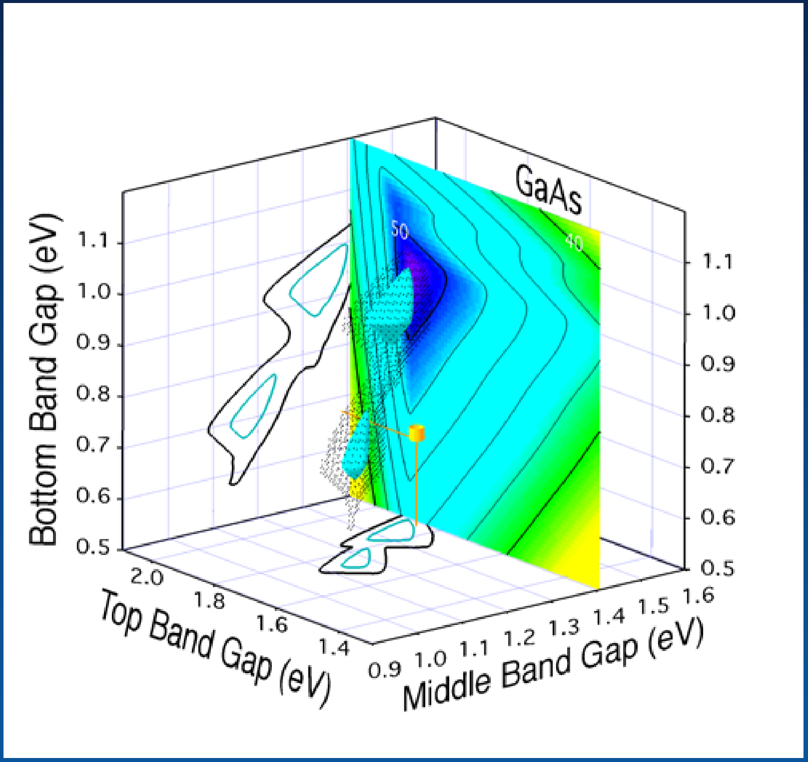
Model for 3 Junction Efficiency



Optimized on Ge

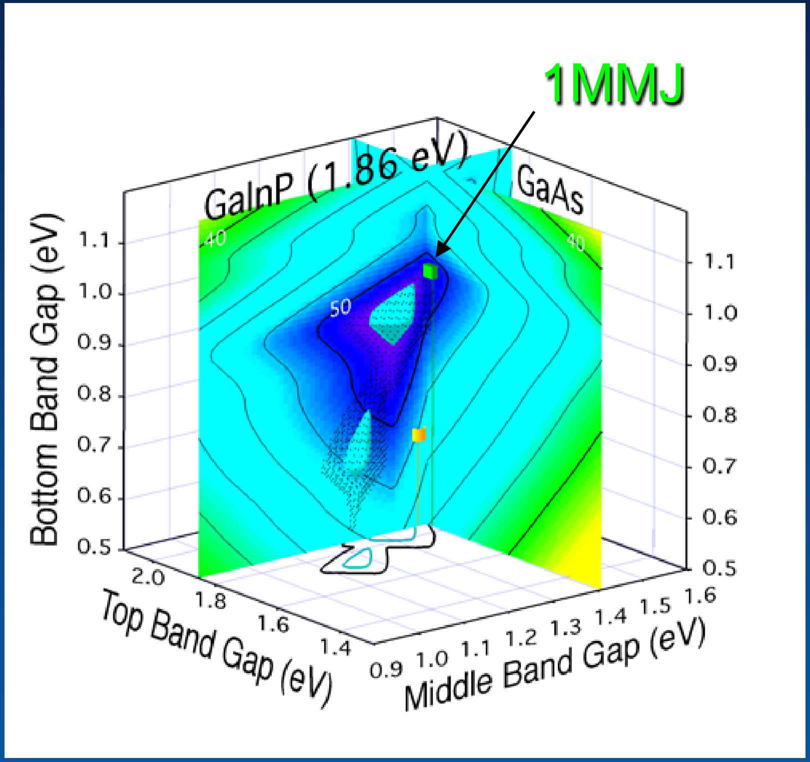
- Lattice-matched not optimized
- Constrained to Ge bottom junction
- Top two junctions lattice-matched to each other (grey line)
- Spectrolab (40.7%)
- Fraunhofer ISE (39.7%)

Model for 3 Junction Efficiency



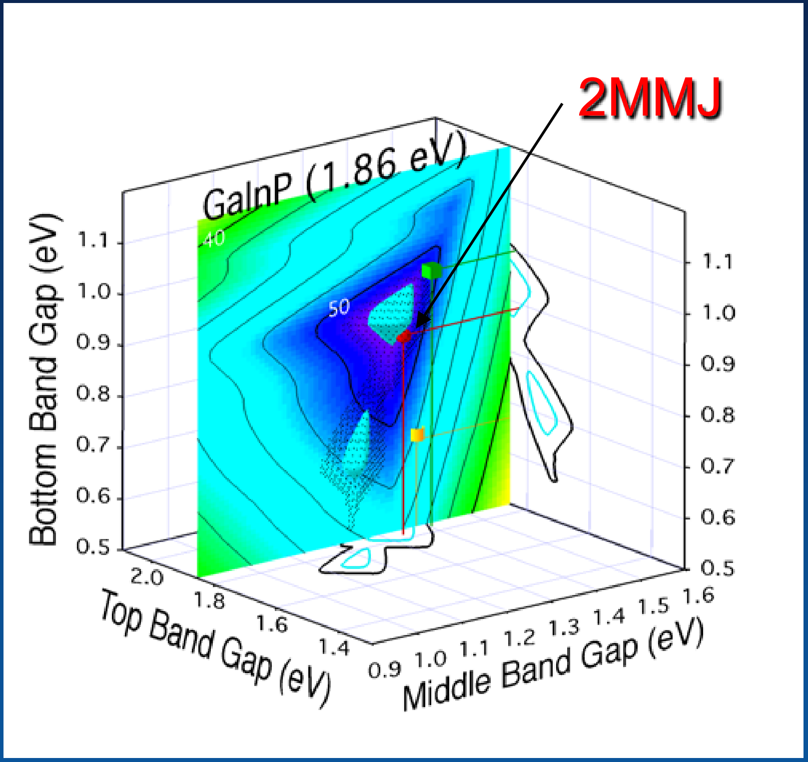
- Constrain middle junction to GaAs

Model for 3 Junction Efficiency



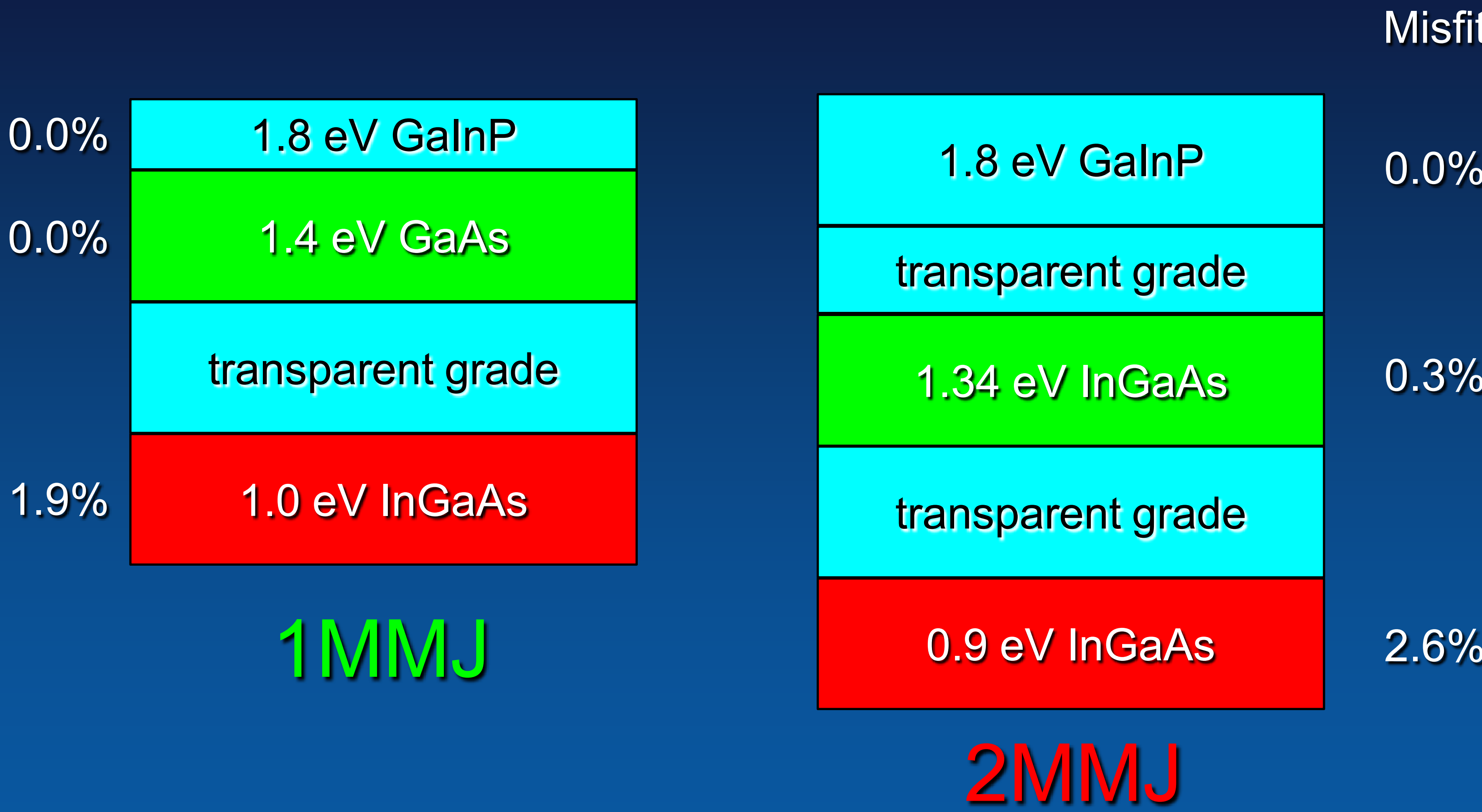
- Constrain middle junction to GaAs
- Constrain top junction to GaInP lattice-matched to GaAs
- Inverted approach

Model for 3 Junction Efficiency



- ~~Constrain middle junction to GaAs~~
- Constrain top junction to GaInP lattice-matched to GaAs
- ✓ Inverted approach
- Relax constraint on middle junction
- Nearly Optimized

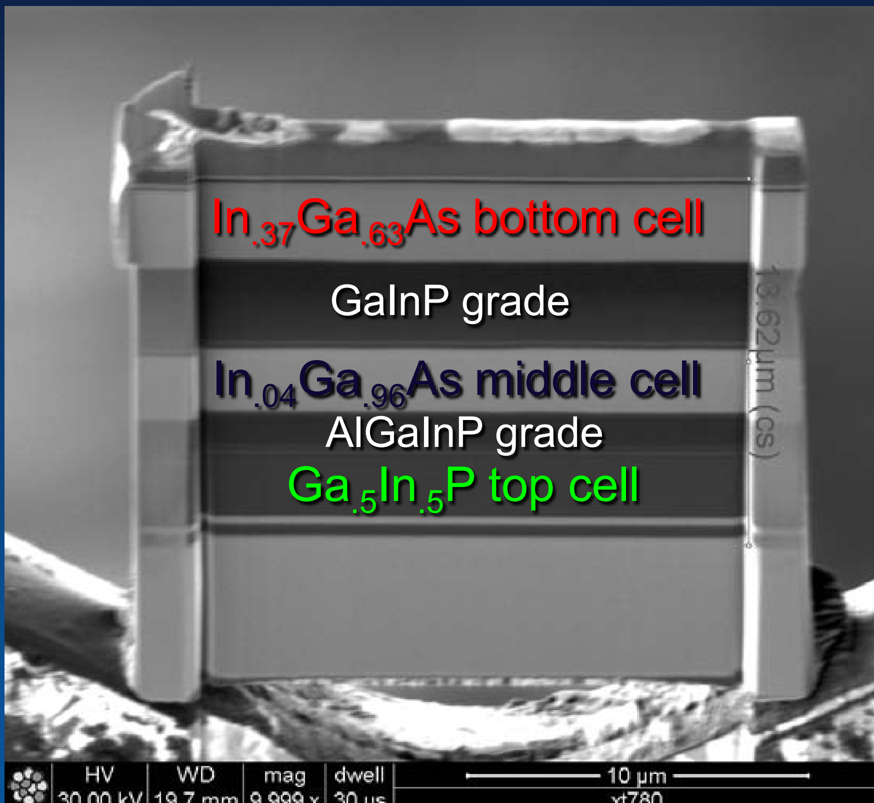
Two Triple-Junction Inverted Metamorphic Designs



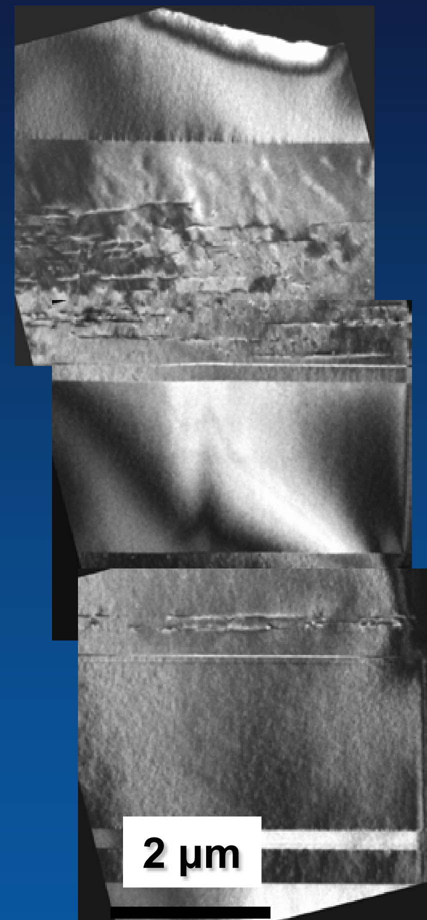
APL, **91**, 023502 (2007)

APL, **93**, 123505 (2008)

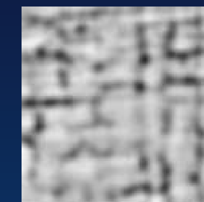
Dislocations in Inverted Triple with Two Mismatched Junctions



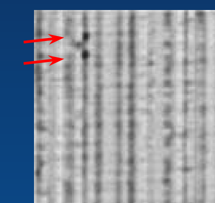
Ion beam image of FIB sample



220DF TEM



$2 \times 10^6\ cm^{-2}$



$1 \times 10^5\ cm^{-2}$

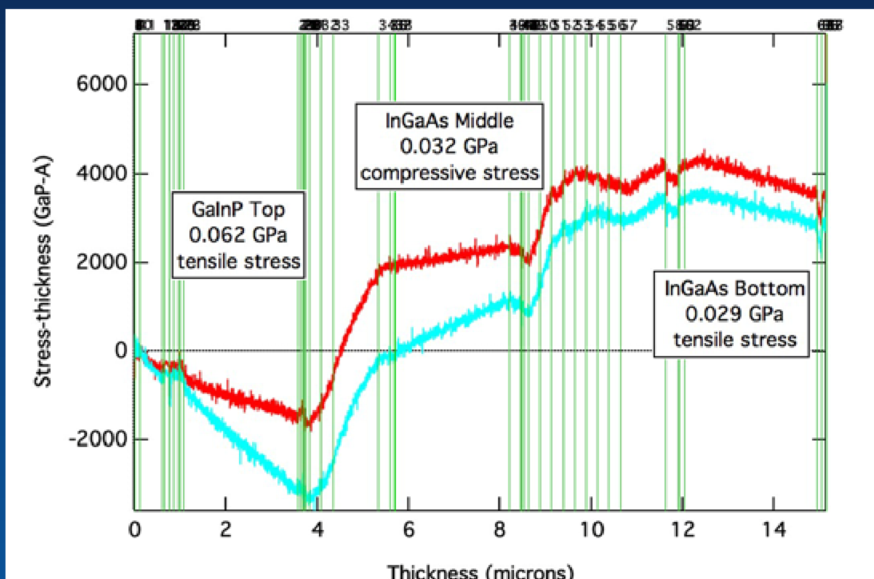
none

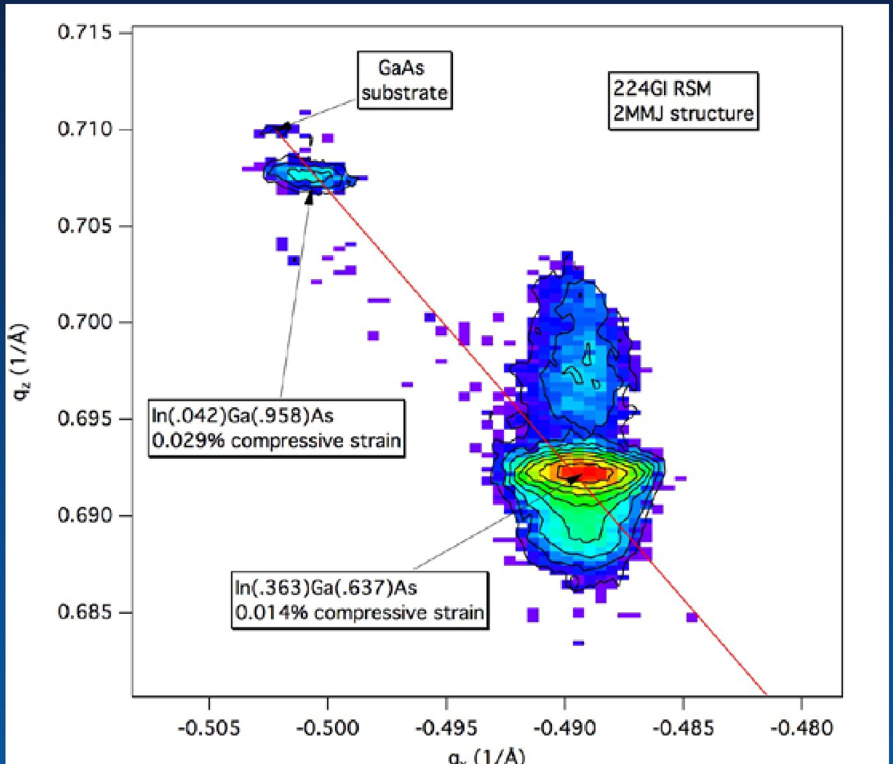
Plan-view CL

40µm x 40µm area

Stress and Strain of 2MMJ

Near zero in both metamorphic junctions



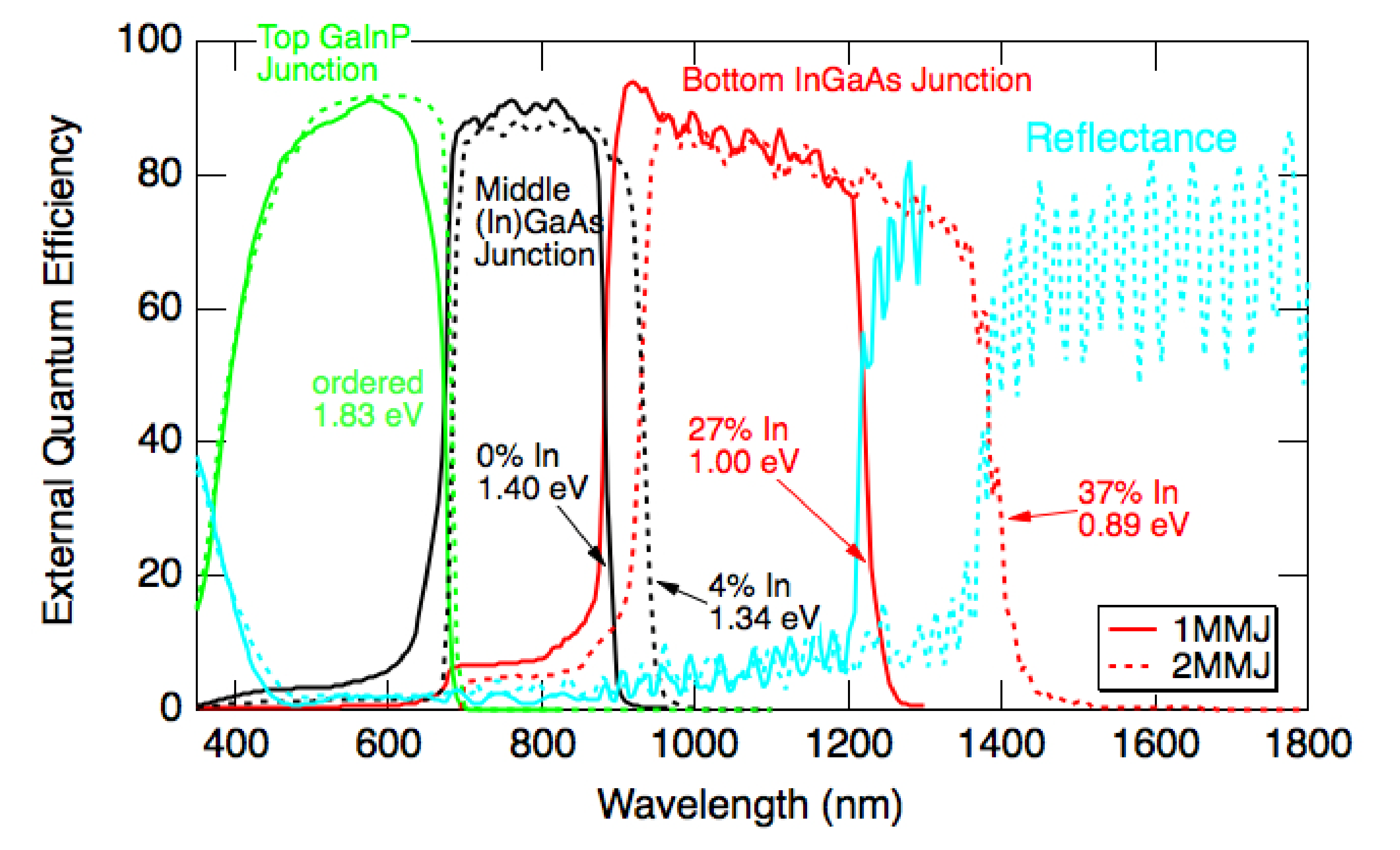


in situ stress
by MOS

ex situ strain
by XRD

(see J. Crystal Growth, **310**, 2339 (2008))

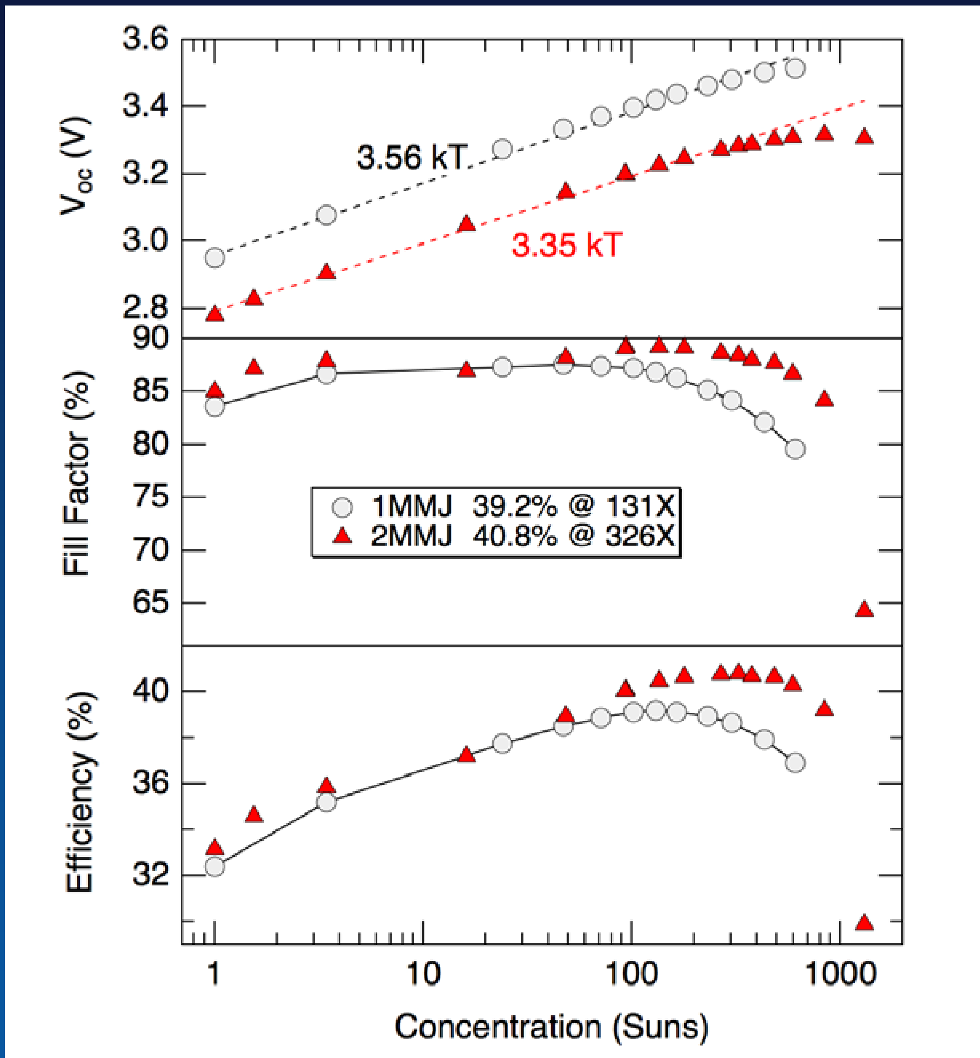
Inverted Solar Cell Comparison



New 2MMJ design has
- **higher current, lower voltage**
- **optically thick junctions**

Both IMM designs reject much unused IR light

Inverted Solar Cell Comparison



High Concentration

40.8% efficiency at 326 suns in triple-junction with 3 different lattice constants!

AM1.5D (low AOD) spectrum

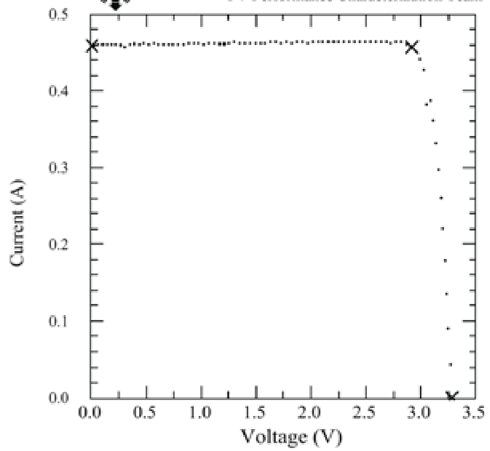
IV Curves of 2MMJ

NREL
GaInP/GaInAs/GaInAs Cell

Sample: MH814#7
Thu, Jun 5, 2008 5:29 PM
Reference Spectrum Lo AOD direct

Device Temperature = 25.5°C
area used = 0.1002 cm^2
Irradiance: 325.7 kW/m^2

HIPSS
PV Performance Characterization Team



V_{oc} = 3.284 V
I_{sc} = 0.4588 A
Fill Factor = 88.42 %

V_{max} = 2.914 V
I_{max} = 0.4571 A
P_{max} = 1.332 W
Efficiency = 40.8 ± 2.4%

R@V_{oc} = 0.324 Ω, R@I_{sc} = 657 Ω

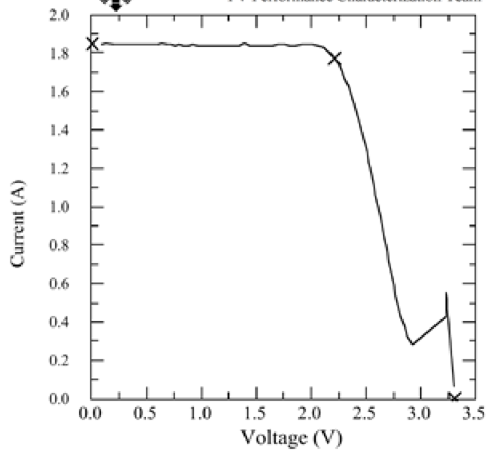
40.8% @ 326 Suns
World Record

NREL
GaInP/GaAs/InGaAs Triple Cell

Sample: MH814#7
Thu, Jun 5, 2008 5:49 PM
PNV 555

Device Temperature = 25.2°C
area used = 0.1002 cm^2
Irradiance: 1311 kW/m^2

HIPSS
PV Performance Characterization Team



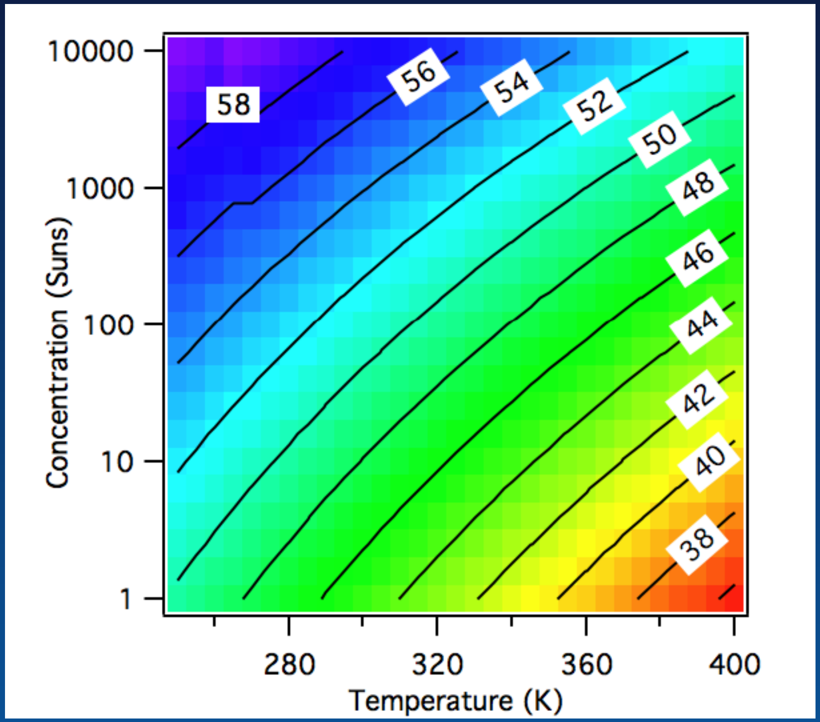
V_{oc} = 3.307 V
I_{sc} = 1.846 A
Fill Factor = 64.30 %

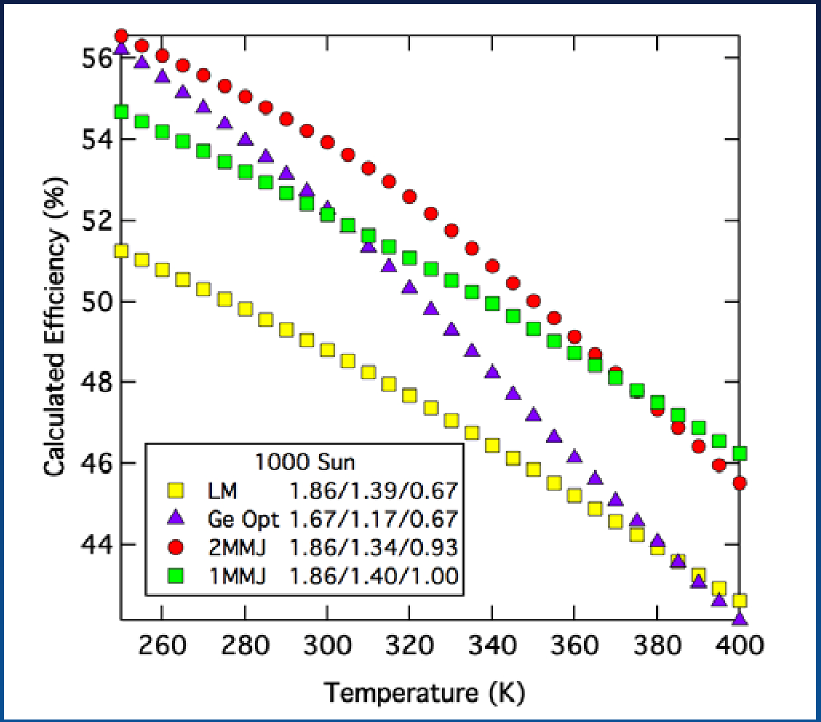
V_{max} = 2.216 V
I_{max} = 1.771 A
P_{max} = 3.926 W

Irradiance is calculated from test device assuming linearity and it's 1-sun I_{sc}
Vst:2.00 dV/dT:12.00 Ap:M PNV:555
point w/ ND=2 filters on ref. 647 has edmund brand. tunnel diode fail
R@V_{oc} = 0.126 Ω, R@I_{sc} = 1970 Ω

Above TJ peak tunneling current @ 1211 Suns

Model Effects of Temperature and Concentration

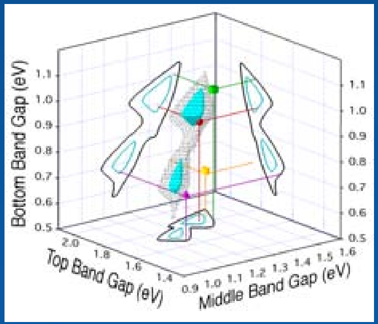




Best 3J efficiencies drop with:

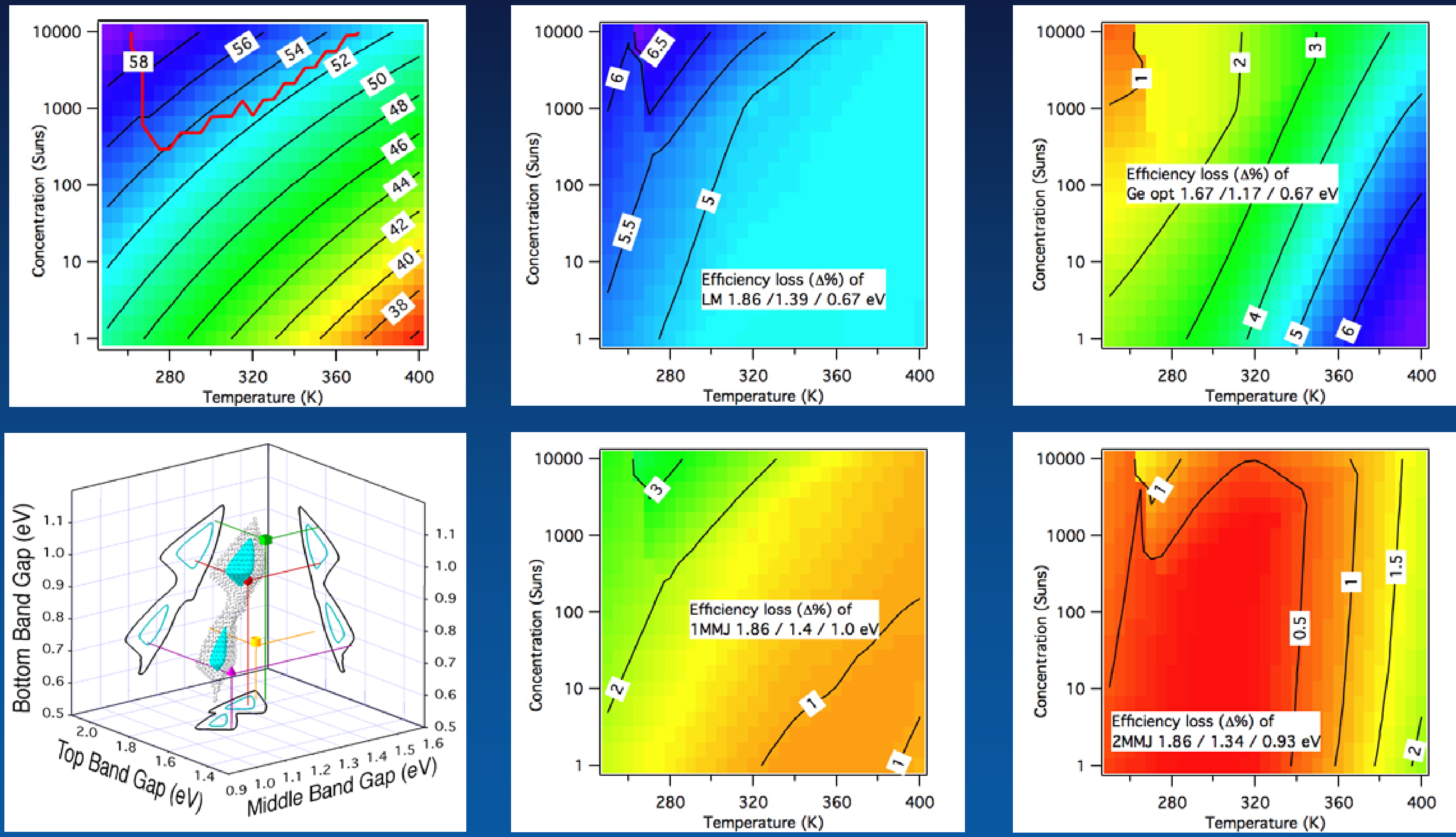
- High temperature
- Low concentration

Specific designs



Specific Designs Relative to Optimal

Optimized for each T,X



300K, 500X

Challenges

- Series resistance, tunnel junctions
- Broadband antireflective coatings
- Long term reliability of lattice mismatched devices
- Measurements of current matched multi-junctions
- More junctions
- Substrate reuse
- Technology transfer to industry

Conclusions

- Record efficiencies with triple-junction inverted metamorphic designs
- Modeling useful to optimize
- Consider operating conditions before choosing design