# Progress in High-Efficiency III-V Multijunction Concentrator Solar Cells

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# Outline

- Solar spectrum and theoretical efficiency
- **Multijunction** cell architectures capable of **>50%**
- Metamorphic (MM) semiconductor materials
  $\Rightarrow$ flexibility in bandgap for multijunction cells
- Experimental results on **metamorphic** (MM) and **lattice-matched** (LM) 3-junction cells over ***40%*** efficiency
- Dislocations and recombination in MM materials
- Bandgap - $V_{oc}$ offset and diode ideality factor for LM and MM
- Highly lattice-mismatched ~1-eV MM GaInAs subcells
- **4-junction** terrestrial concentrator cells with reduced series resistance power losses

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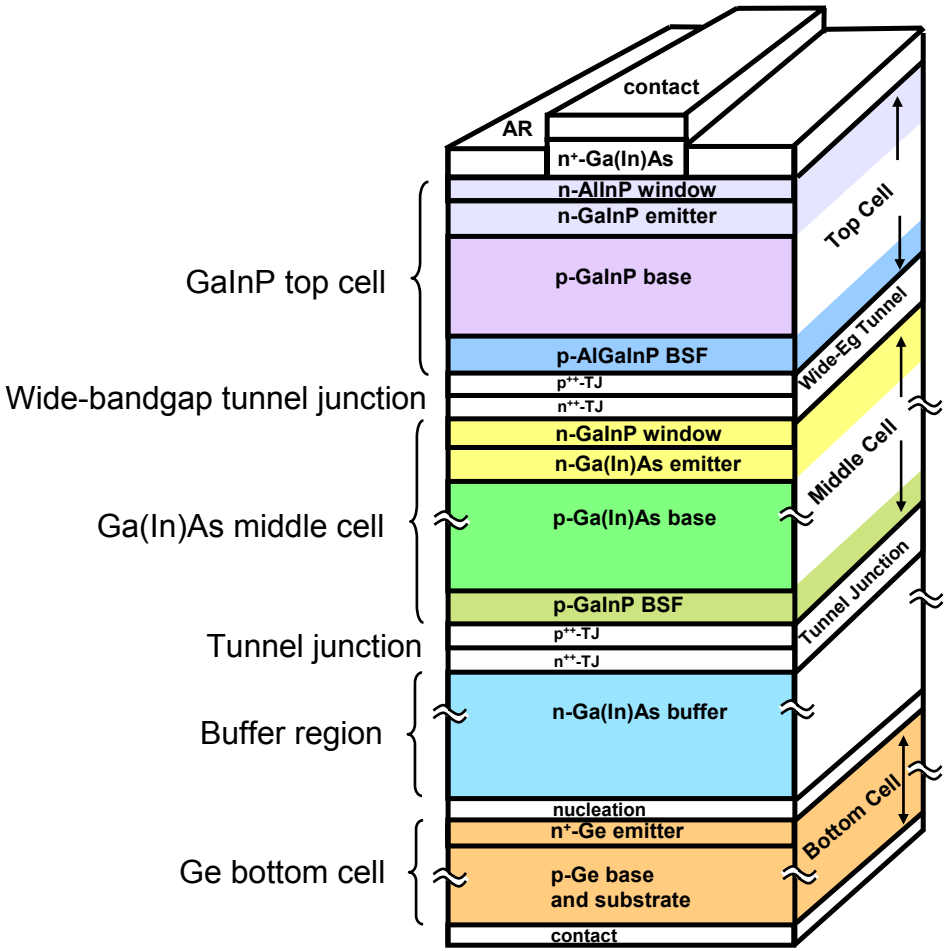
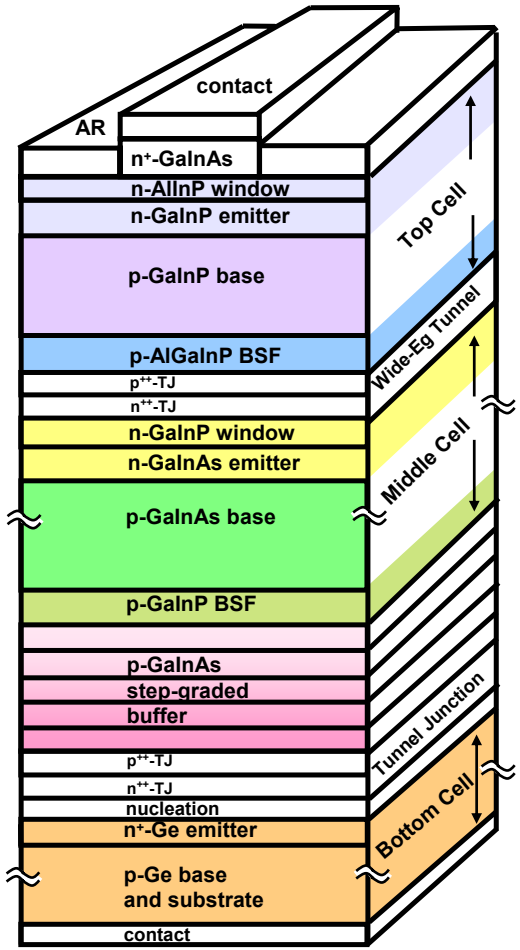
# LM and MM 3-Junction Cell Cross-Section




**Lattice-Matched (LM)**




**Lattice-Mismatched or Metamorphic (MM)**

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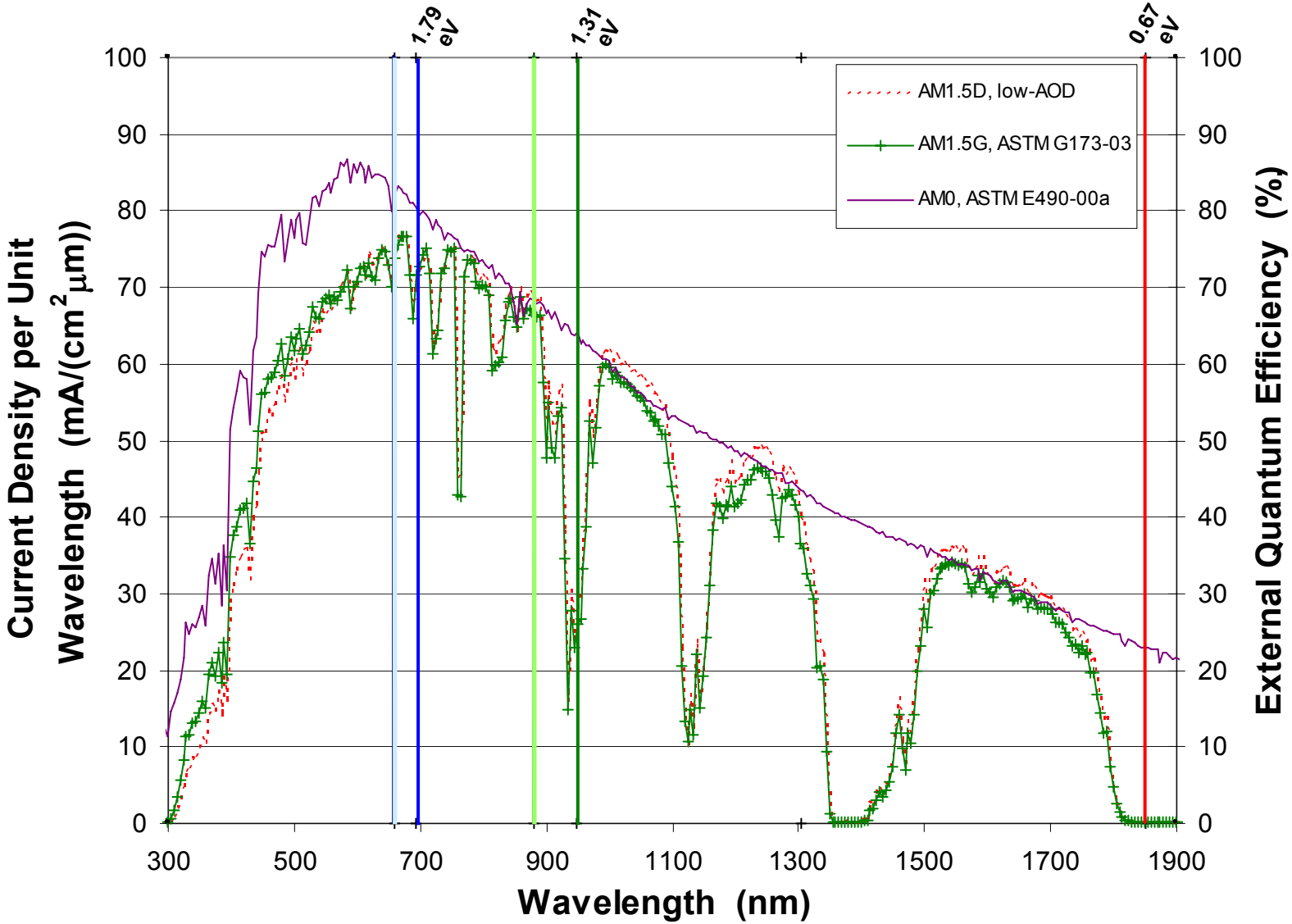
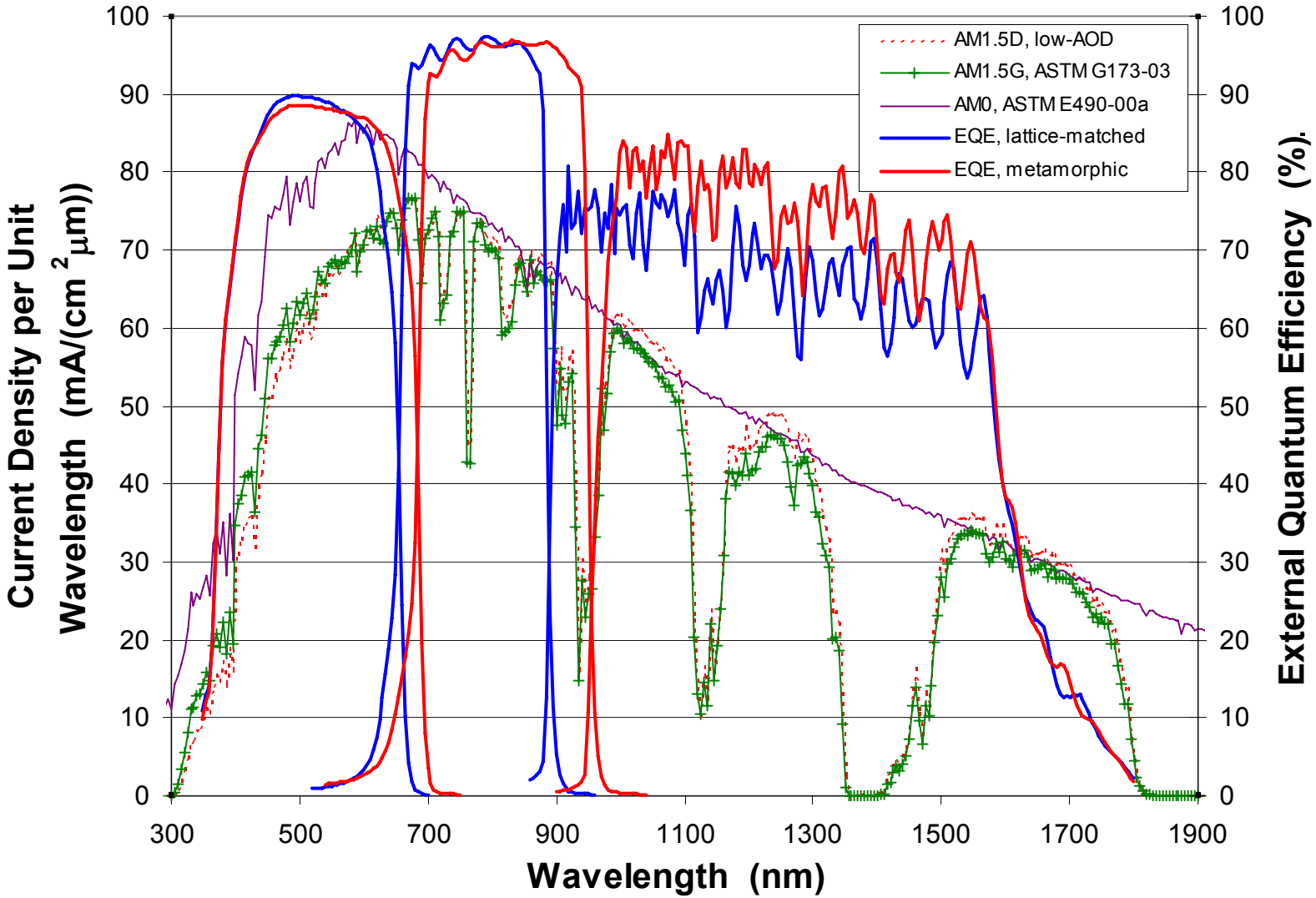
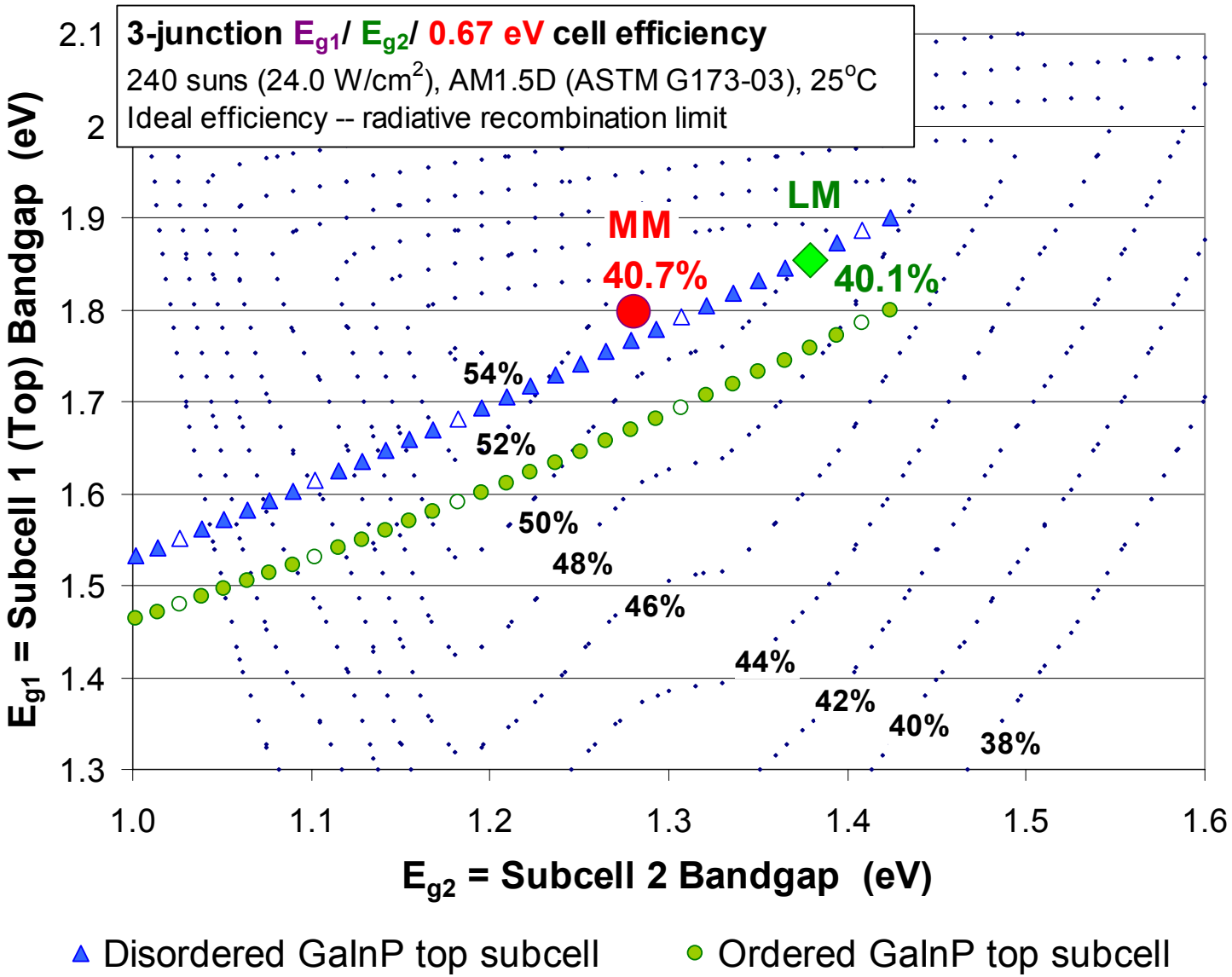
# Solar Spectrum Partition for 3-Junction Cell



# External QE of LM and MM 3-Junction Cells



# 3-Junction Theoretical Eff. — Vary $E_{g1}$ and $E_{g2}$



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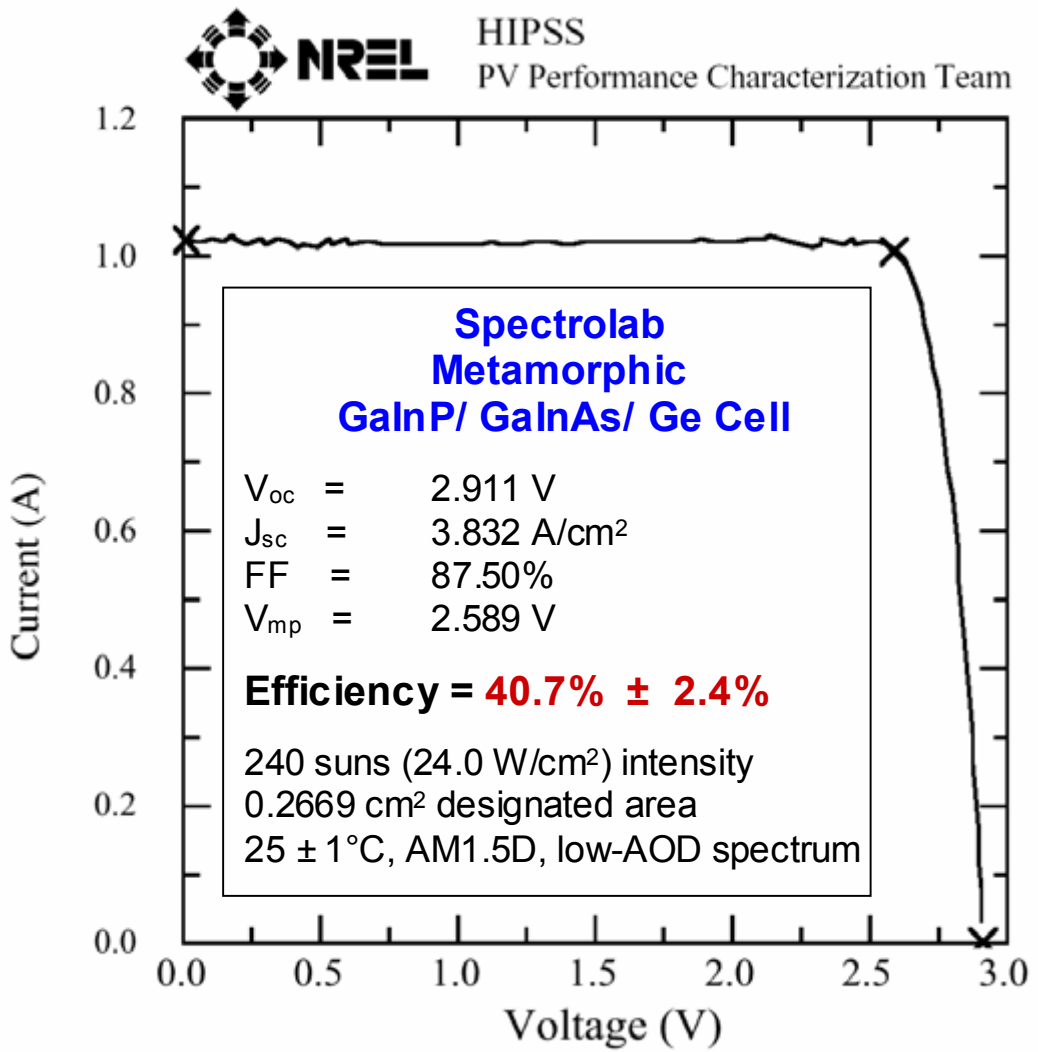
# Record 40.7%-Efficient Concentrator Solar Cell




- **Highest solar conversion efficiency for any type of photovoltaic device demonstrated to date**
- **First solar cell of any kind to reach over *40%* efficiency**

*Concentrator cell light I-V independently verified by J. Kiehl, T. Moriarty, K. Emery – NREL*

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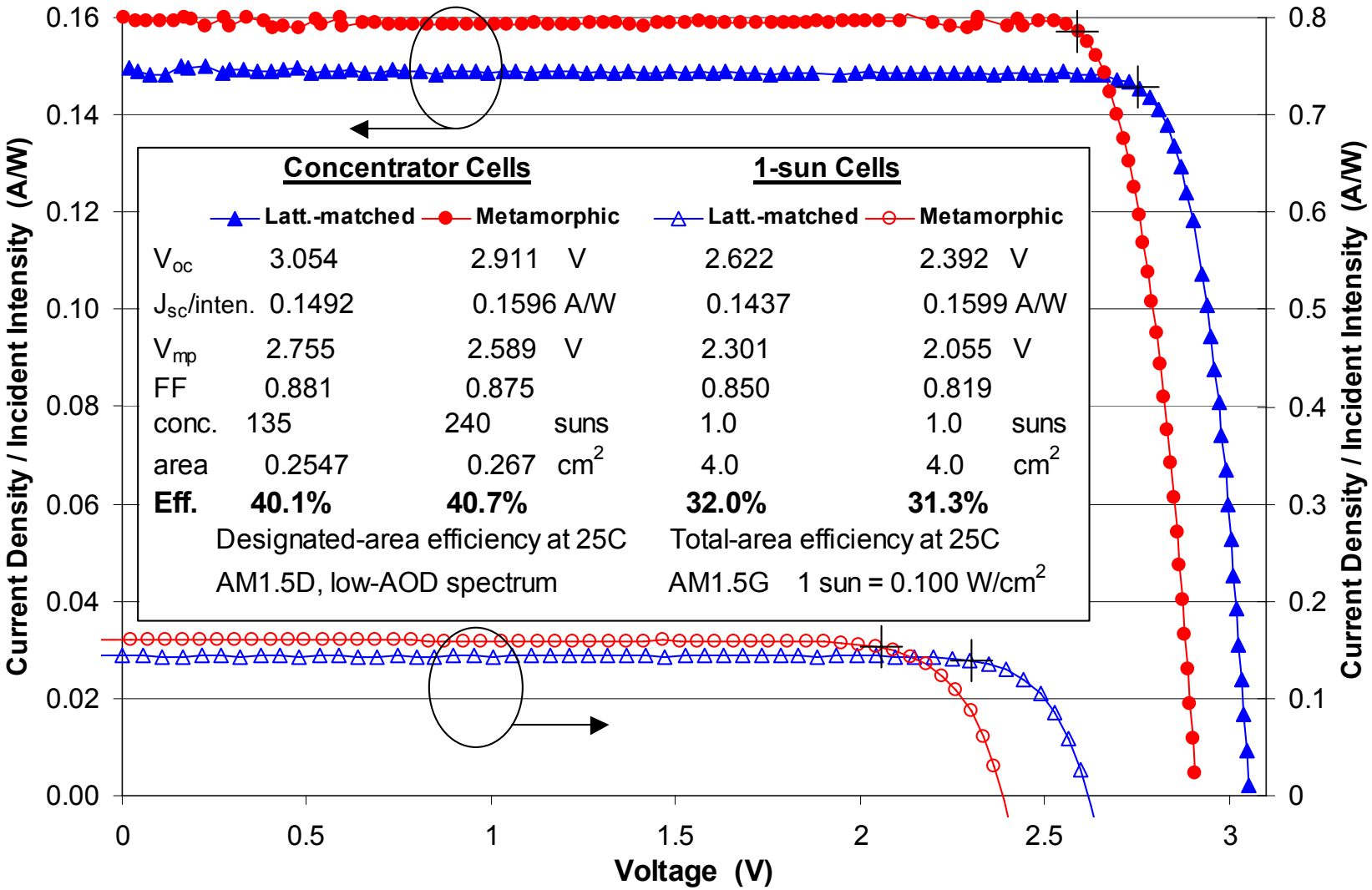
# Lattice-Matched and Metamorphic Cells Over 40%




| | Concentrator Cells | | 1-sun Cells | |
|---|---|---|---|---|
| | Latt.-matched | Metamorphic | Latt.-matched | Metamorphic |
| $V_{oc}$ | 3.054 | 2.911 V | 2.622 | 2.392 V |
| $J_{sc}$/inten. | 0.1492 | 0.1596 A/W | 0.1437 | 0.1599 A/W |
| $V_{mp}$ | 2.755 | 2.589 V | 2.301 | 2.055 V |
| FF | 0.881 | 0.875 | 0.850 | 0.819 |
| conc. | 135 | 240 suns | 1.0 | 1.0 suns |
| area | 0.2547 | 0.267 $cm^2$ | 4.0 | 4.0 $cm^2$ |
| **Eff.** | **40.1%** | **40.7%** | **32.0%** | **31.3%** |
| | Designated-area efficiency at 25C | | Total-area efficiency at 25C | |
| | AM1.5D, low-AOD spectrum | | AM1.5G 1 sun = 0.100 $W/cm^2$ | |

# Record Cell Efficiencies for a Variety of PV Technologies

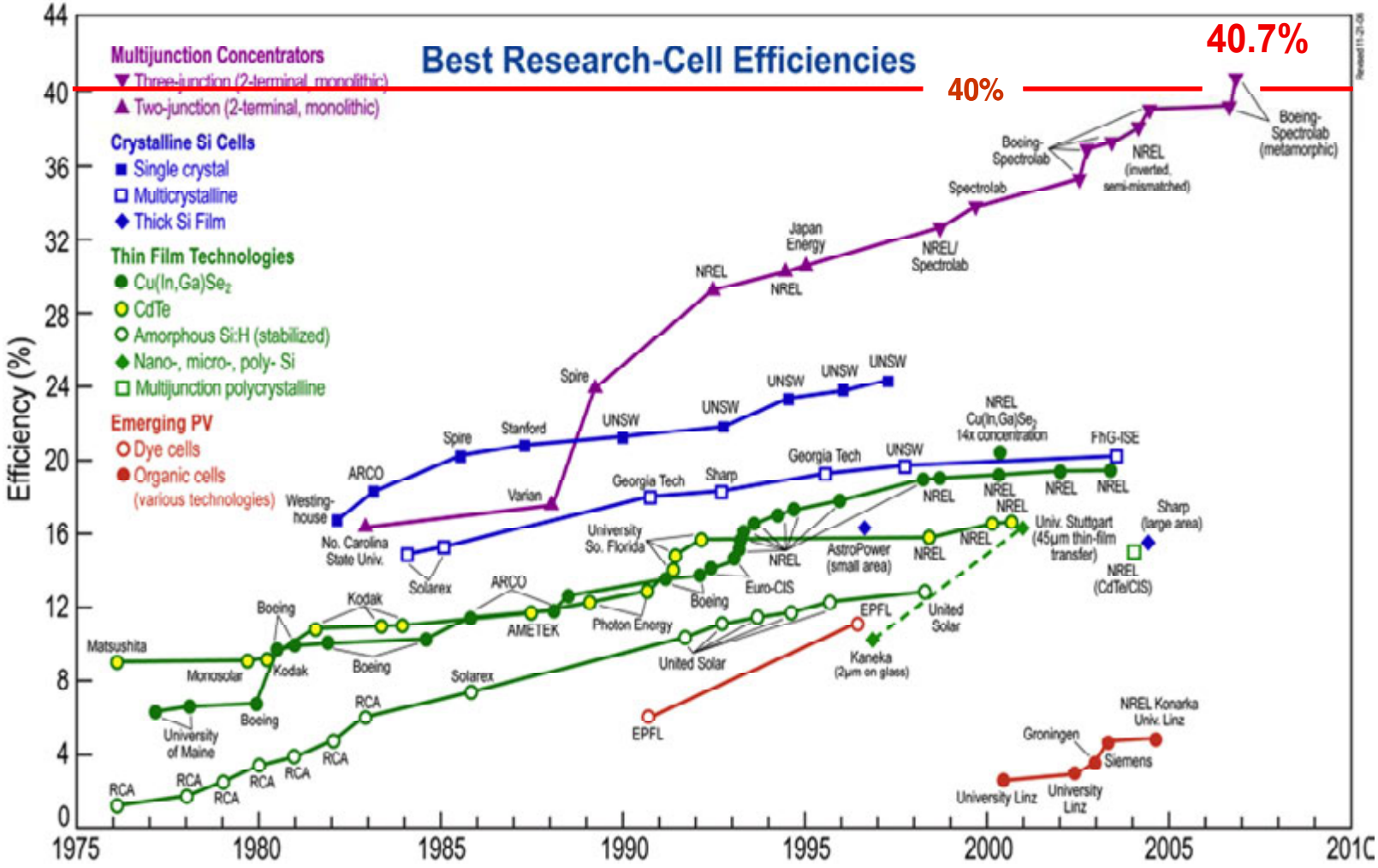
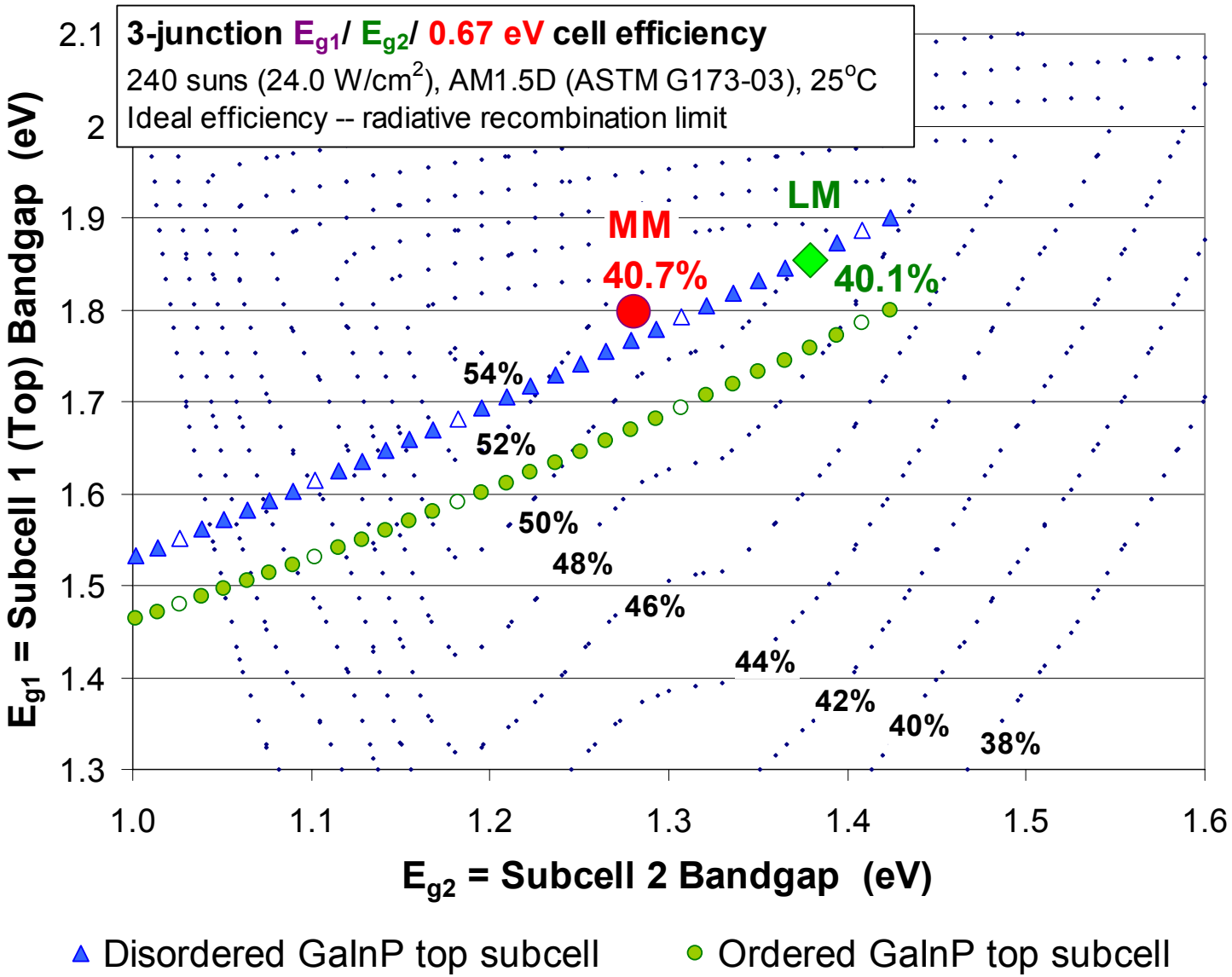



Chart courtesy of Bob McConnell, NREL

# 3-Junction Theoretical Eff. — Vary $E_{g1}$ and $E_{g2}$



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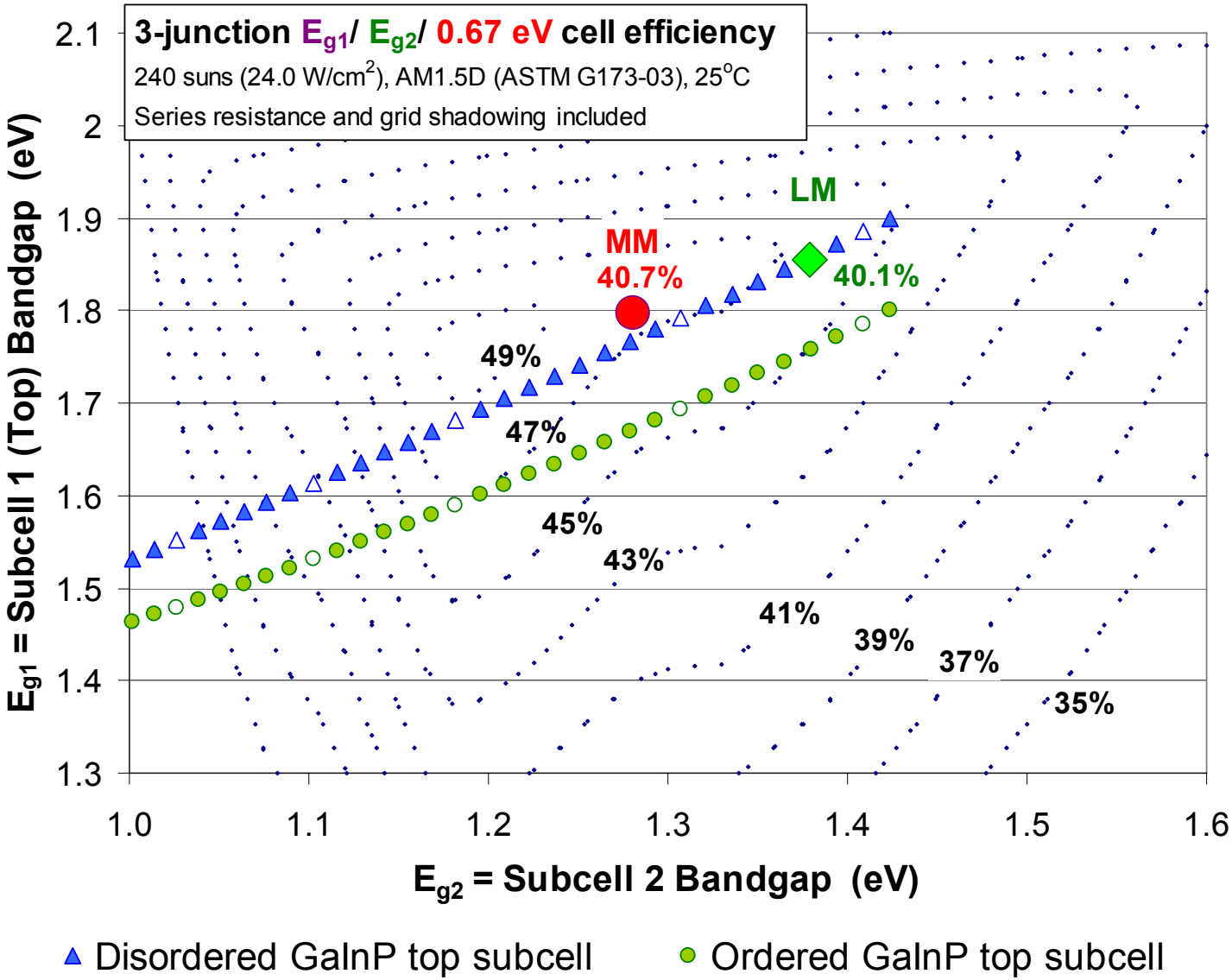
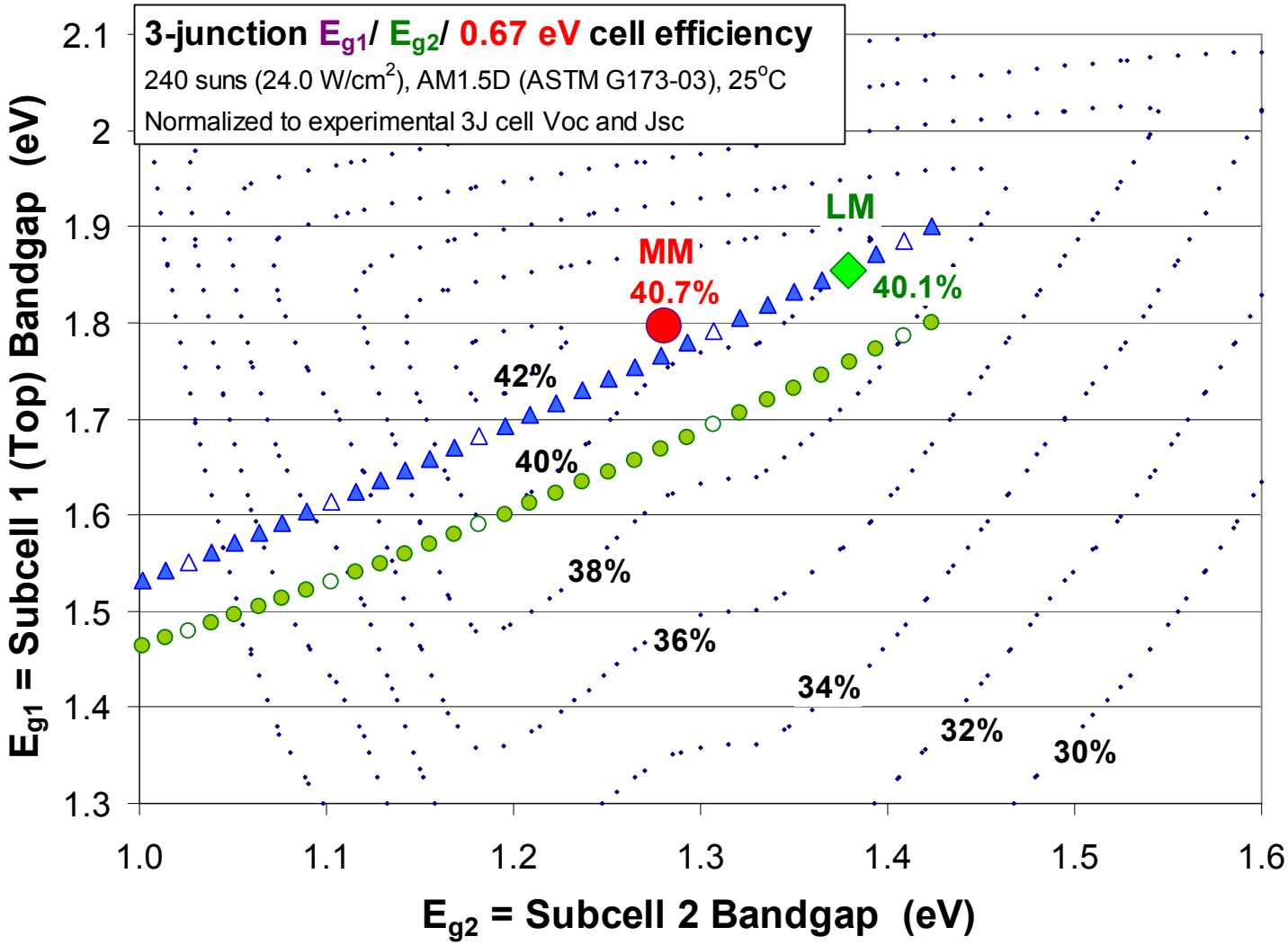
# 3-Junction Efficiency – Series Res. and Shadowing



# 3-Junction Efficiency – Based on Expt. Values



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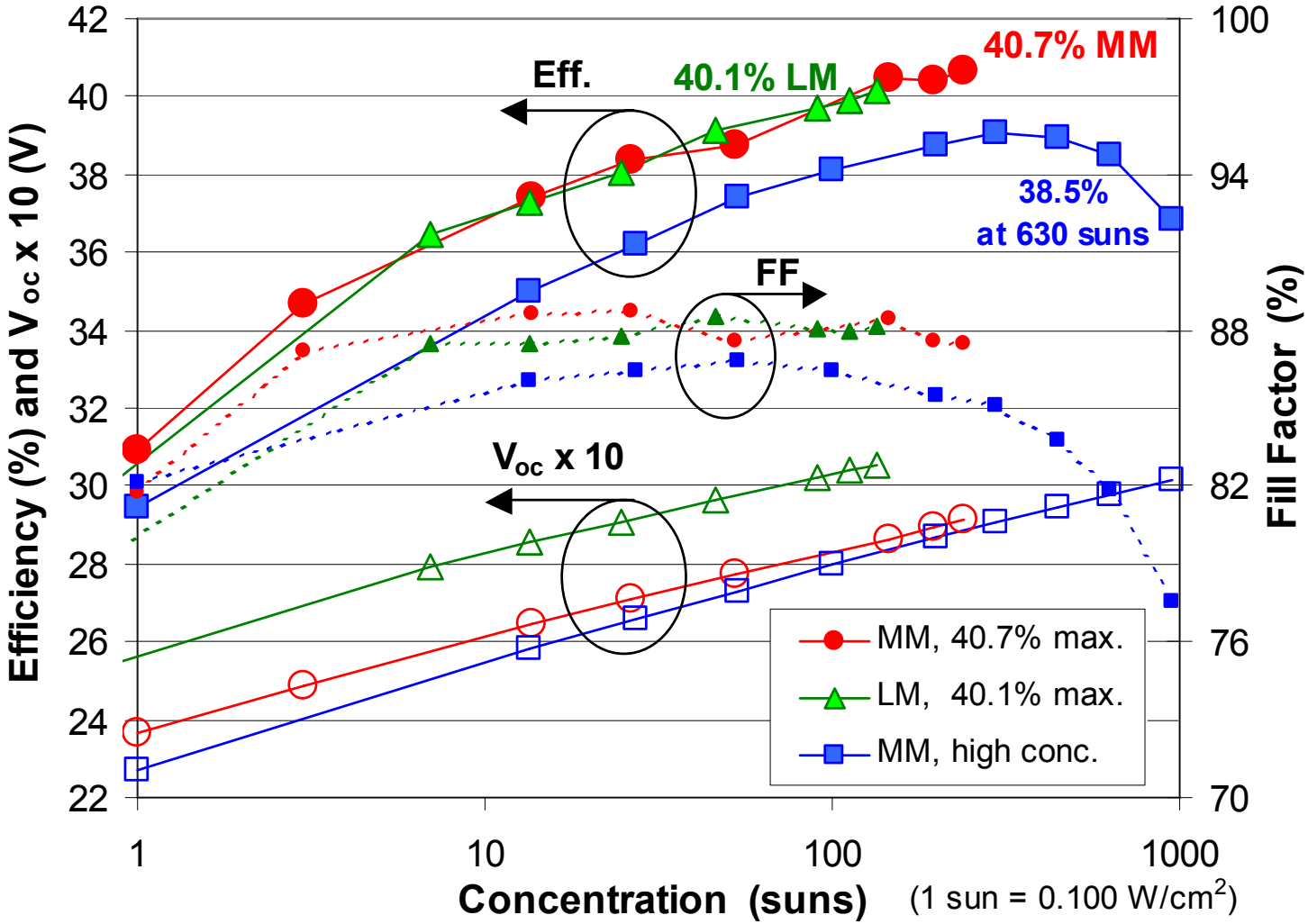
# Record Cell Performance vs. Concentration



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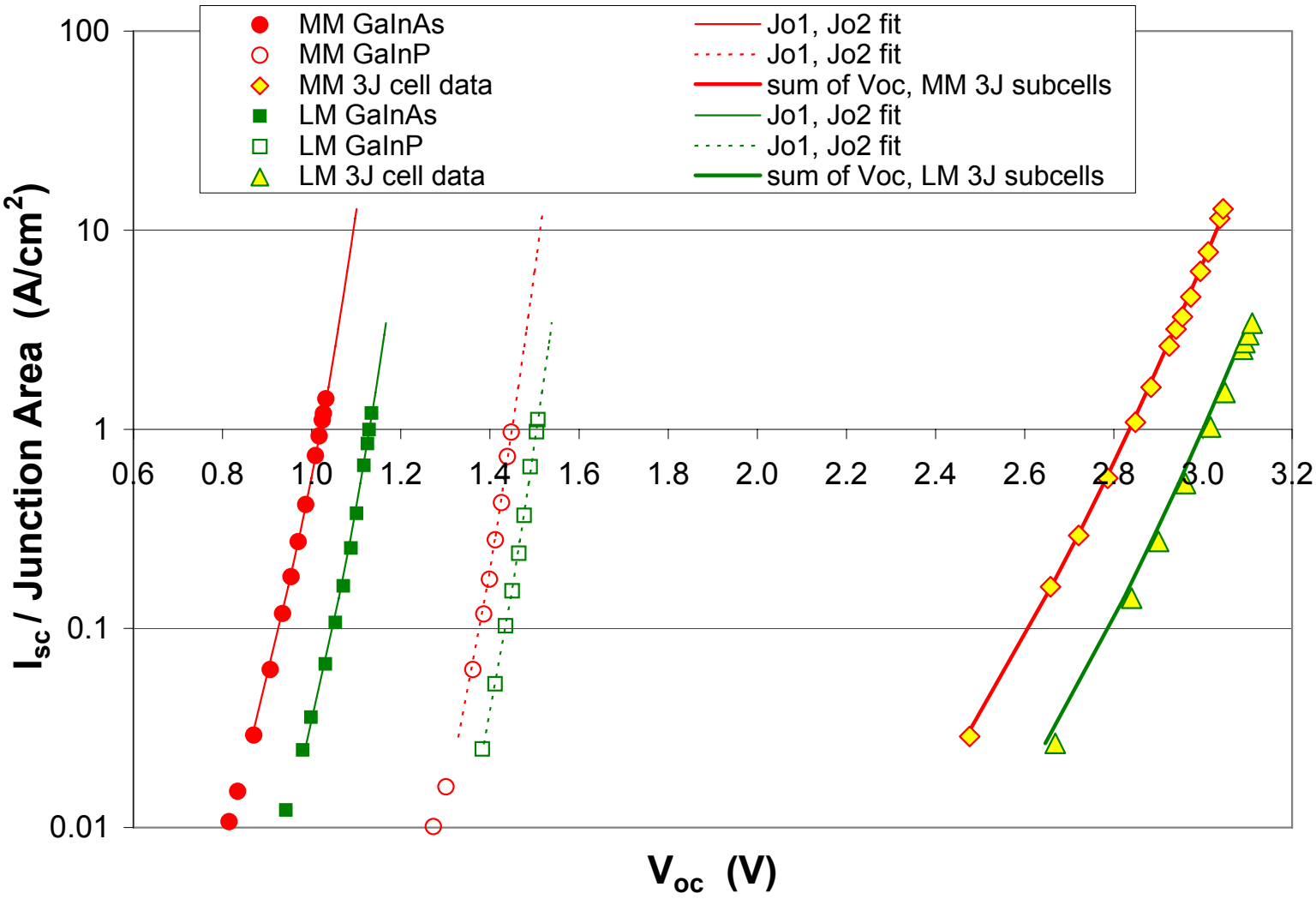
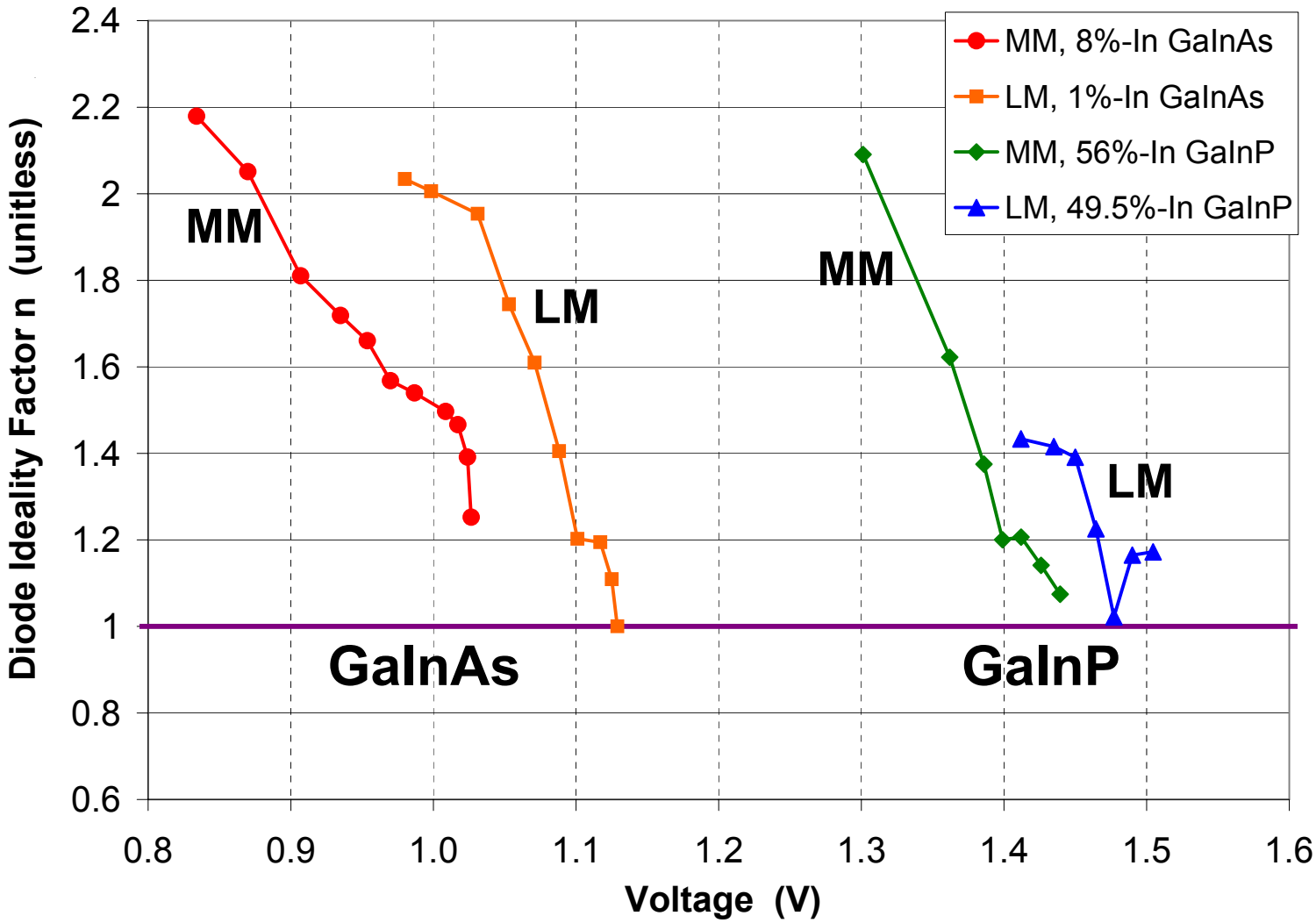
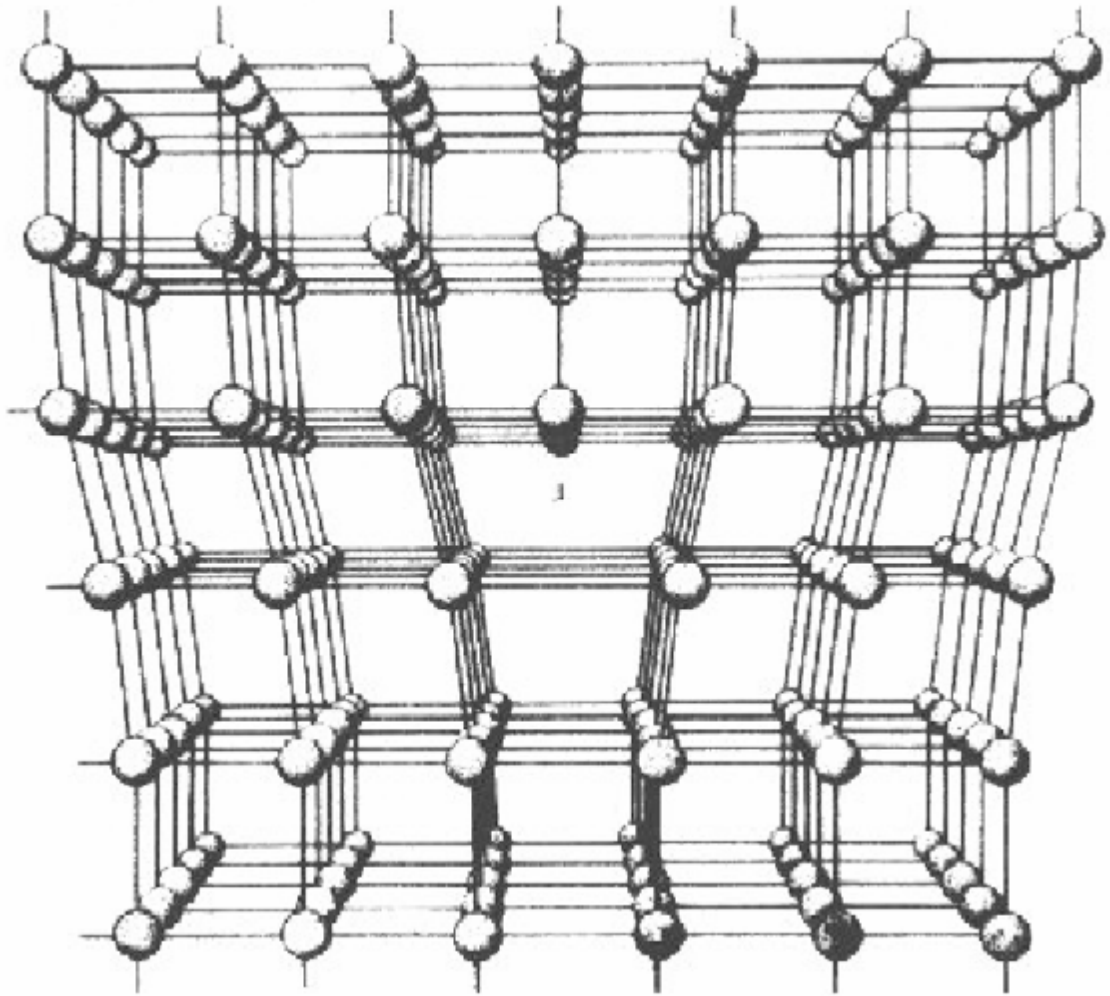
# Jsc vs. Voc Measurements for MM and LM GaInAs and GaInP



# Diode Ideality vs. Voltage for MM and LM GaInAs & GaInP



# Visualizing Dislocations in III-V Materials

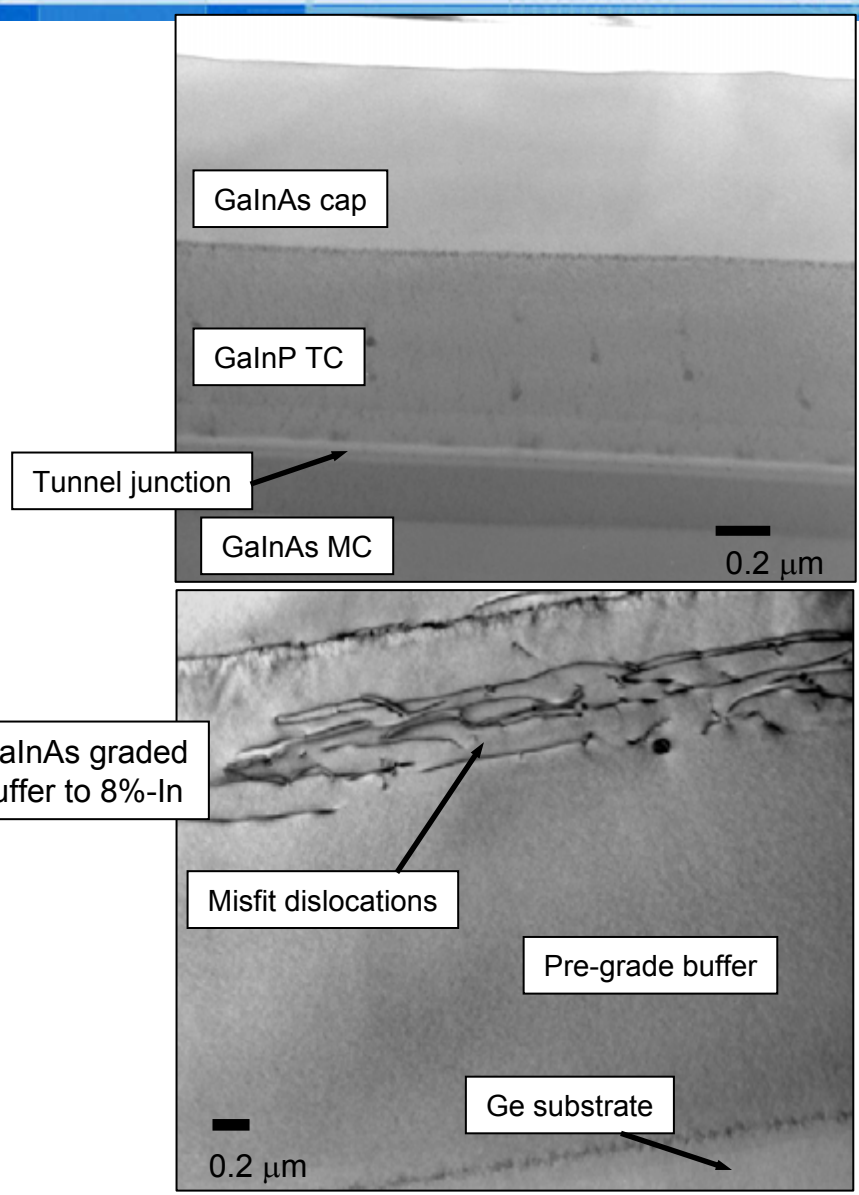


# Cross sectional TEM
## $Ga_{0.44}In_{0.56}P$/ $Ga_{0.92}In_{0.08}As$/ Ge Cell

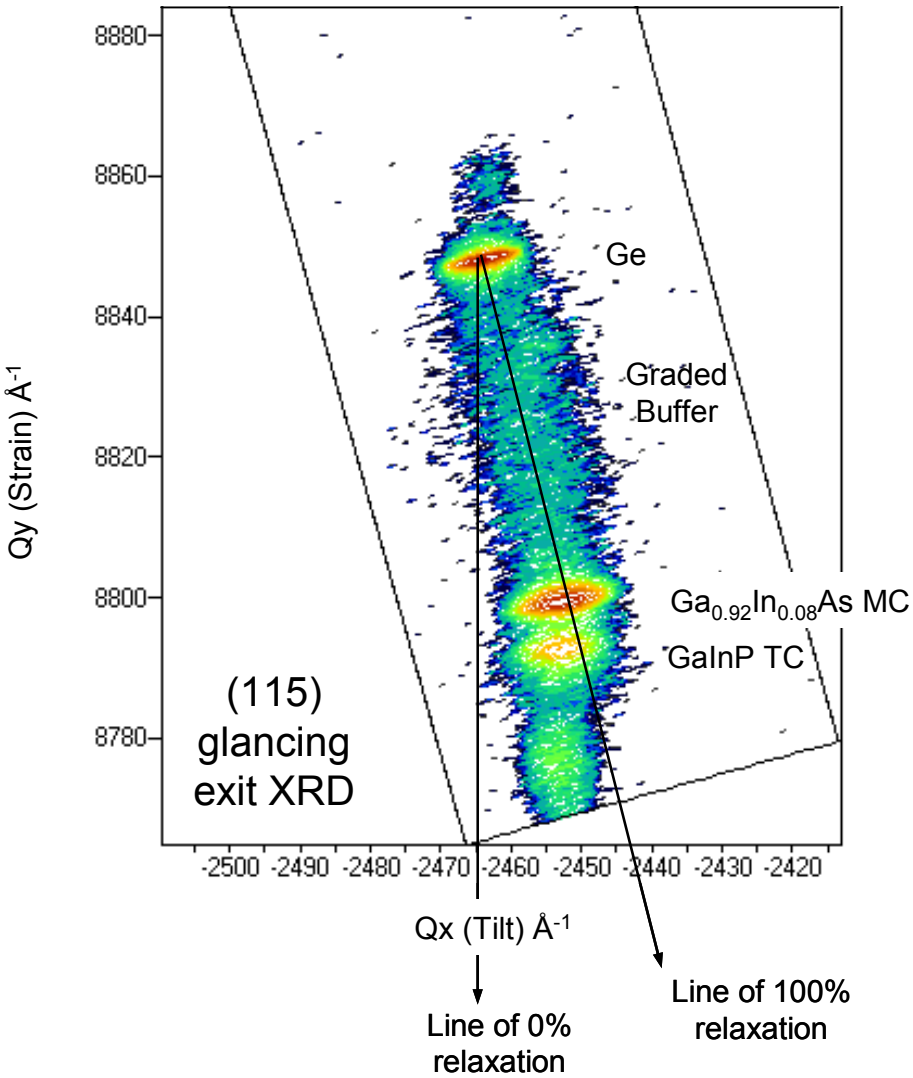
- Low dislocation density in active cell layers in top portion of epilayer stack:

  ~ 2 x $10^5$ $cm^{-2}$ from EBIC and CL meas.

- Dislocations confined to graded buffer layers in bottom portion of epilayer stack



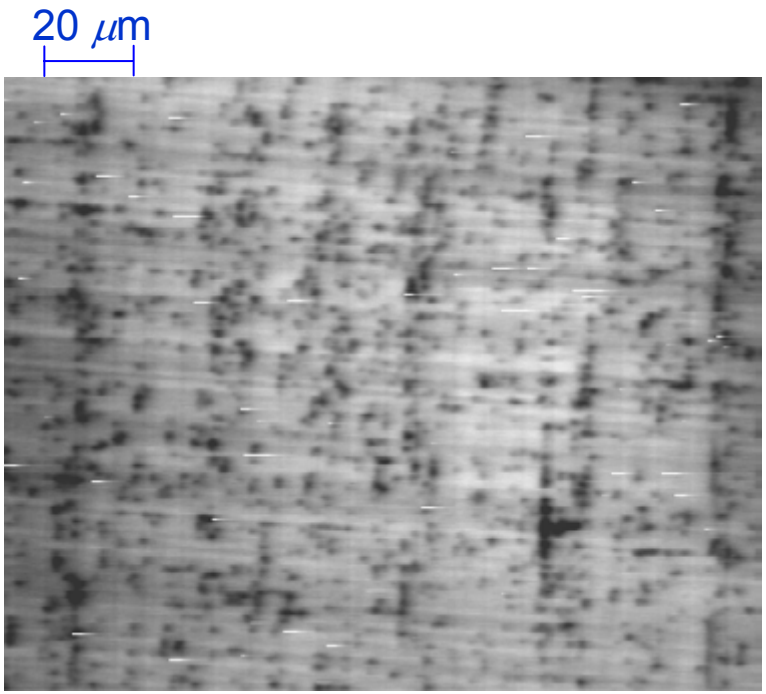
# High-Resolution XRD Reciprocal Space Map (RSM)




- GaInP/ 8%-In GaInAs/ Ge metamorphic (MM) cell structure
- Nearly 100% relaxed step-graded buffer → removes driving force for dislocations to propagate into active cell layers
- 56%-In GaInP top cell pseudomorphic with respect to GaInAs middle cell

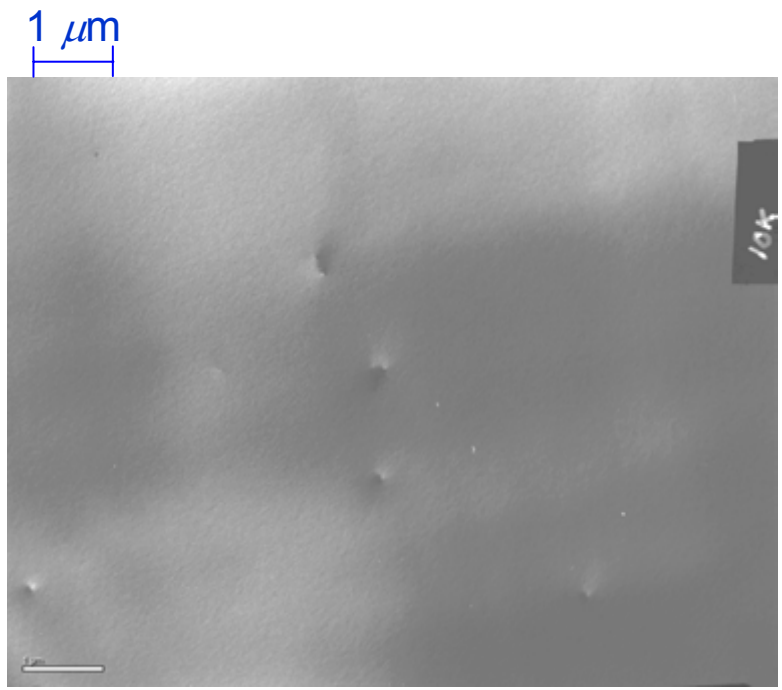
# Dislocation Imaging in 23%-In GaInAs

## 23%-In GaInAs double heterostructure on Ge




**Cathodoluminescence (CL)**

**disloc. density = 4.4 x $10^6$ $cm^{-2}$**




**Plan-View Transmission Electron Microscopy (TEM)**

**disloc. density = 3.1 x $10^6$ $cm^{-2}$**

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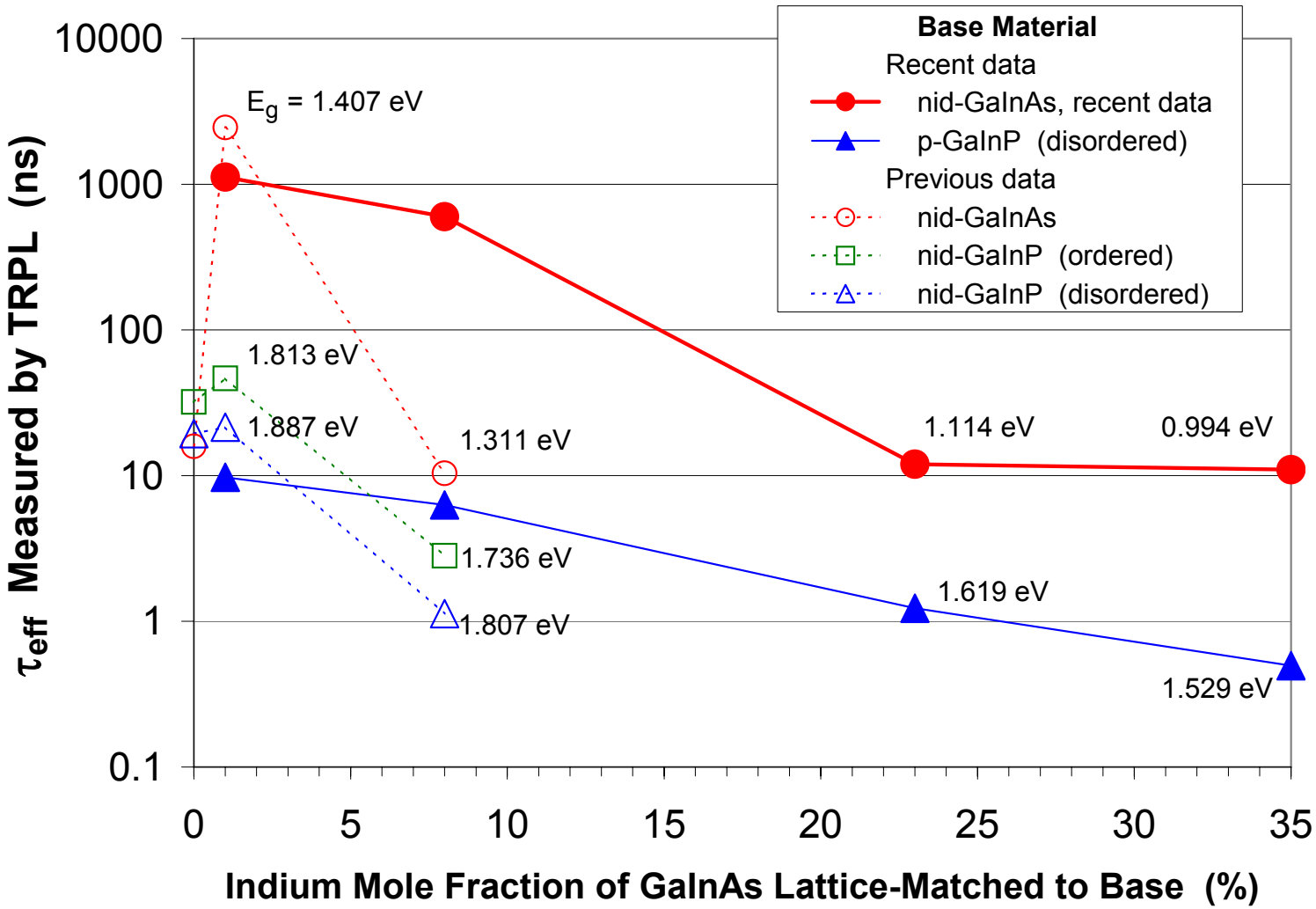
# Time-Resolved PL of LM & MM Double Heterostructures




*Time-resolved PL meas. courtesy of W. Metzger, B. Keyes, and R. Ahrenkiel – NREL*

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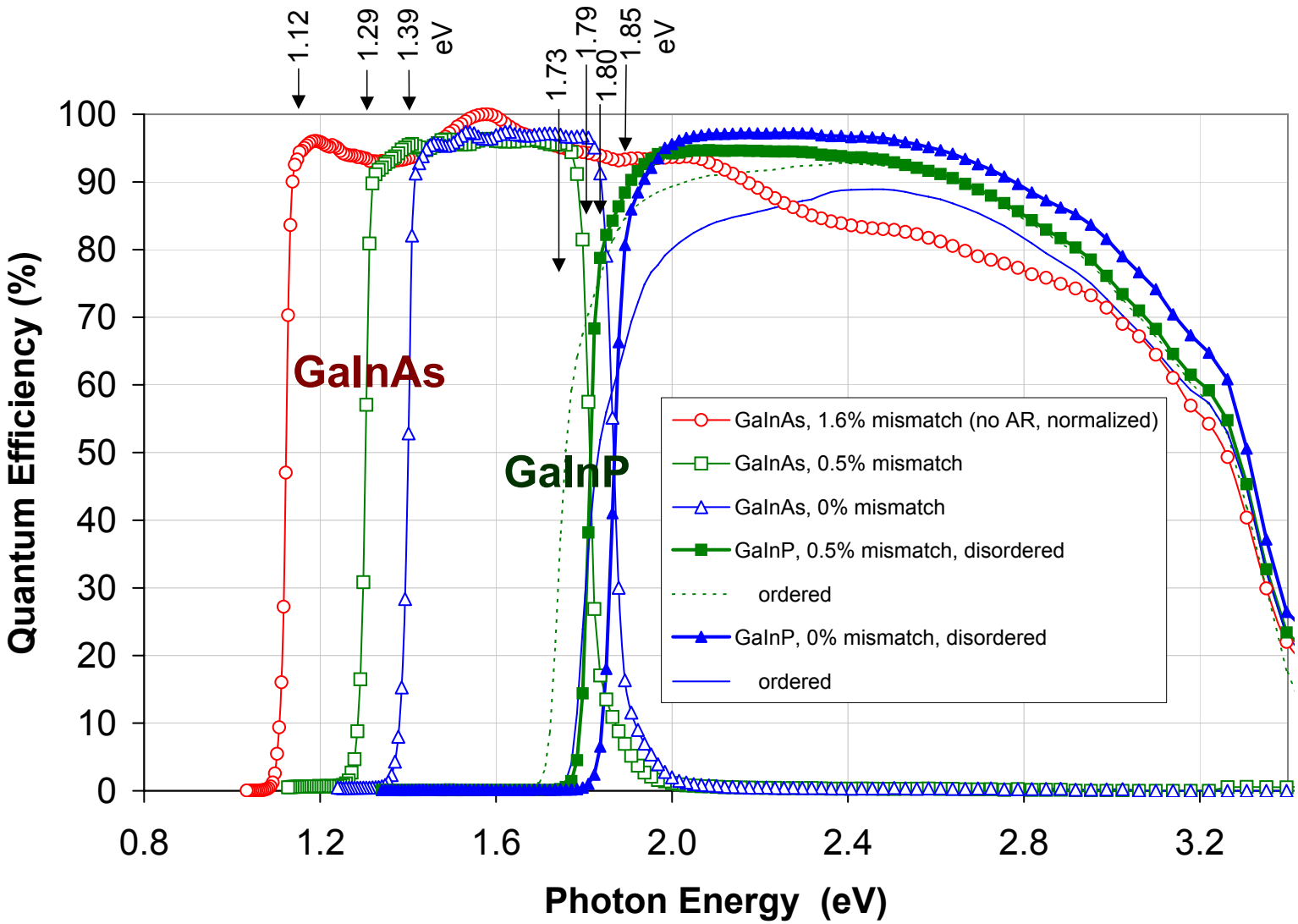
# Quantum Eff. of Metamorphic GaInAs and GaInP Cells on Ge



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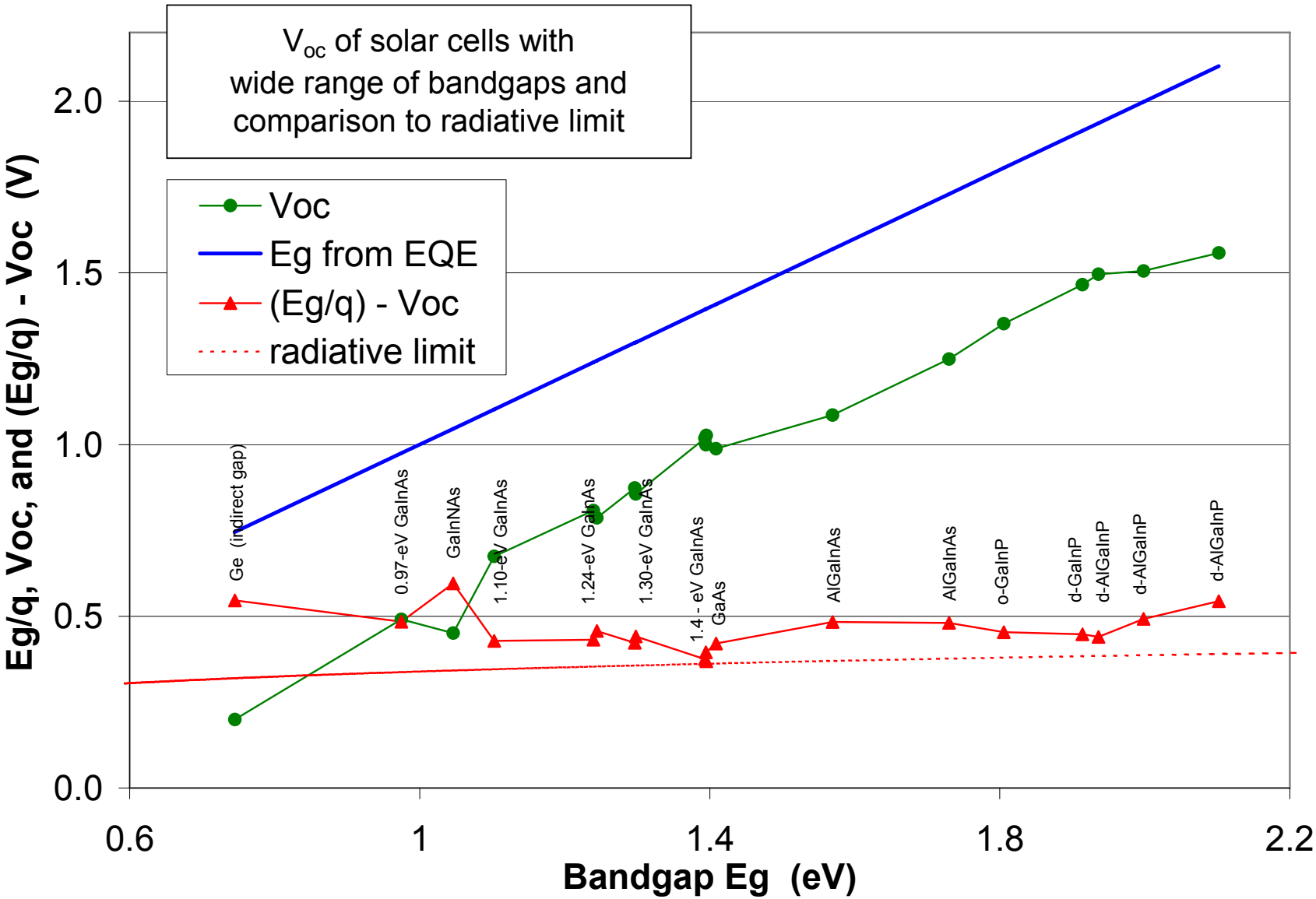
# Bandgap - Voltage Offset ($E_g/q$) - $V_{oc}$ for Single-Junction Solar Cells



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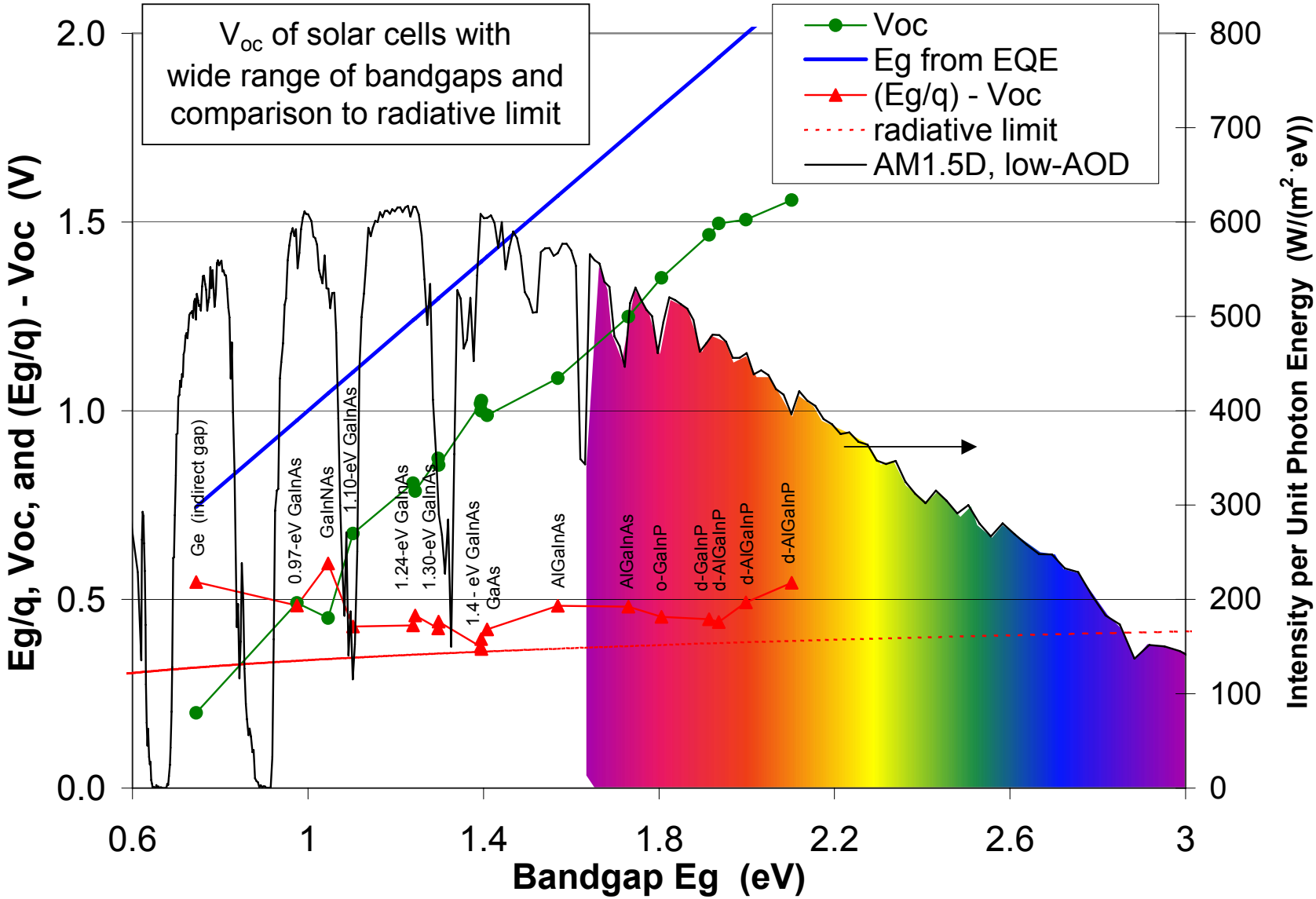
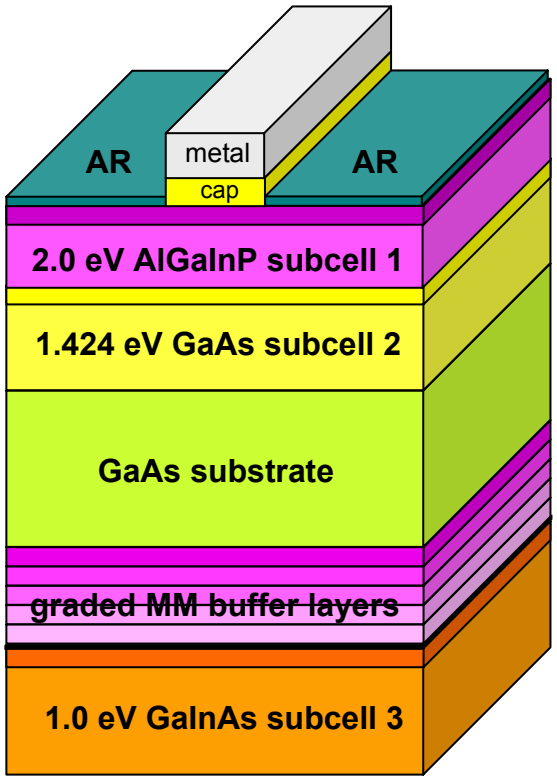
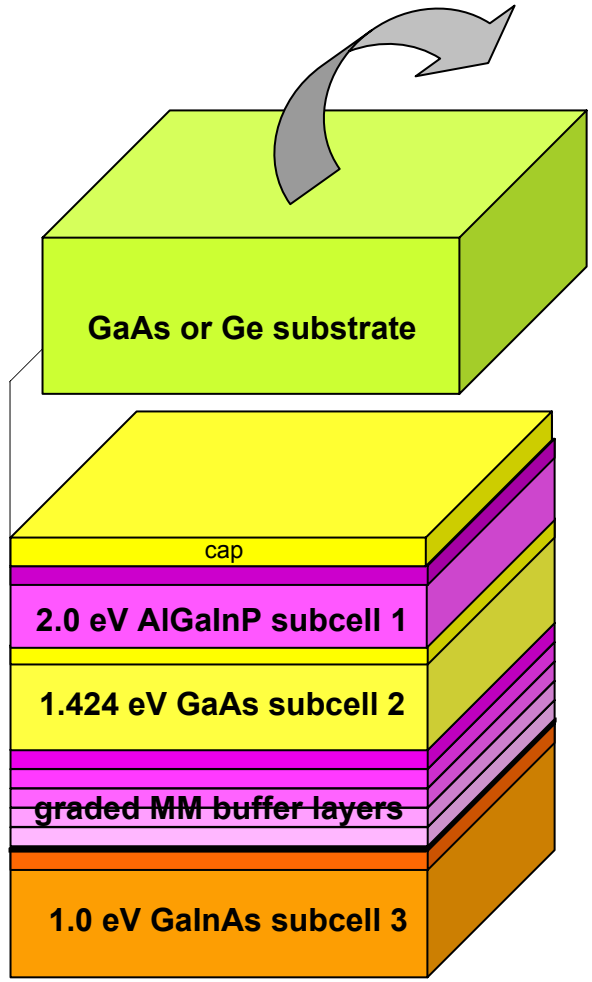


# Metamorphic (MM) 3-Junction Cells — Inverted 1.0-eV GaInAs Subcell




Growth on both sides of GaAs substrate




Growth on one side of GaAs or Ge substrate, followed by substrate removal

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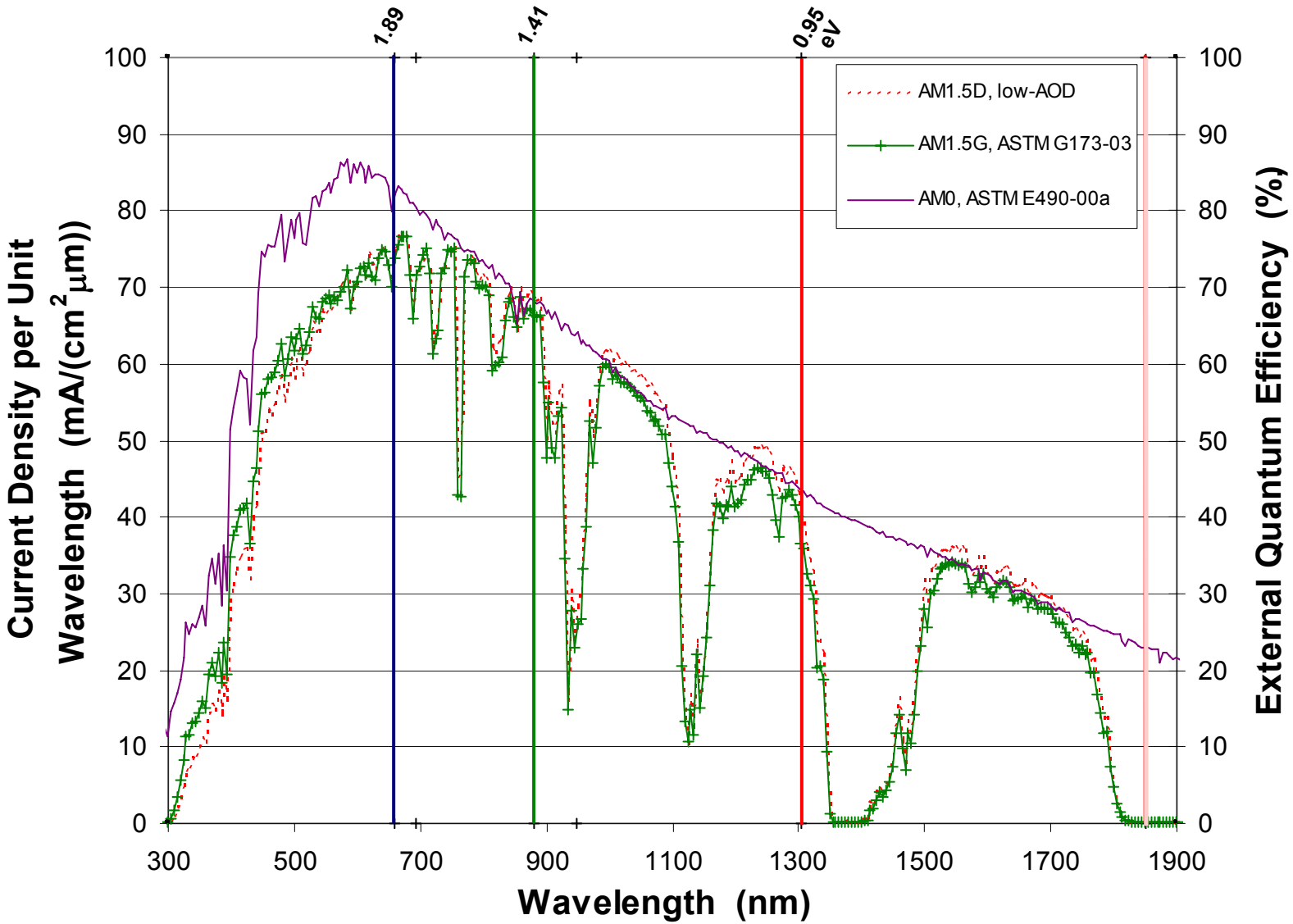
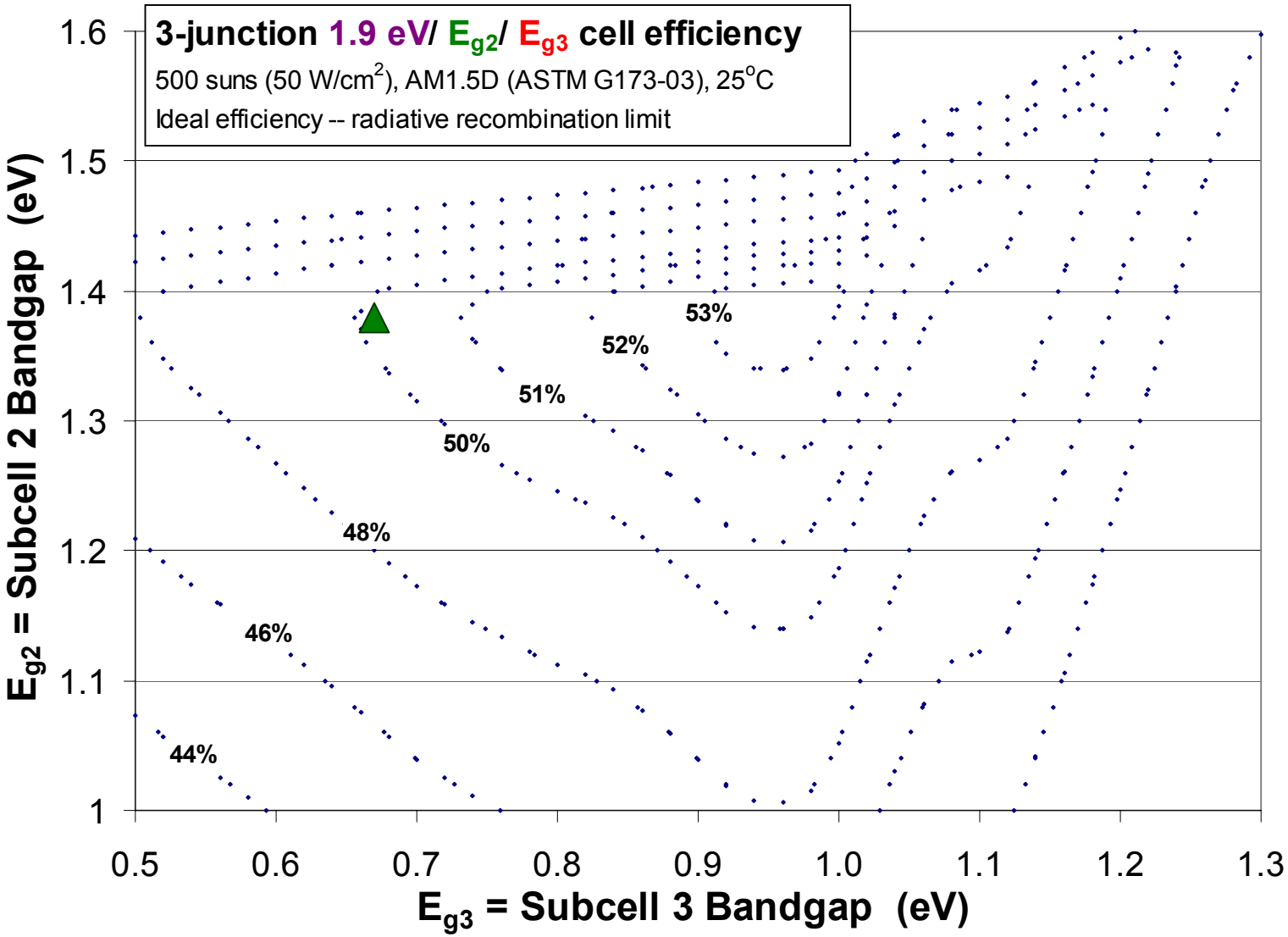
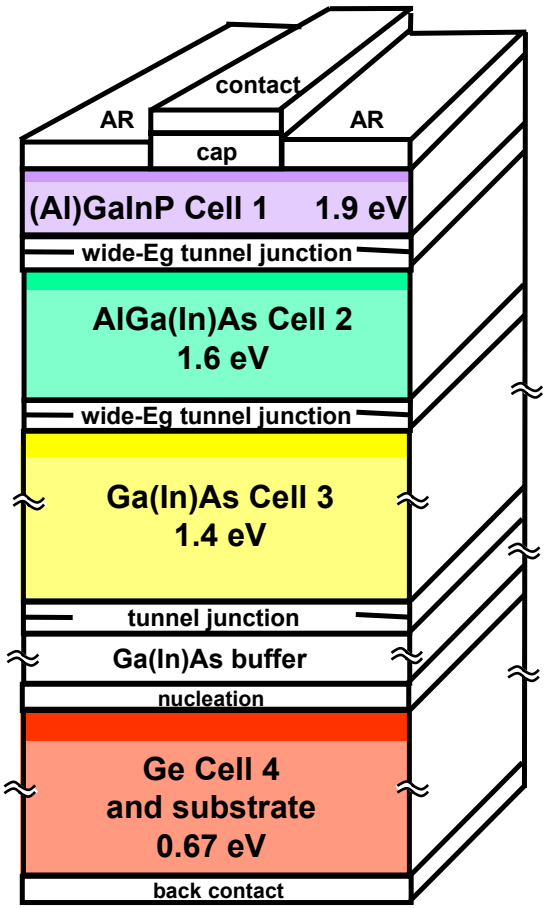
# Solar Spectrum Partition for 3-Junction Cell



# 3-Junction Theoretical Eff. — Vary $E_{g2}$ and $E_{g3}$



# 4-Junction Terrestrial Concentrator Cell




- Divides available current density above GaAs $E_g$ among 3 subcells instead of 2
- High-voltage, low-current design
- Approx. 2/3 current density of 3-junction cell
- $(2/3)^2$ or less than half of series resistance loss
  $\rightarrow$ Crucial for concentrators

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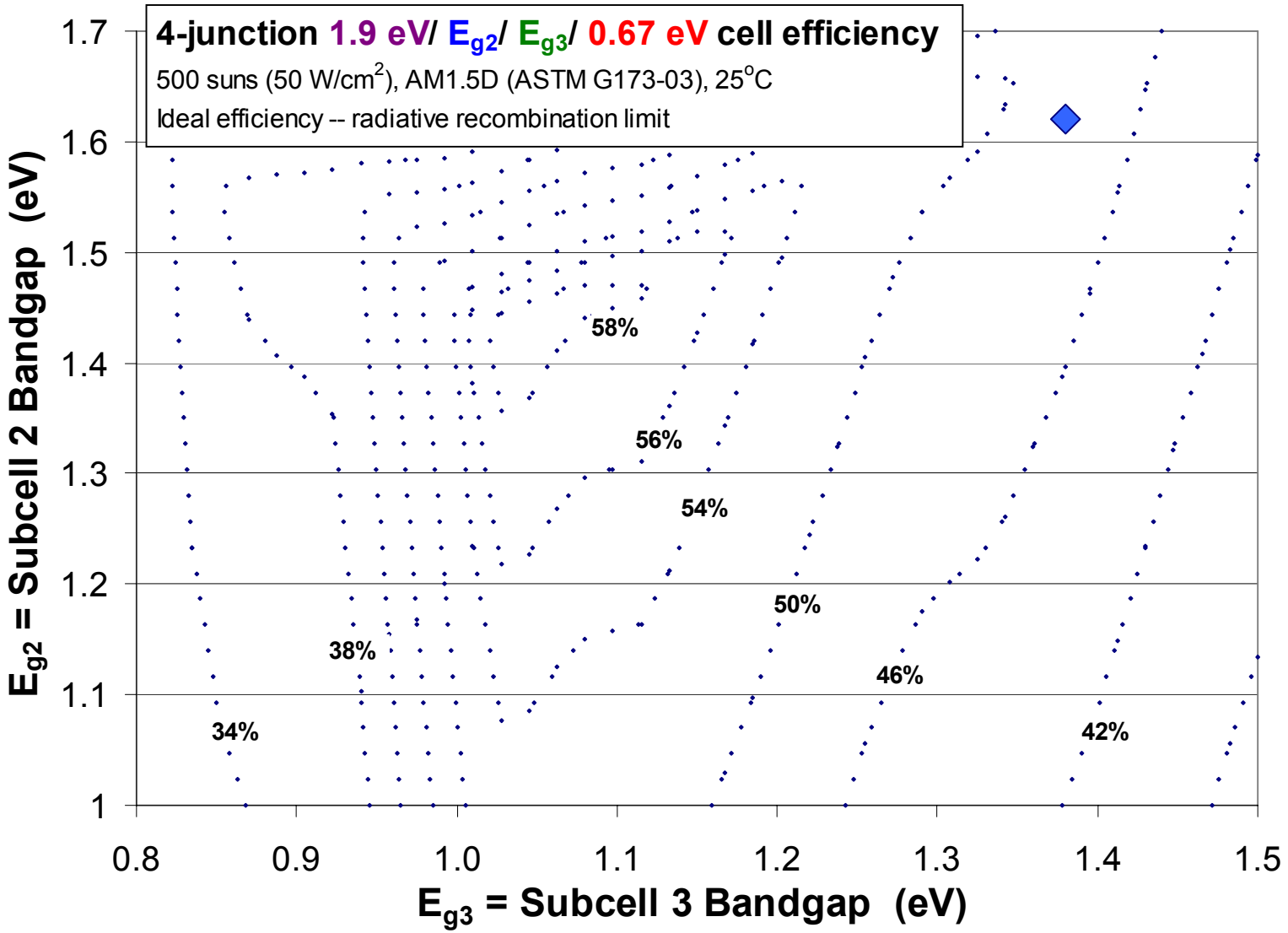
# 4-Junction Theoretical Efficiency



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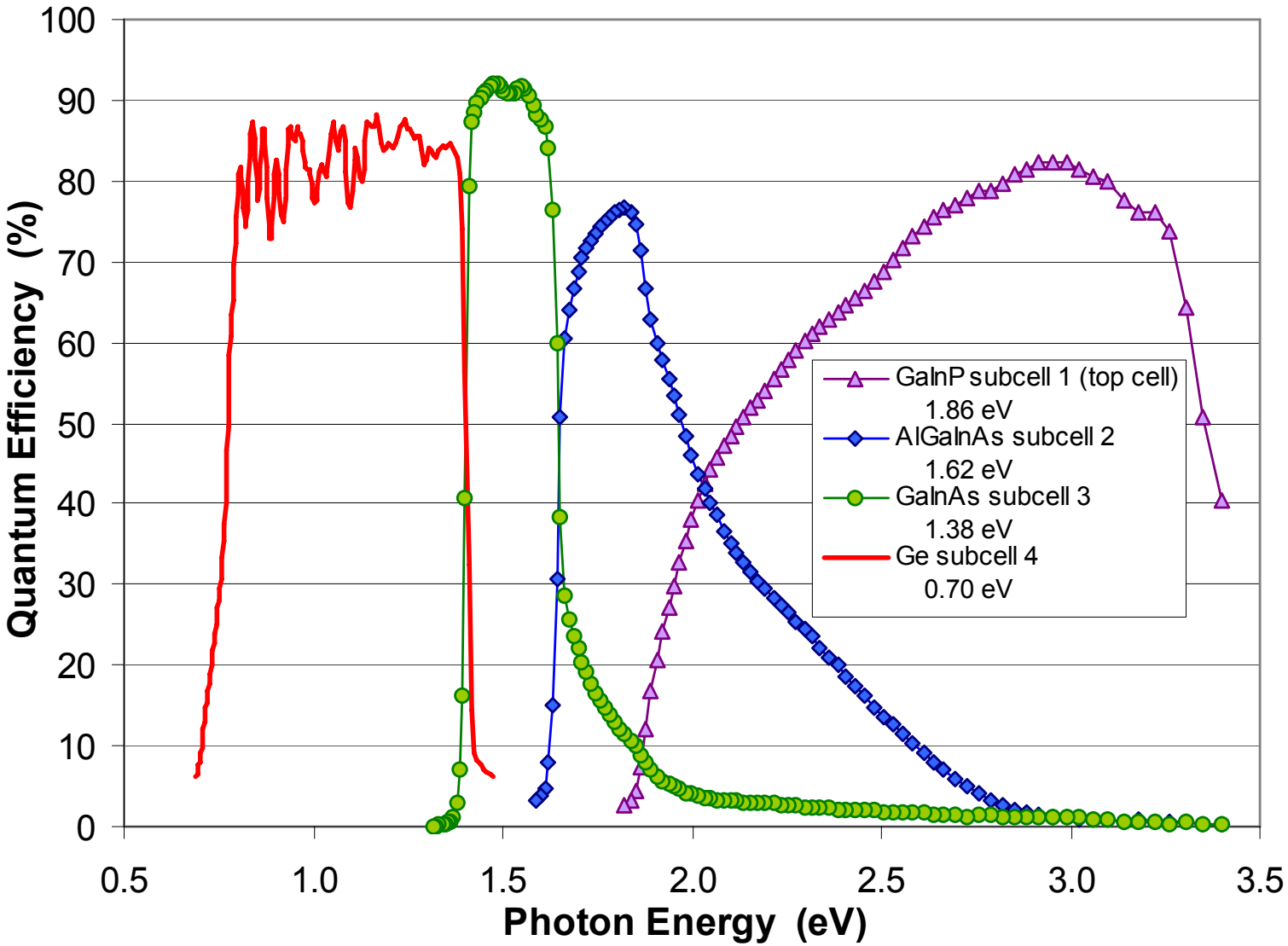
# External QE – 4-Junction Concentrator Cell



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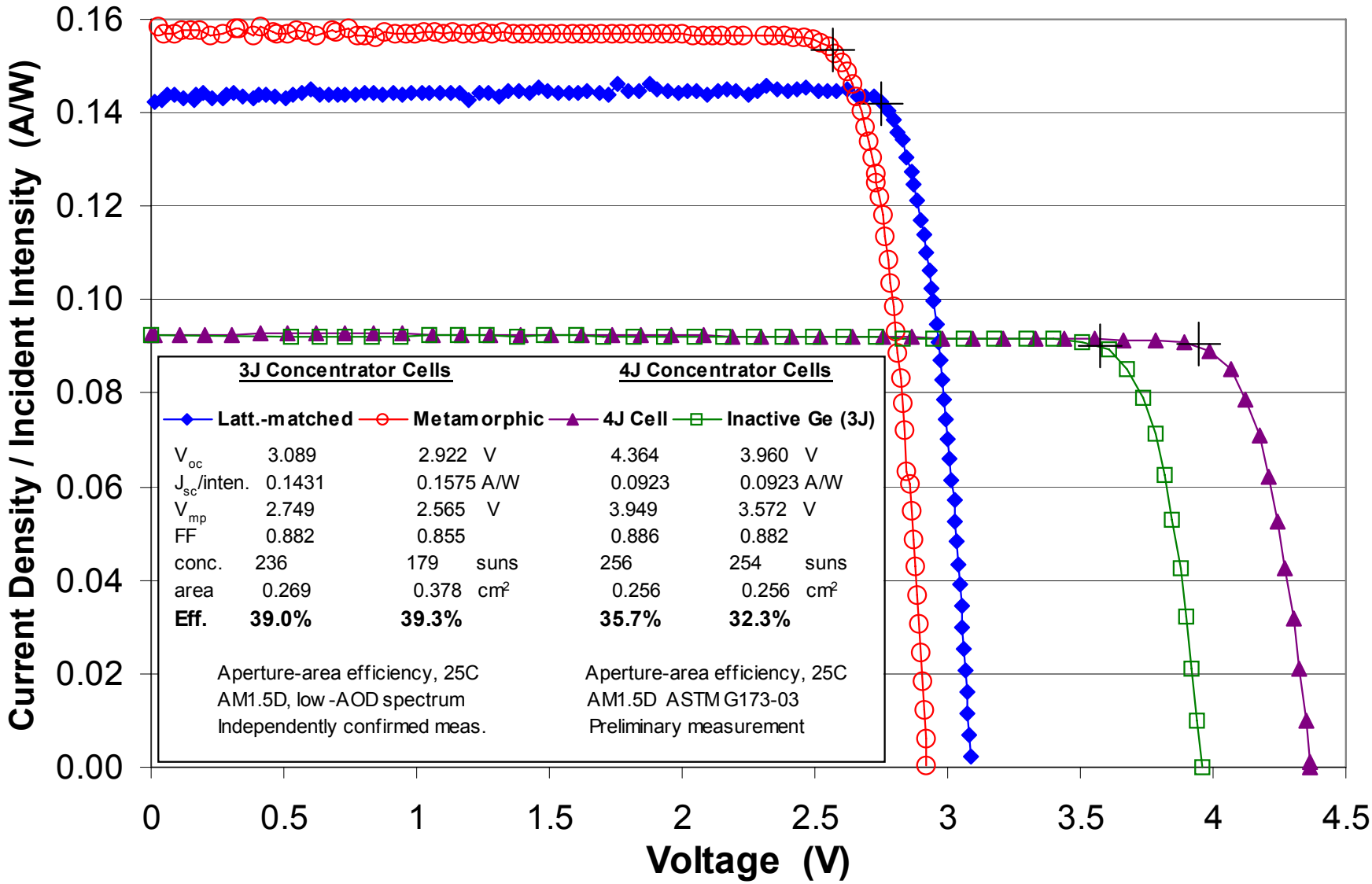
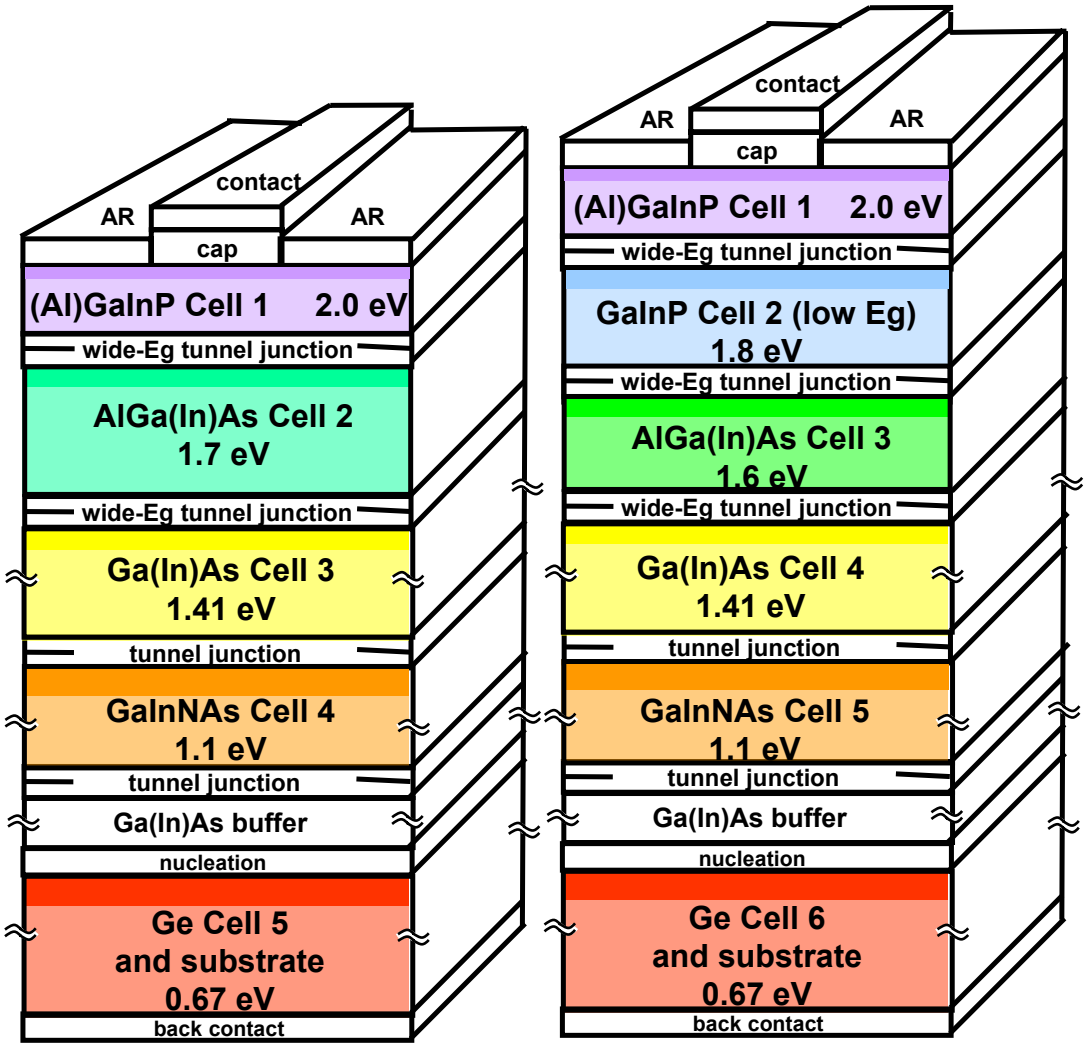
# 4-Junction Light I-V at 250 Suns – Active and Inactive Ge



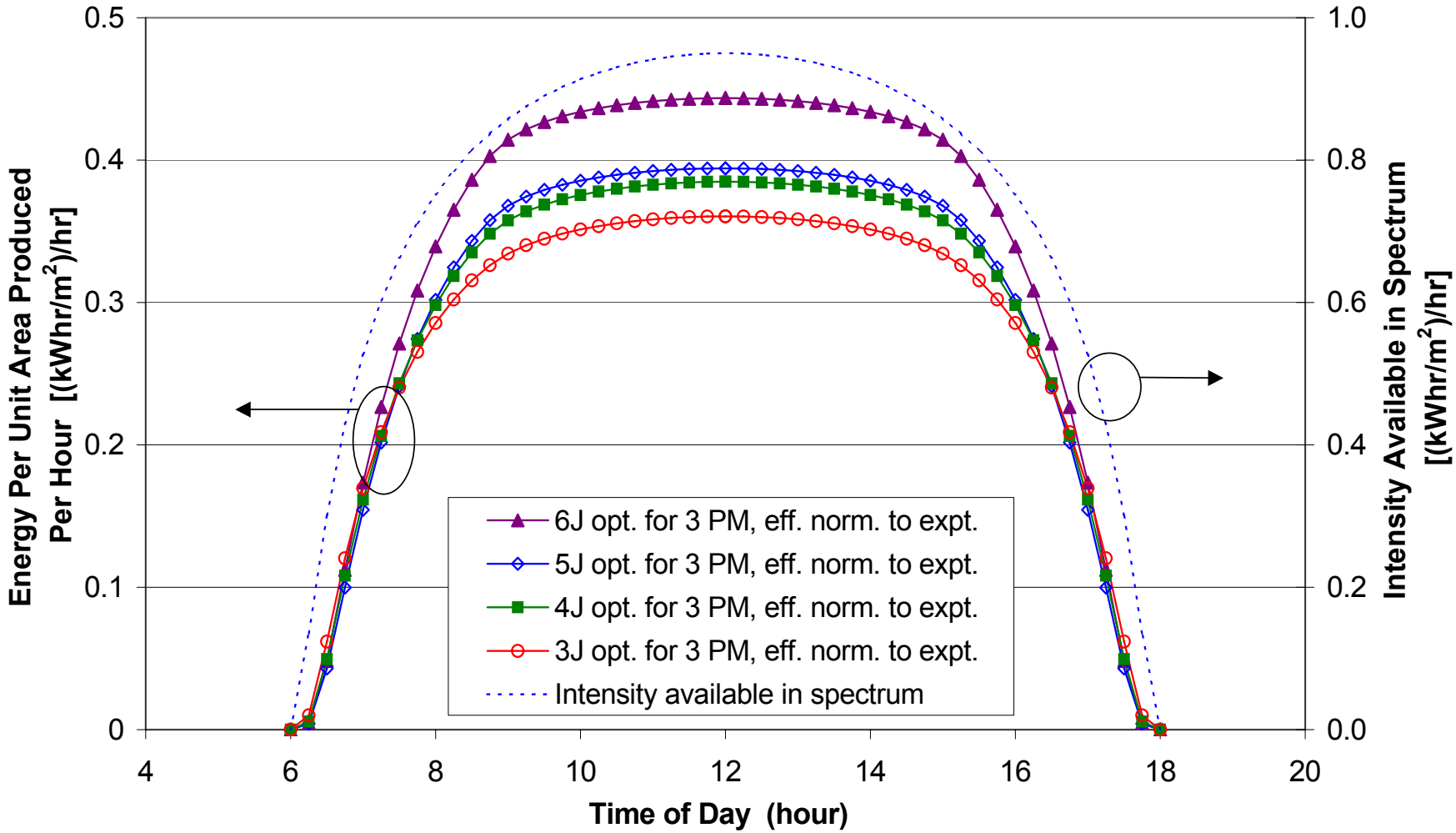
# 5- and 6-Junction Cells




- Divides available current density above GaAs $E_g$ among 3-4 subcells
- Allows low-current GaInNAs cell to be matched to other subcells
- Lower series resistance

Ref.: U.S. Pat. No. 6,316,715, Spectrolab, Inc., filed 3/15/00, issued 11/13/01.

# 3-6 Junction Energy Production – Norm. to Expt.




- Energy generation increases from 3J → 4J → 5J → 6J, due to series res., better use of spectrum
- Large difference between 5J and 6J due to inclusion of ~1-eV subcell

# Summary

- $\eta$ > **50%** achievable by solar spectrum division in MJ cells with the right subcell bandgaps

- **4-6 junction** terrestrial cells → strong advantage at high concentrations from lower series resistance losses → **35.7%** 4J conc. cell measured

- ***Metamorphic materials give new opportunity for bandgap engineering***
  - ✓ High $V_{oc}$ and $\tau$ demonstrated on **1.1-eV** and **1.3-eV** MM GaInAs subcells
- Faster voltage increase with ↑ incident intensity meas. for MM cells
- New heights in terrestrial concentrator cells reported here:
  - **40.7%** metamorphic (MM) 3J cell
  - **40.1%** lattice-matched (LM) 3J cell

→ ***First solar cells to reach over 40%***

→ Highest solar conversion efficiency for PV device of any kind to date

→ ***Metamorphic cells now exceed best lattice-matched designs***