Raising the Efficiency Ceiling in Multijunction Solar Cells

Richard R. King

Spectrolab, Inc.
A Boeing Company

Stanford Photonics Research Center Symposium
Sep. 14-16, 2009
Stanford, CA

SPECTROLAB
A BOEING COMPANY

Acknowledgments

BOEING

- **Martha Symko-Davies, Fannie Posey-Eddy, Larry Kazmerski, Manuel Romero, Carl Osterwald, Keith Emery, John Geisz, Sarah Kurtz – NREL**
- **Angus Rockett – University of Illinois**
- **Rosina Bierbaum – University of Michigan, Ann Arbor**
- **Pierre Verlinden, John Lasich – Solar Systems, Australia**
- **Kent Barbour, Andreea Boca, Dhananjay Bhusari, Ken Edmondson, Chris Fetzer, William Hong, Jim Ermer, Russ Jones, Nasser Karam, Geoff Kinsey, Dimitri Krut, Diane Larrabee, Daniel Law, Phil Liu, Shoghig Mesropian, Mark Takahashi, and the entire multijunction solar cell team at Spectrolab**

This work was supported in part by the U.S. Dept. of Energy through the NREL High-Performance Photovoltaics (HiPerf PV) program (ZAT-4-33624-12), the DOE Technology Pathways Partnership (TPP), and by Spectrolab.

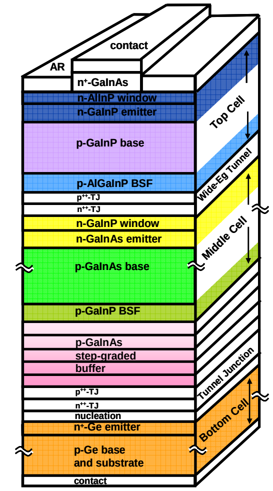
Thank You !

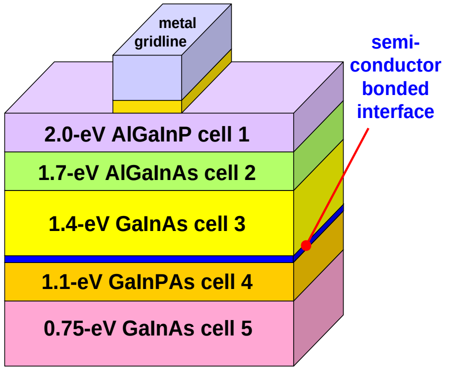
SPECTROLAB
A BOEING COMPANY

Outline

BOEING

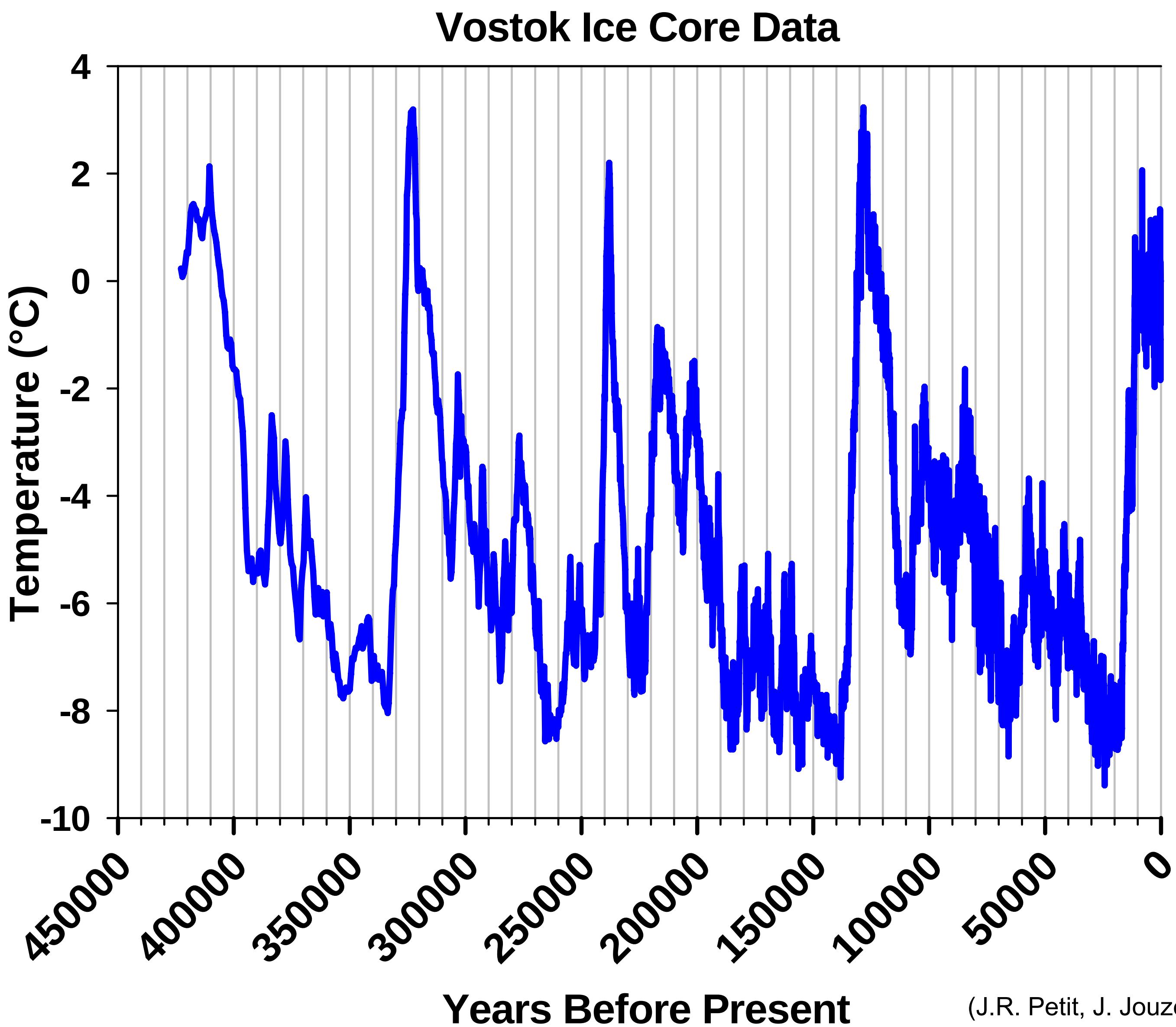
- **Global climate change and the solar resource**
- **Solar cell theoretical efficiency limits**
  - Opportunities to change ground rules for higher terrestrial efficiency
  - Cell architectures capable of **>70%** in theory, **>50%** in practice
- **Metamorphic semiconductor materials**
  - Control of band gap to tune to solar spectrum
  - Dislocations in metamorphic III-Vs imaged by ***CL*** and ***EBIC***
- **High-efficiency Multijunction terrestrial concentrator cells**
  - **Metamorphic (MM)** and **lattice-matched (LM)** 3-junction solar cells with ***>40%*** efficiency
  - ***4-junction*** MM and LM concentrator cells
  - Inverted metamorphic structure, semiconductor bonded technology (SBT) for MJ terrestrial concentrator cells
- **Concentrator photovoltaic (CPV) systems and economics**





Global Climate Change

Climate and CO_2 Over the Last 400,000 Years



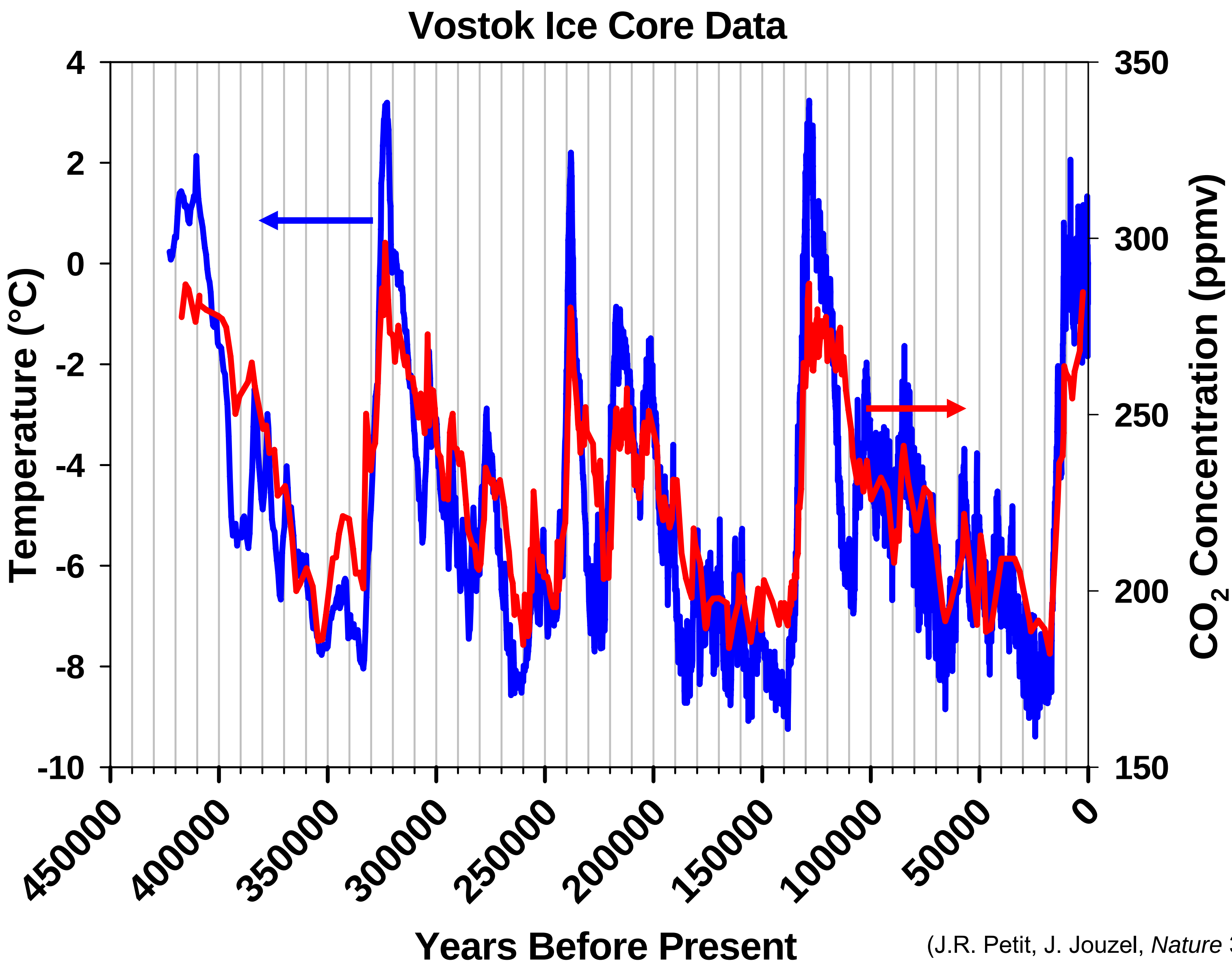
(J.R. Petit, J. Jouzel, *Nature* 399:429-436)

- Antarctic ice core data allows for mapping of temperature and CO_2 profiles

SPECTROLAB
A BOEING COMPANY

Climate and CO_2 Over the Last 400,000 Years

BOEING



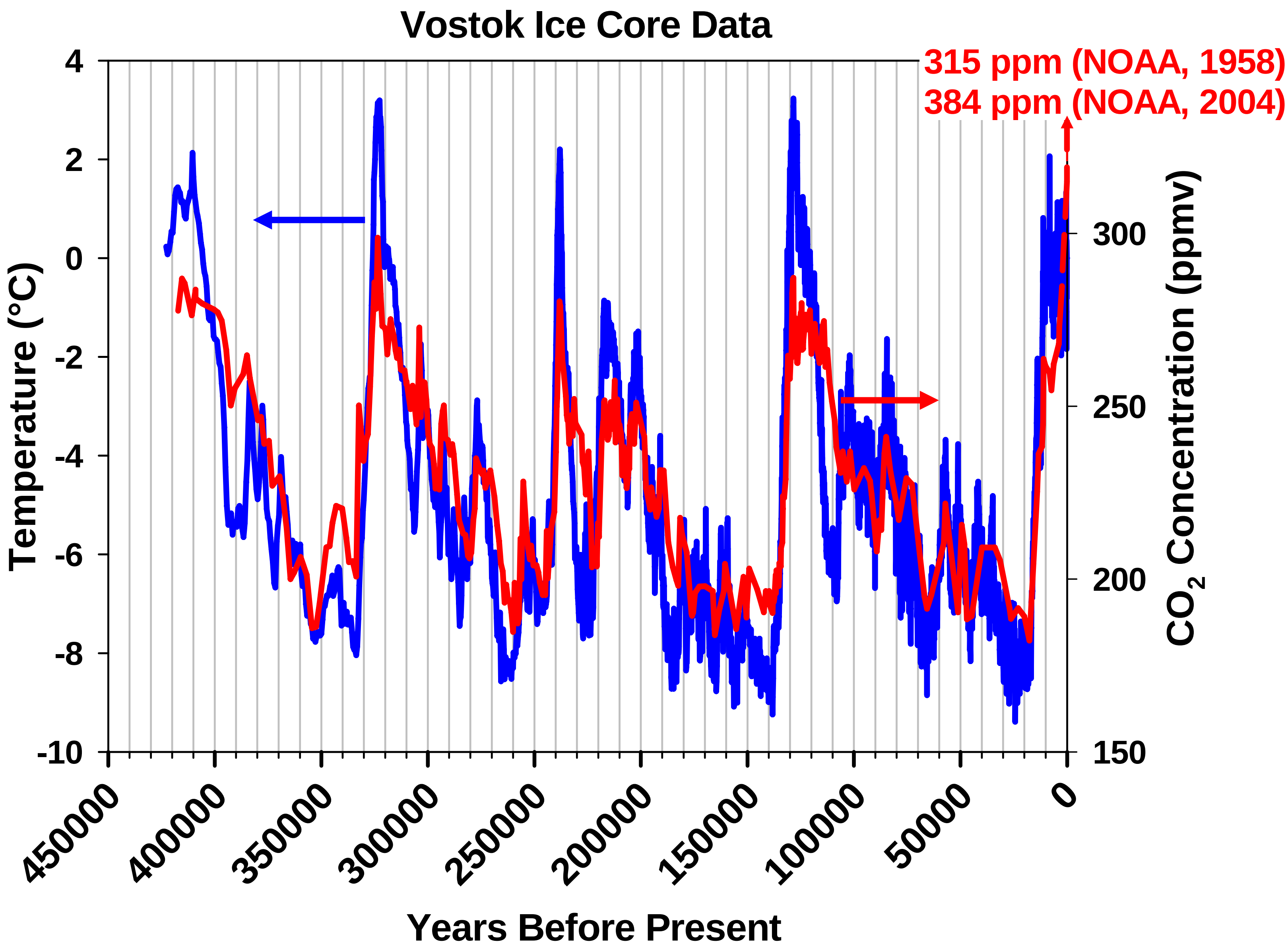
(J.R. Petit, J. Jouzel, *Nature* 399:429-436)

- Clear correlation between temperature and CO_2 levels

SPECTROLAB
A BOEING COMPANY

Climate and CO_2 – Recent History

BOEING

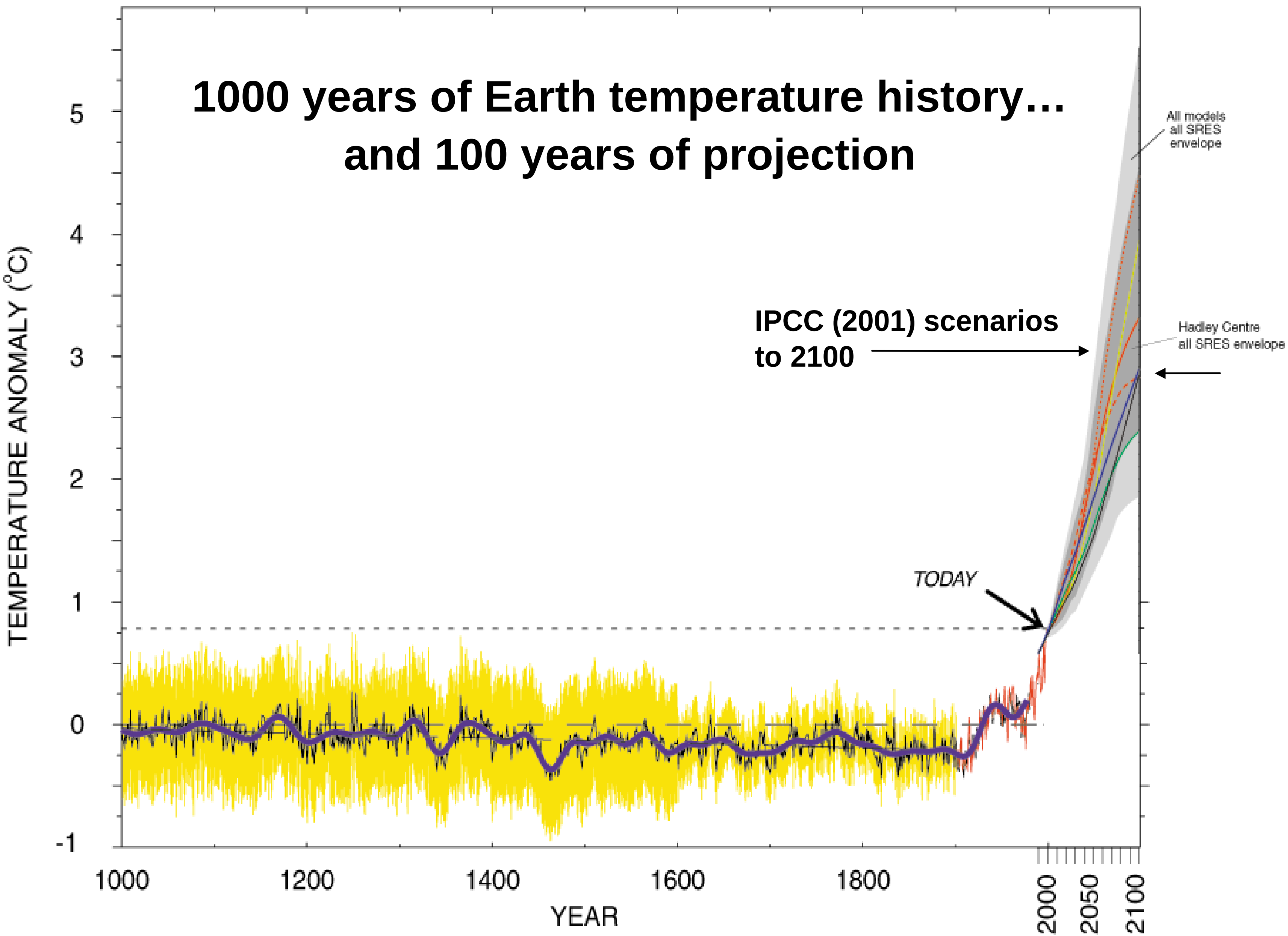


- CO_2 has reached levels never before seen in measured history
- If we do nothing, we allow this rising trend to continue at our own peril

SPECTROLAB
A BOEING COMPANY

Temperature Anomaly by Year

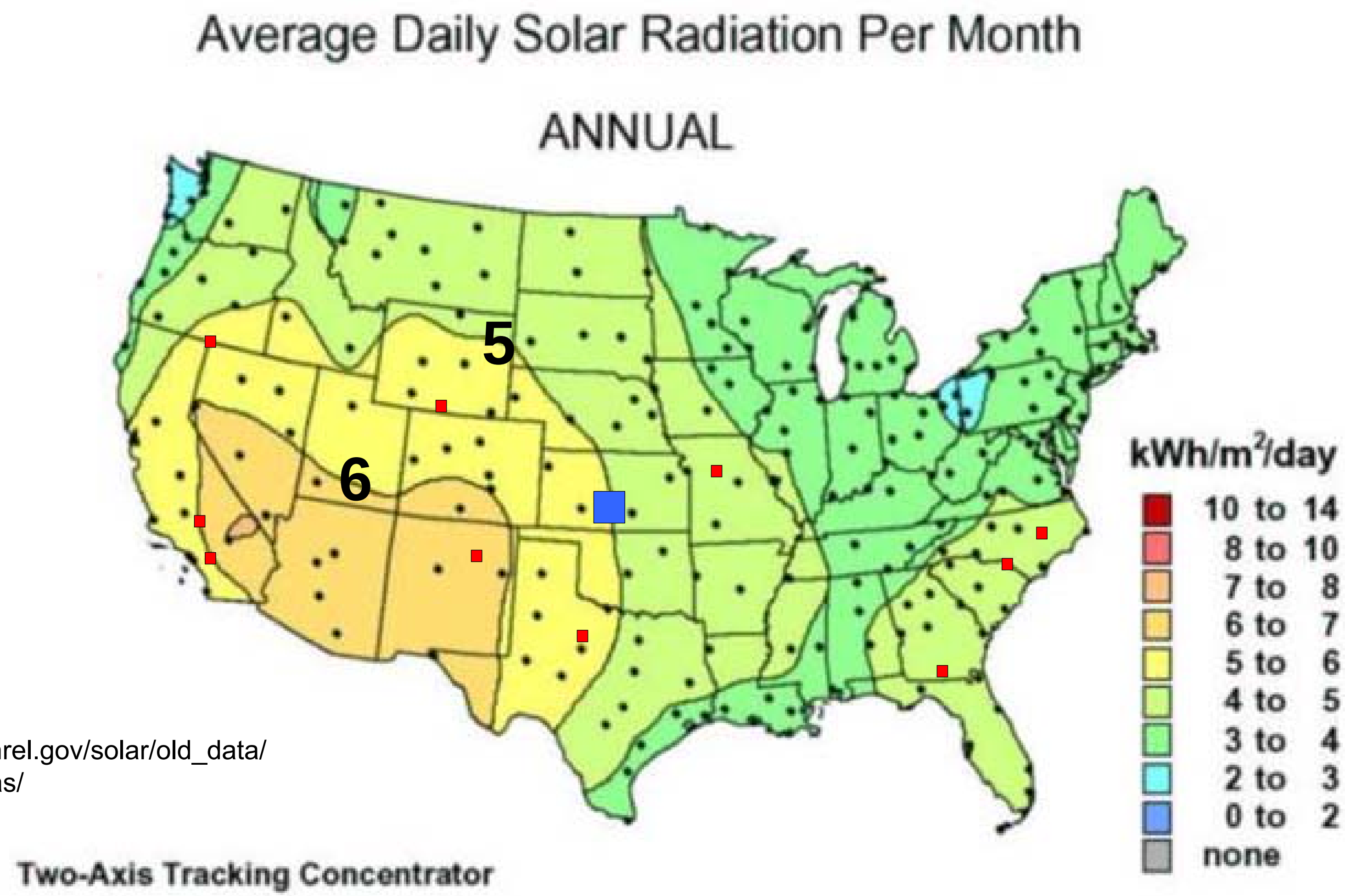
BOEING



Rosina Bierbaum, Univ. of Michigan, IPCC

The Solar Resource

The Solar Resource

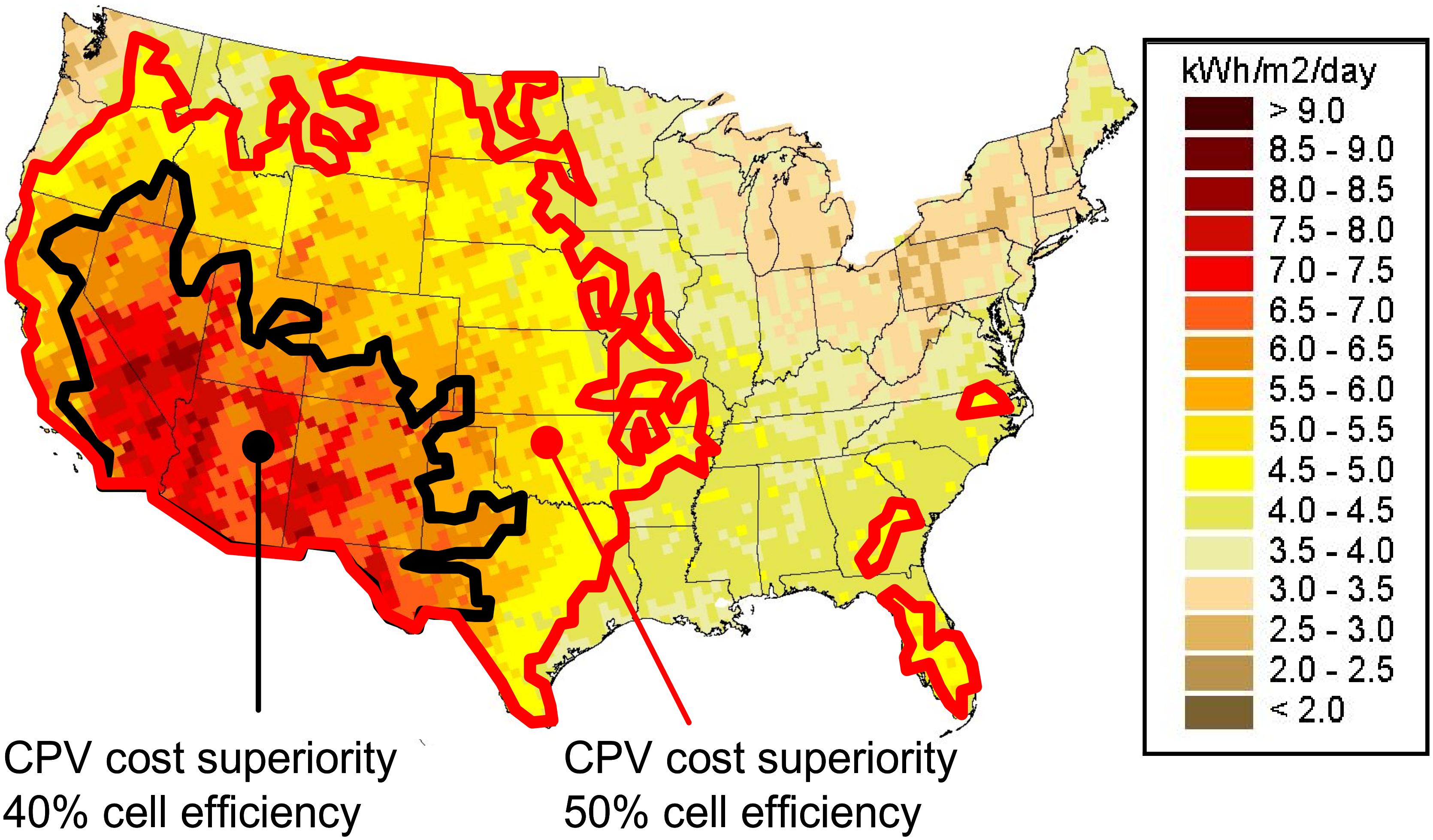


Ref.: http://rredc.nrel.gov/solar/old_data/nsrdb/redbook/atlas/

- **Entire US electricity demand can be provided by concentrator PV arrays using 37%-efficient cells on:**

150 km x 150 km area of land **or** **ten 50 km x 50 km areas**
or **similar division across US**

Concentrator Photovoltaic (CPV) Electricity Generation



Map source: http://www.nrel.gov/gis/images/map_csp_us_annual_may2004.jpg

Higher multijunction cell efficiency has a huge impact on the economics of CPV, and on the way we will generate electricity.

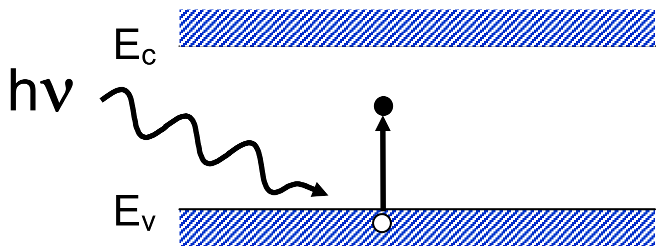
Solar Cell Theoretical Efficiency

Energy Transitions in Semiconductors

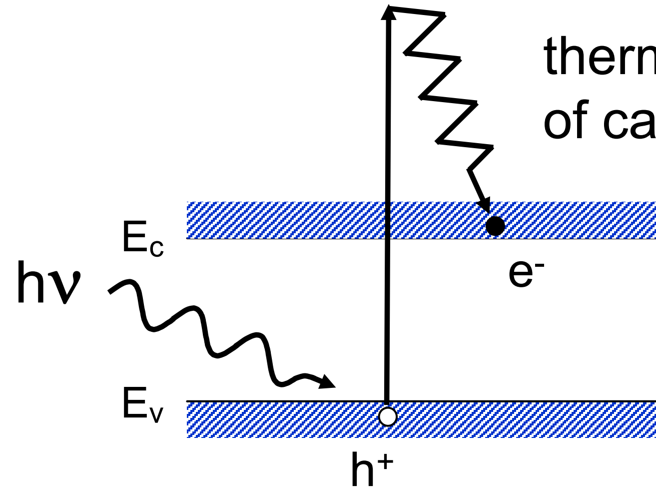
SPECTROLAB
A BOEING COMPANY

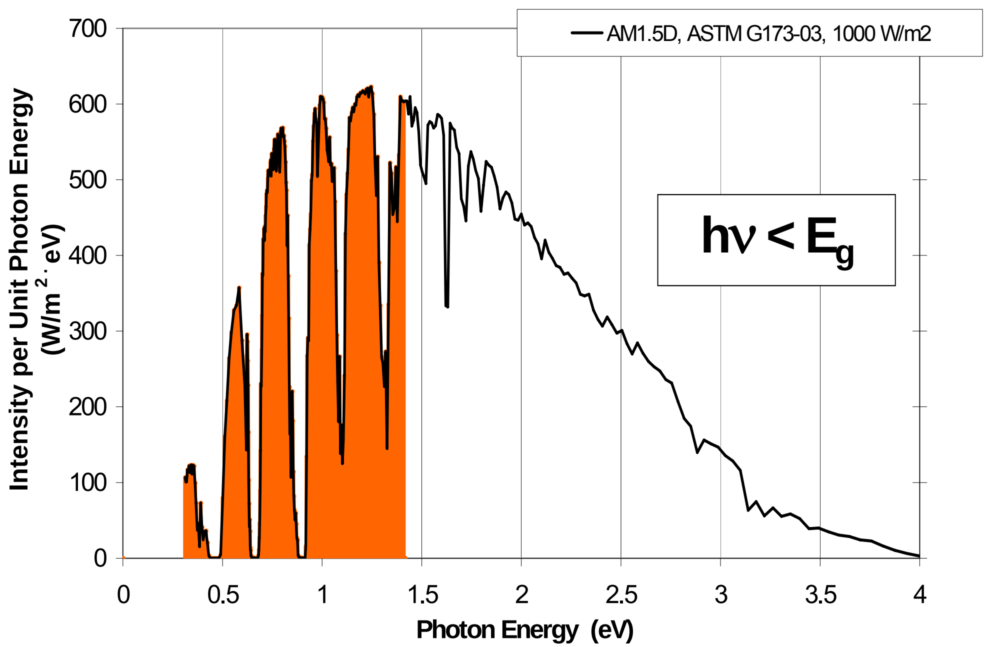
BOEING

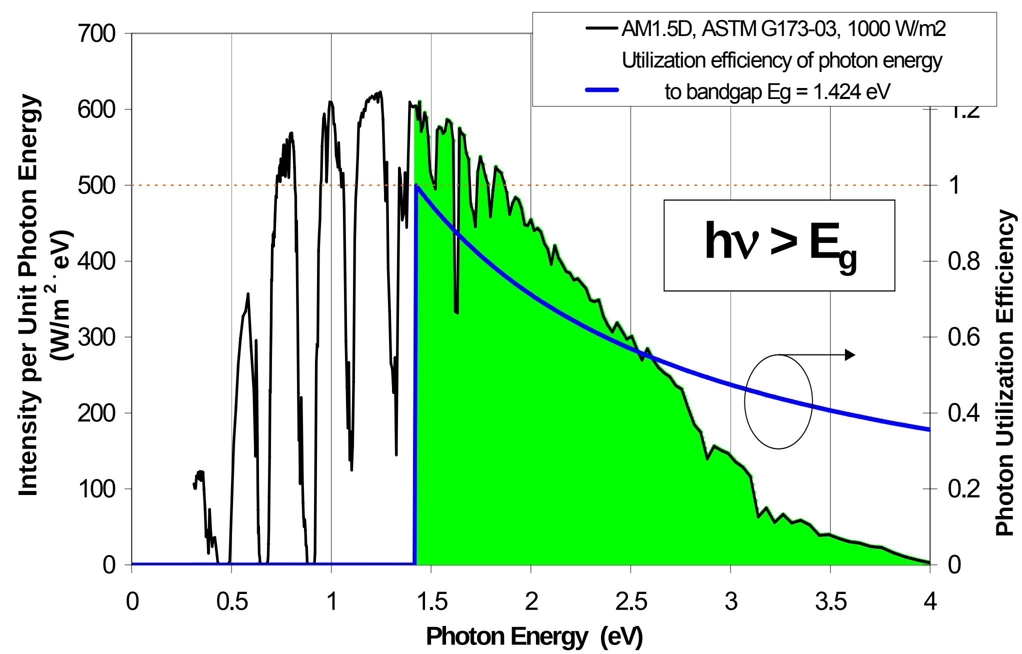
insufficient energy to reach E_c



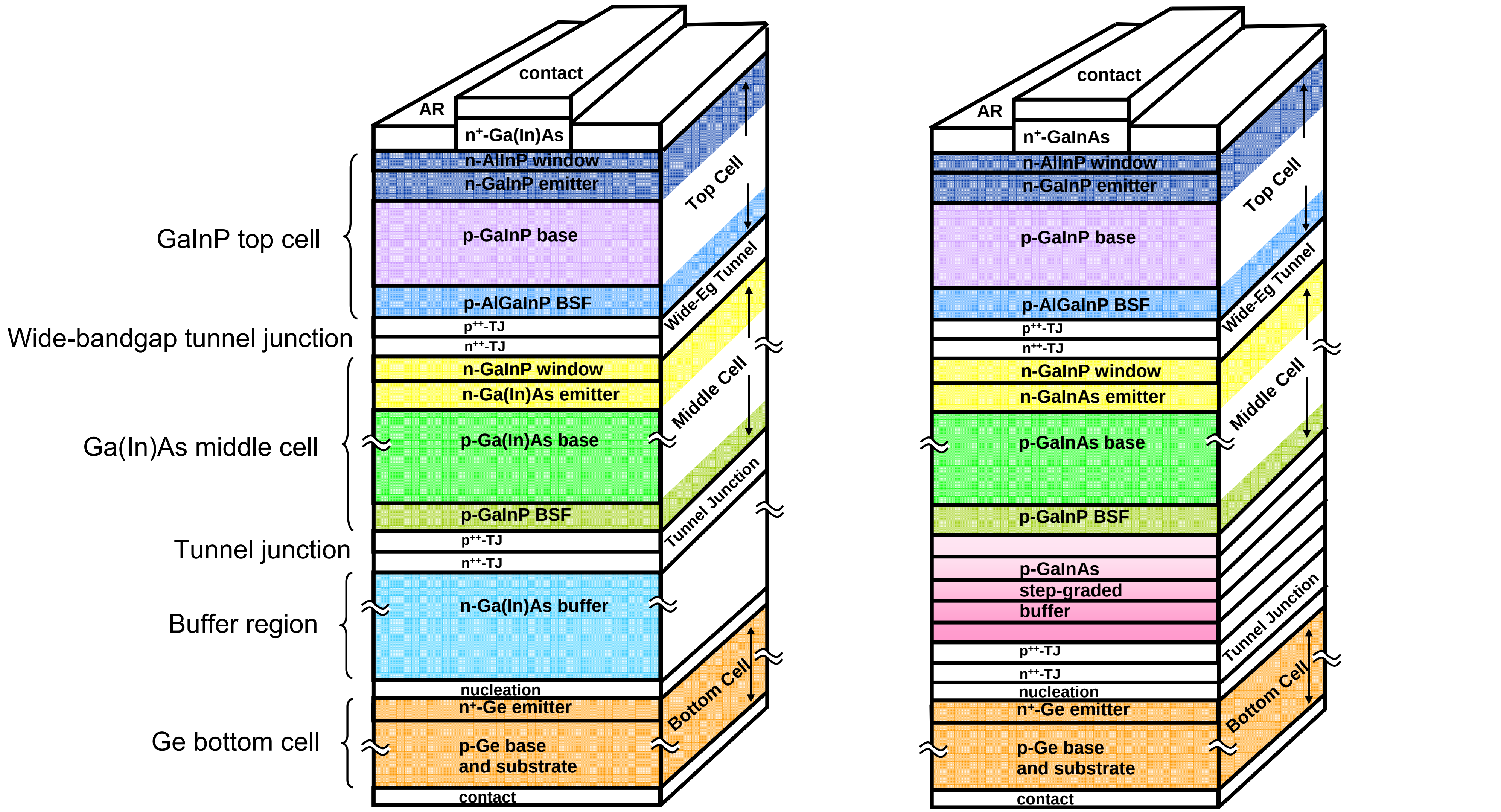
thermalization of carriers







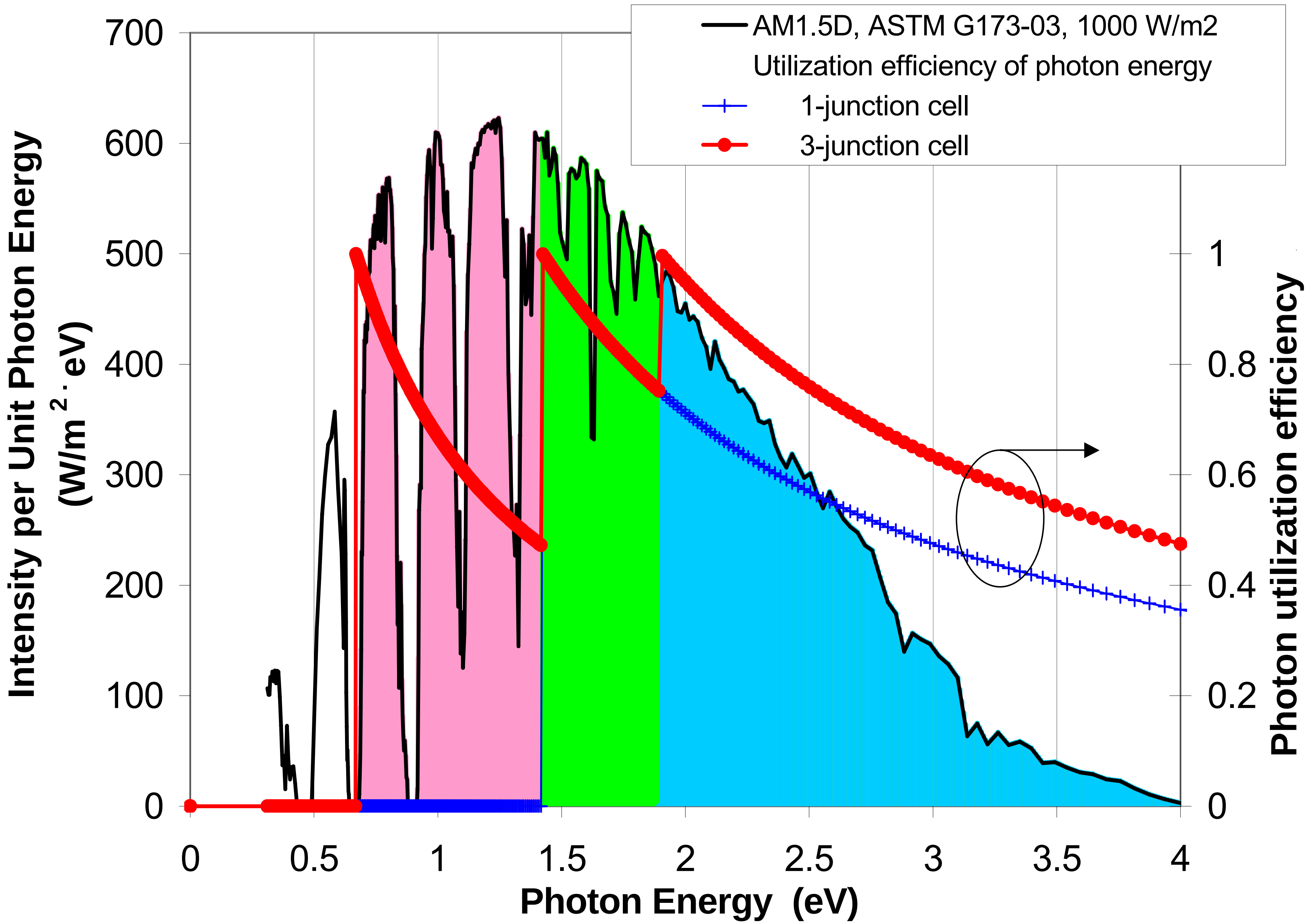
LM and MM 3-Junction Cell Cross-Section



Lattice-Matched (LM)

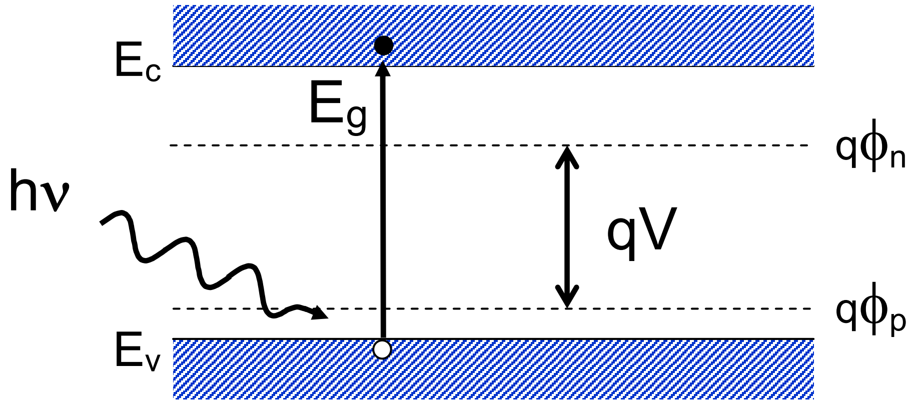
Lattice-Mismatched or Metamorphic (MM)

Photon Utilization Efficiency
3-Junction Solar Cells



R. R. King, Stanford Photonics Research Center Symposium, Stanford, CA, Sep. 14-16, 2009

Energy Transitions in Semiconductors



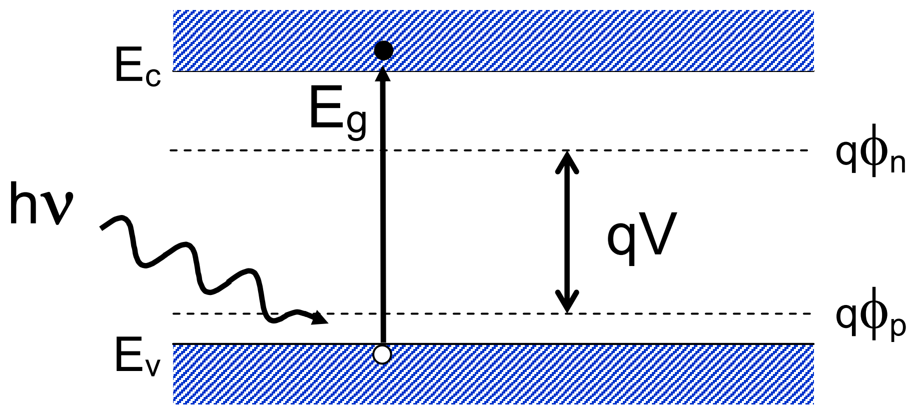
V = voltage of solar cell

= quasi-Fermi level splitting

$= |\phi_p - \phi_n|$

- Not all of bandgap energy is available to be collected at terminals, even though electron in conduction band has energy E_g
- Only $qV = q|\phi_p - \phi_n|$ is available at solar cell terminals
- Due to difference in entropy S of carriers at low concentration in conduction band, and at high concentration in contact layers: $G = H - TS$

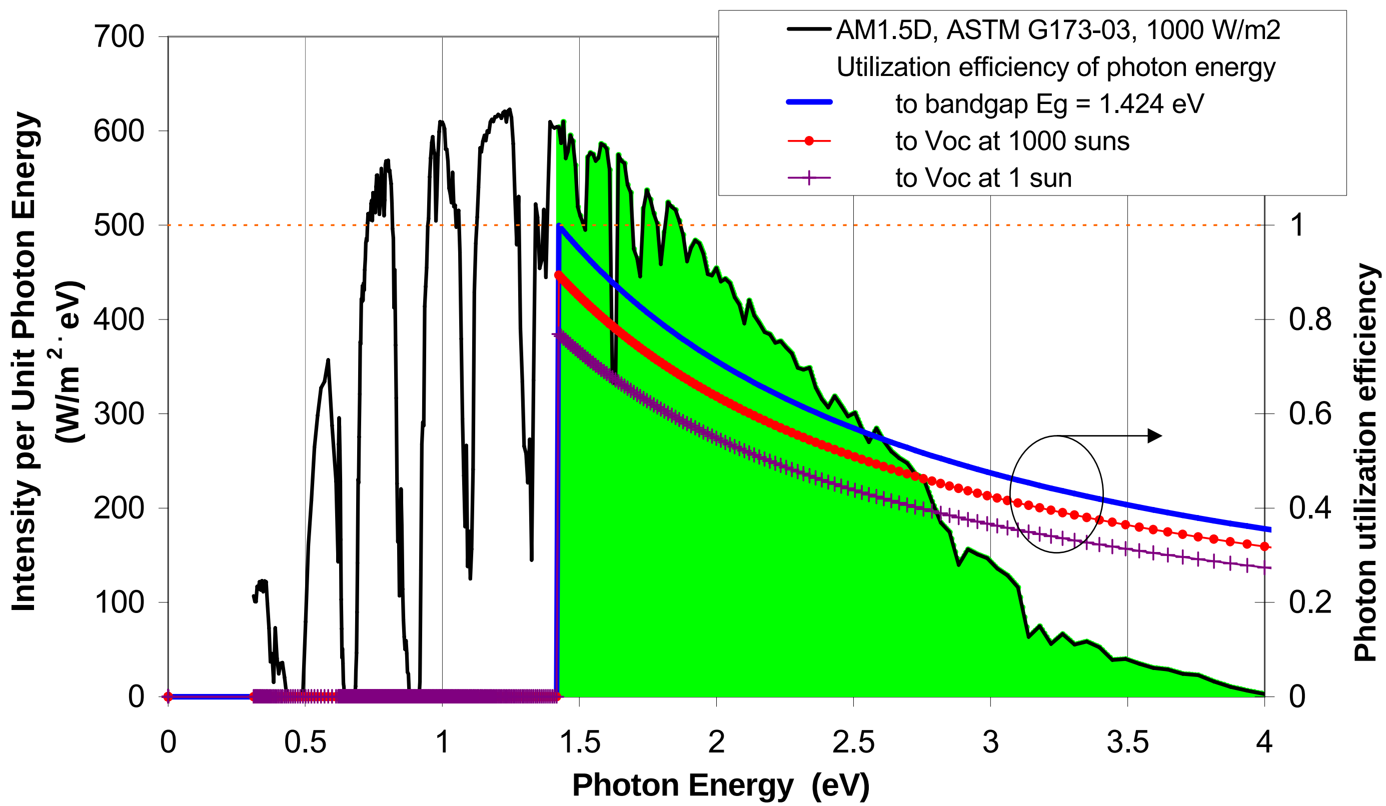
Energy Transitions in Semiconductors



V = voltage of solar cell

= quasi-Fermi level splitting

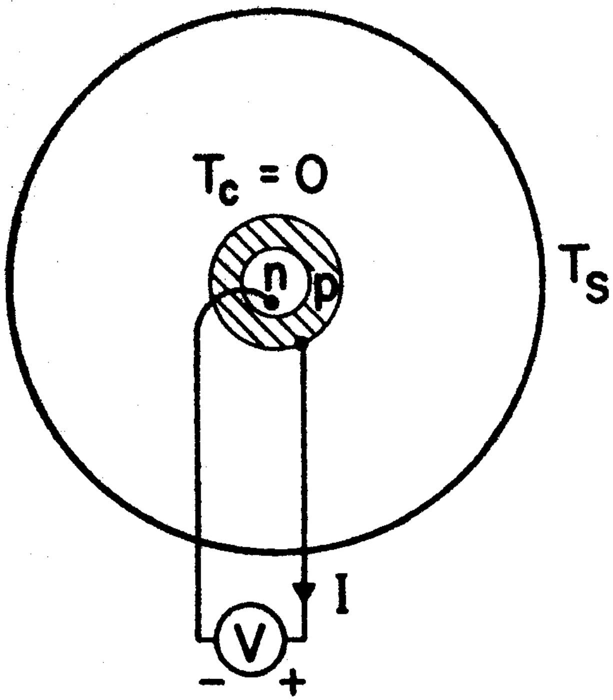
$= \left| \phi_p - \phi_n \right|$



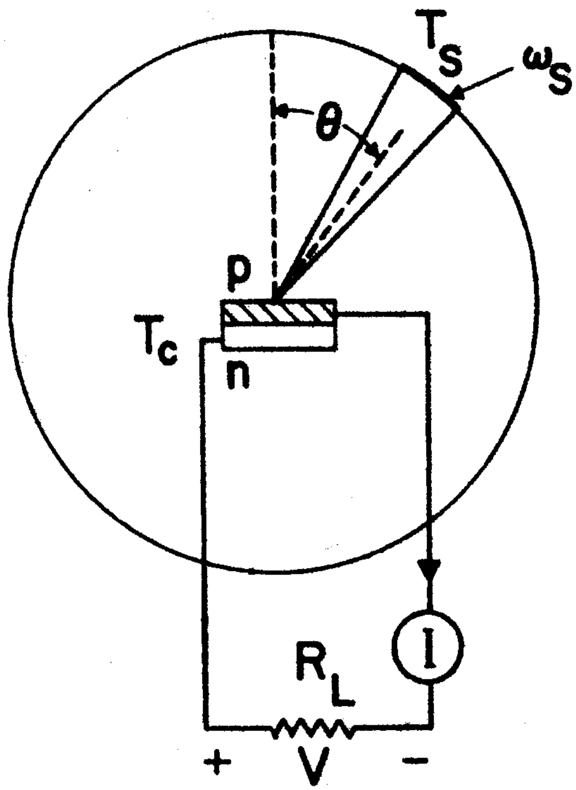
R. R. King, Stanford Photonics Research Center Symposium, Stanford, CA, Sep. 14-16, 2009

Shockley and Queisser (1961)

Detailed Balance Limit of Solar Cell Efficiency



(a)



(b)

- **30%** efficient single-gap solar cell at one sun, for 1 e^-/photon
- **44%** ultimate efficiency for device with single cutoff energy

SPECTROLAB
A BOEING COMPANY

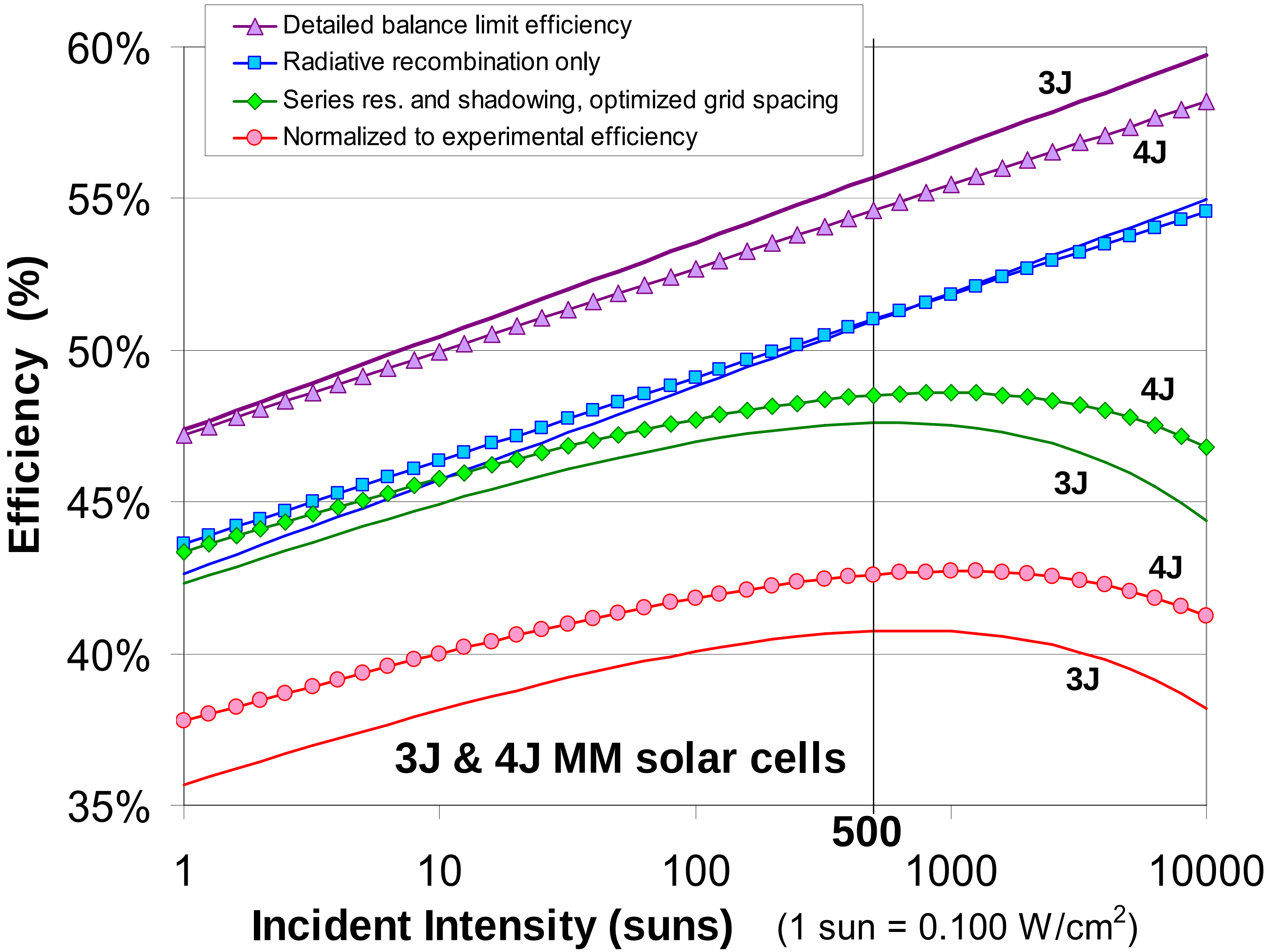
Assumptions → Opportunities

BOEING

- Assumptions for theoretical efficiency in Shockley and Quiesser (1961)
- Viewed from a different angle, these assumptions represent new opportunities, for devices that overcome these barriers

Assumption limiting solar cell efficiency	**Device principle overcoming this limitation**
Single band gap energy	Multijunction solar cells Quantum well, quantum dot solar cells
One e^--h^+ pair per photon	Down conversion Multiple exciton generation Avalanche multiplication
Non-use of sub-band-gap photons	Up conversion
Single population of each charge carrier type	Hot carrier solar cells Intermediate-band solar cells Quantum well, quantum dot solar cells
One-sun incident intensity	Concentrator solar cells

Theoretical Multijunction Cell Efficiency



SPECTROLAB
A BOEING COMPANY

Maximum Solar Cell Efficiencies

Measured **Theoretical**

References
C. H. Henry, "Limiting efficiencies of ideal single and multiple energy gap terrestrial solar cells," *J. Appl. Phys.*, **51**, 4494 (1980).
W. Shockley and H. J. Queisser, "Detailed Balance Limit of Efficiency of *p-n* Junction Solar Cells," *J. Appl. Phys.*, **32**, 510 (1961).
J. H. Werner, S. Kolodinski, and H. J. Queisser, "Novel Optimization Principles and Efficiency Limits for Semiconductor Solar Cells," *Phys. Rev. Lett.*, **72**, 3851 (1994).
R. R. King *et al.*, "Band-Gap-Engineered Architectures for High-Efficiency Multijunction Concentrator Solar Cells," *24th European Photovoltaic Solar Energy Conf.*, Hamburg, Germany, Sep. 21-25, 2009.
R. R. King et al., "40% efficient metamorphic GaInP / GaInAs / Ge multijunction solar cells," *Appl. Phys. Lett.*, **90**, 183516 (4 May 2007).
M. Green, K. Emery, D. L. King, Y. Hishikawa, W. Warta, "Solar Cell Efficiency Tables (Version 27)", *Progress in Photovoltaics*, **14**, 45 (2006).
A. Slade, V. Garboushian, "27.6%-Efficient Silicon Concentrator Cell for Mass Production," *Proc. 15th Int'l. Photovoltaic Science and Engineering Conf.*, Beijing, China, Oct. 2005.
R. P. Gale *et al.*, "High-Efficiency GaAs/CuInSe$_2$ and AlGaAs/CuInSe$_2$ Thin-Film Tandem Solar Cells," *Proc. 21st IEEE Photovoltaic Specialists Conf.*, Kissimmee, Florida, May 1990.
J. Zhao, A. Wang, M. A. Green, F. Ferrazza, "Novel 19.8%-efficient 'honeycomb' textured multicrystalline and 24.4% monocrystalline silicon solar cells," *Appl. Phys. Lett.*, **73**, 1991 (1998).

Measured

3-gap GaInP/GaInAs/Ge LM cell, 364 suns (Spectrolab) **41.6%**
3-gap GaInP/GaInAs/Ge MM cell, 240 suns (Spectrolab) **40.7%**

3-gap GaInP/GaAs/GaInAs cell at 1 sun (NREL) **33.8%**

1-gap solar cell (silicon, 1.12 eV) at 92 suns (Amonix) **27.6%**
1-gap solar cell (GaAs, 1.424 eV) at 1 sun (Kopin) **25.1%**
1-gap solar cell (silicon, 1.12 eV) at 1 sun (UNSW) **24.7%**

Theoretical

95% Carnot eff. = $1 - T/T_{sun}$ $T = 300$ K, $T_{sun} \approx 5800$ K
93% Max. eff. of solar energy conversion
$= 1 - TS/E = 1 - (4/3)T/T_{sun}$ (Henry)

72% Ideal 36-gap solar cell at 1000 suns (Henry)

56% Ideal 3-gap solar cell at 1000 suns (Henry)
50% Ideal 2-gap solar cell at 1000 suns (Henry)

44% Ultimate eff. of device with cutoff E_g: (Shockley, Queisser)
43% 1-gap cell at 1 sun with carrier multiplication
(>1 e-h pair per photon) (Werner, Kolodinski, Queisser)

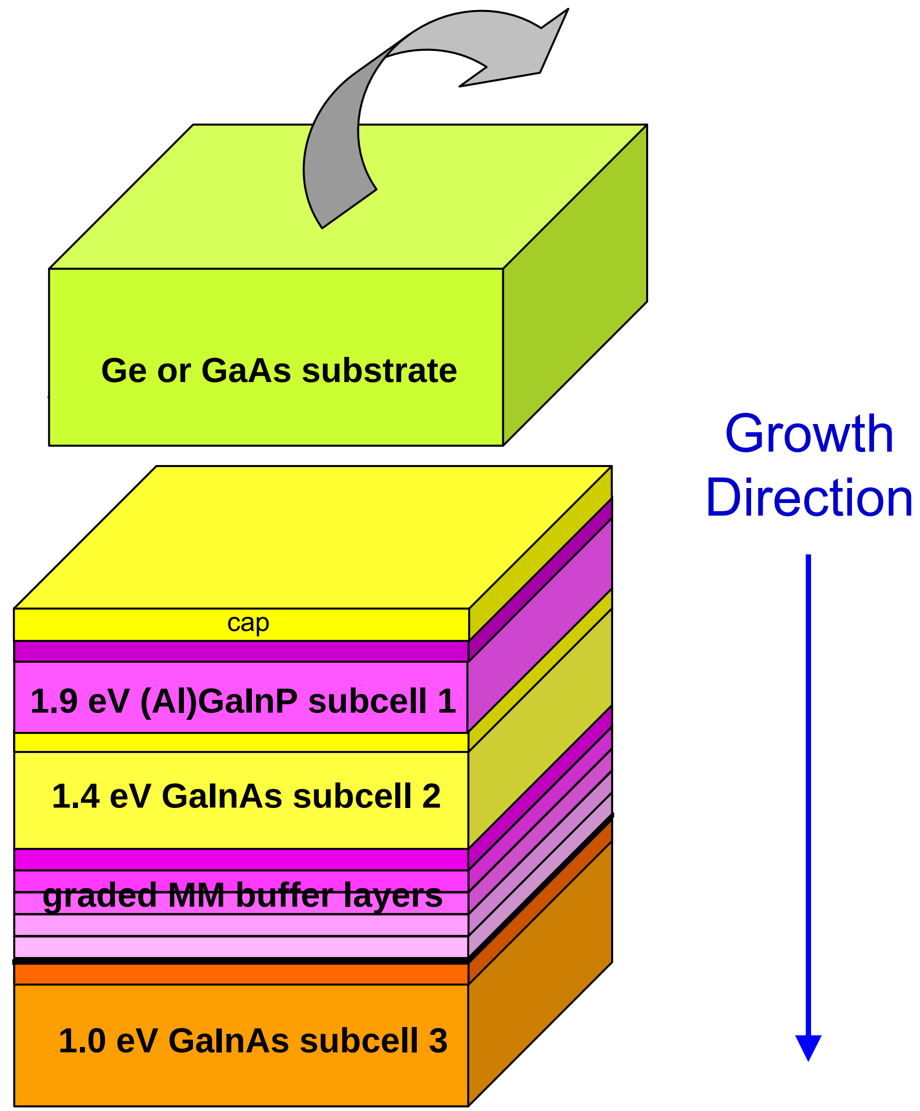
37% Ideal 1-gap solar cell at 1000 suns (Henry)

31% Ideal 1-gap solar cell at 1 sun (Henry)
30% Detailed balance limit of 1 gap solar cell at 1 sun
(Shockley, Queisser)

SPECTROLAB
A BOEING COMPANY

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

BOEING

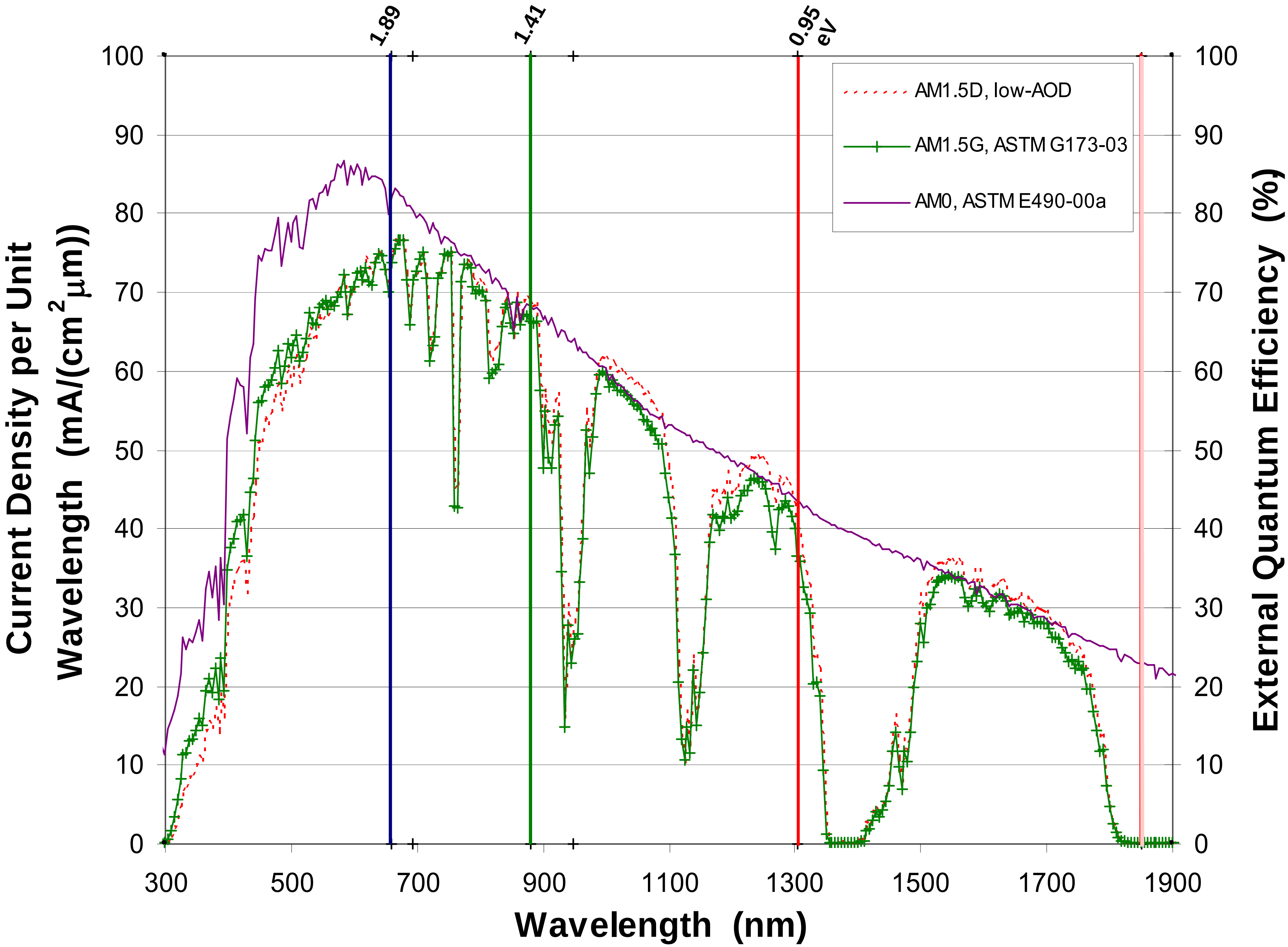


Growth on Ge or GaAs substrate, followed by substrate removal from sunward surface

SPECTROLAB
A BOEING COMPANY

Solar Spectrum Partition for 3-Junction Cell

BOEING

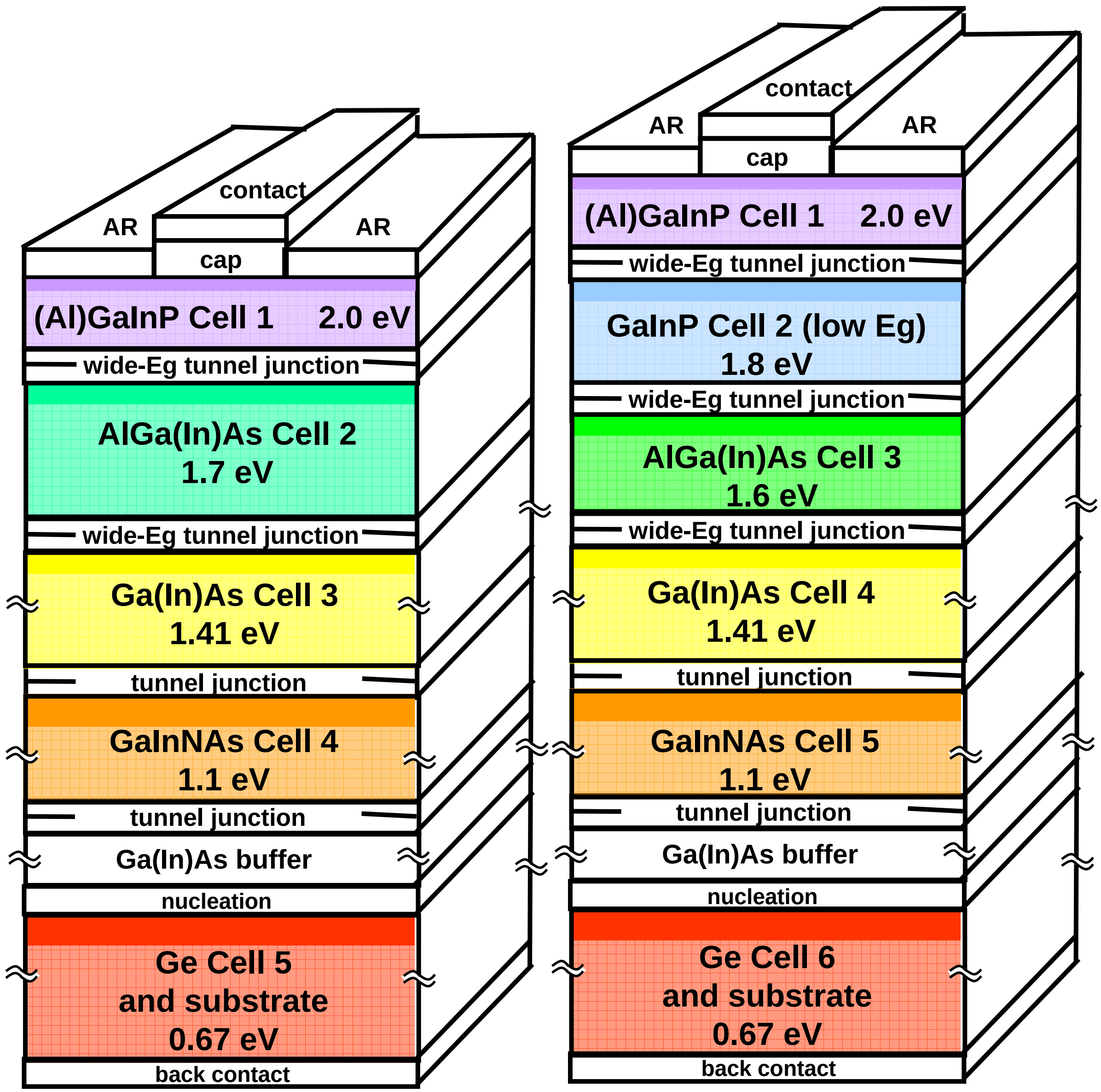


R. R. King, Stanford Photonics Research Center Symposium, Stanford, CA, Sep. 14-16, 2009

5- and 6-Junction Cells

SPECTROLAB
A BOEING COMPANY

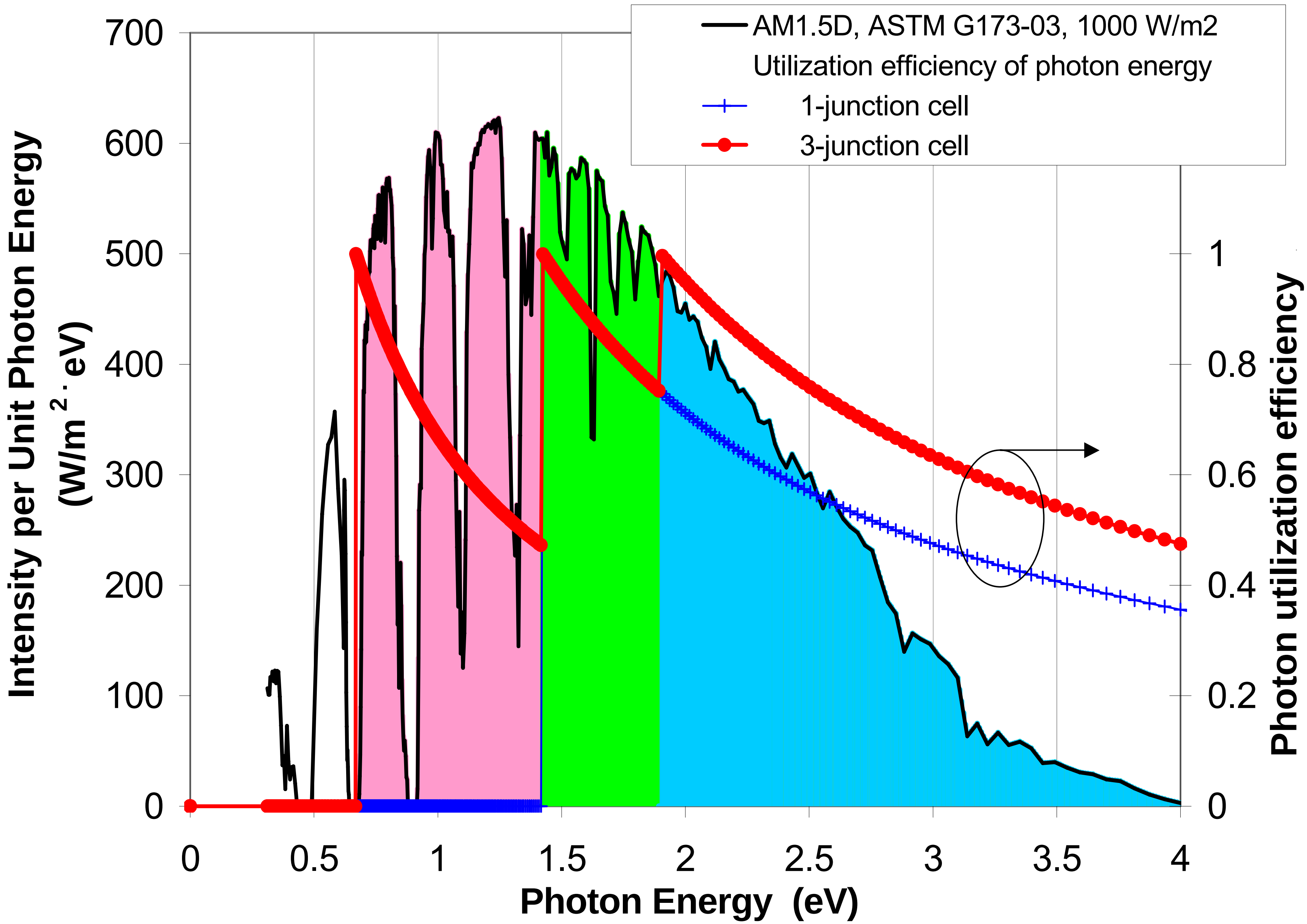
BOEING



- **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**

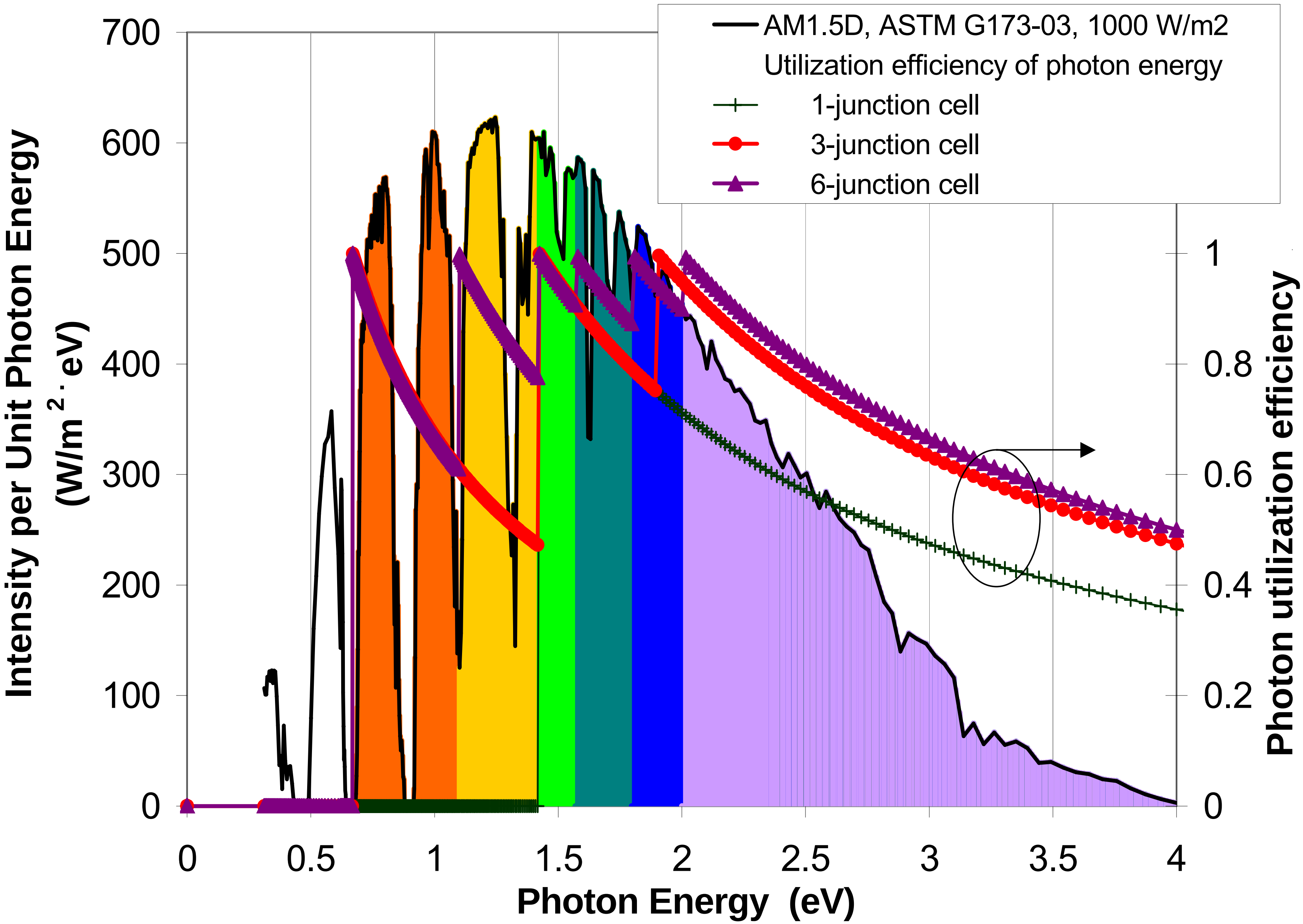
Ref.: U.S. Pat. No. 6,316,715, Spectrolab, Inc., filed 3/15/00, issued 11/13/01.

Photon Utilization Efficiency 3-Junction Solar Cells



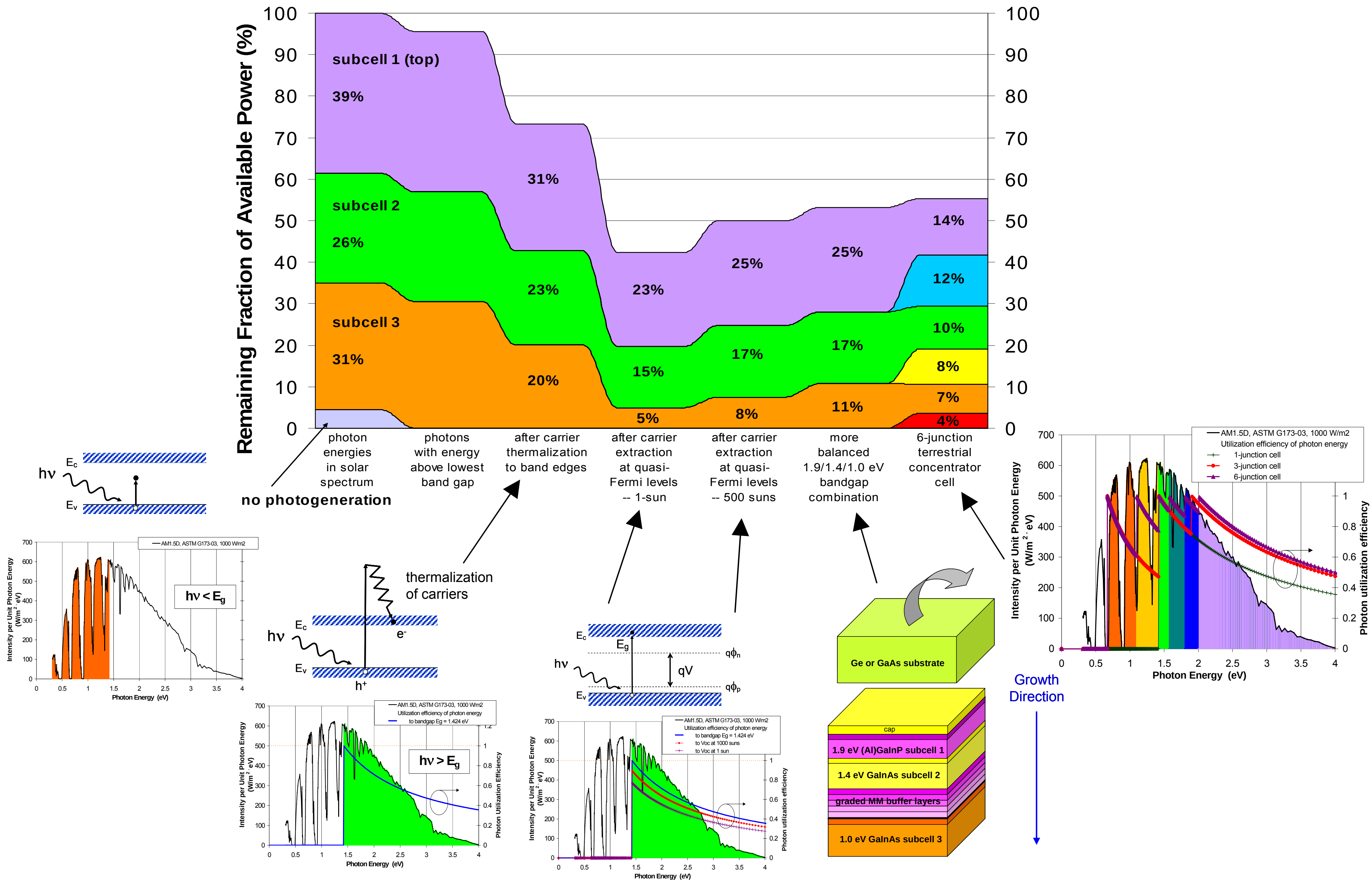
R. R. King, Stanford Photonics Research Center Symposium, Stanford, CA, Sep. 14-16, 2009

Photon Utilization Efficiency
6-Junction Solar Cells



R. R. King, Stanford Photonics Research Center Symposium, Stanford, CA, Sep. 14-16, 2009

3-Junction Cell Efficiency Losses from 100%

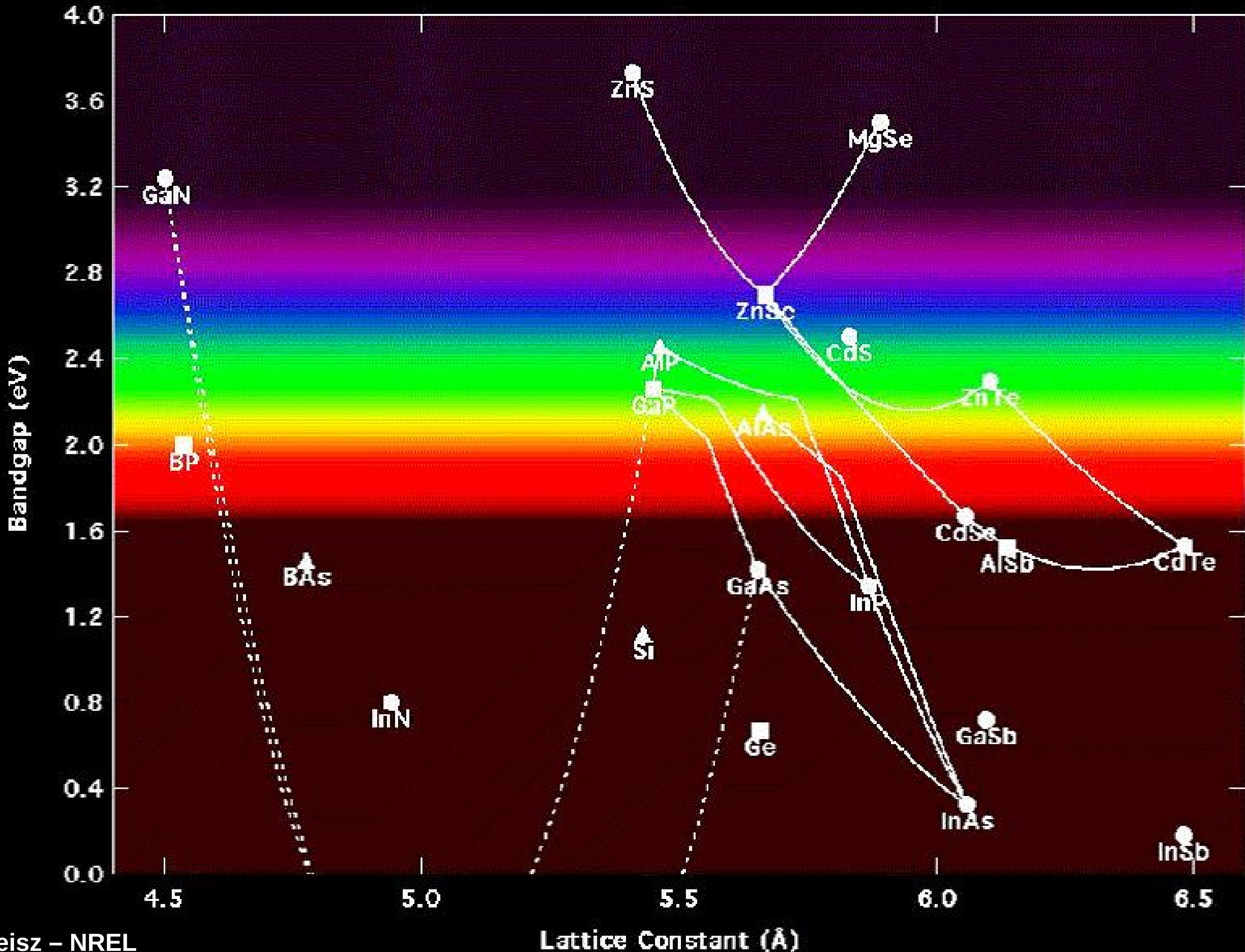


Metamorphic Semiconductor Materials

Metamorphic (MM) Semiconductor Materials

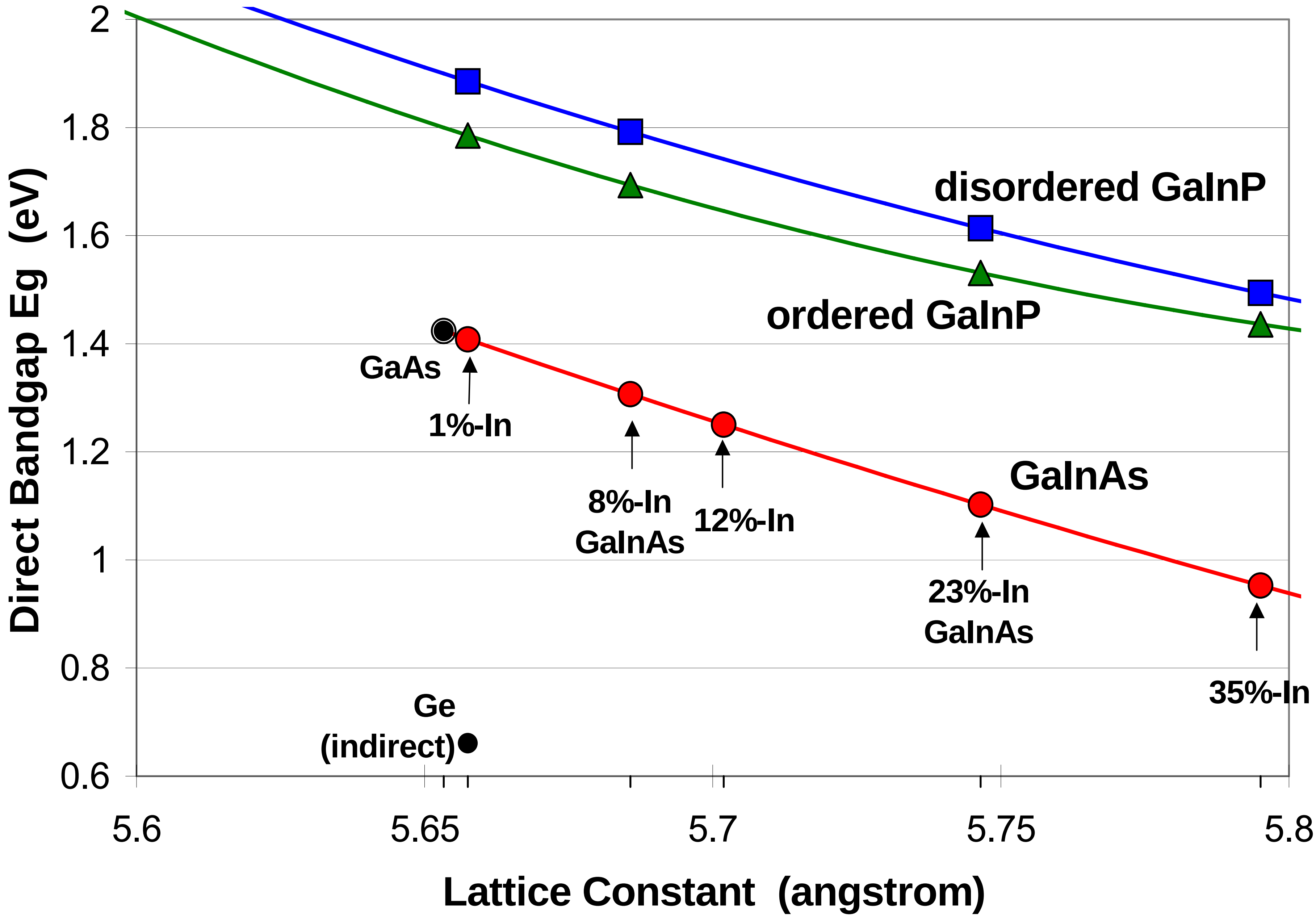
- Metamorphic = "changed form"
- Thick, relaxed epitaxial layers grown with different lattice constant than growth substrate
- Allows access to subcell band gaps desired for more efficient division of the solar spectrum in multijunction solar cells
- Also called lattice-mismatched
- Misfit dislocations are allowed to form in metamorphic buffer, which typically has graded composition and lattice constant
- Threading dislocations which can propagate up into active device layers grown on buffer are minimized as much as possible

Bandgap vs. Lattice Constant



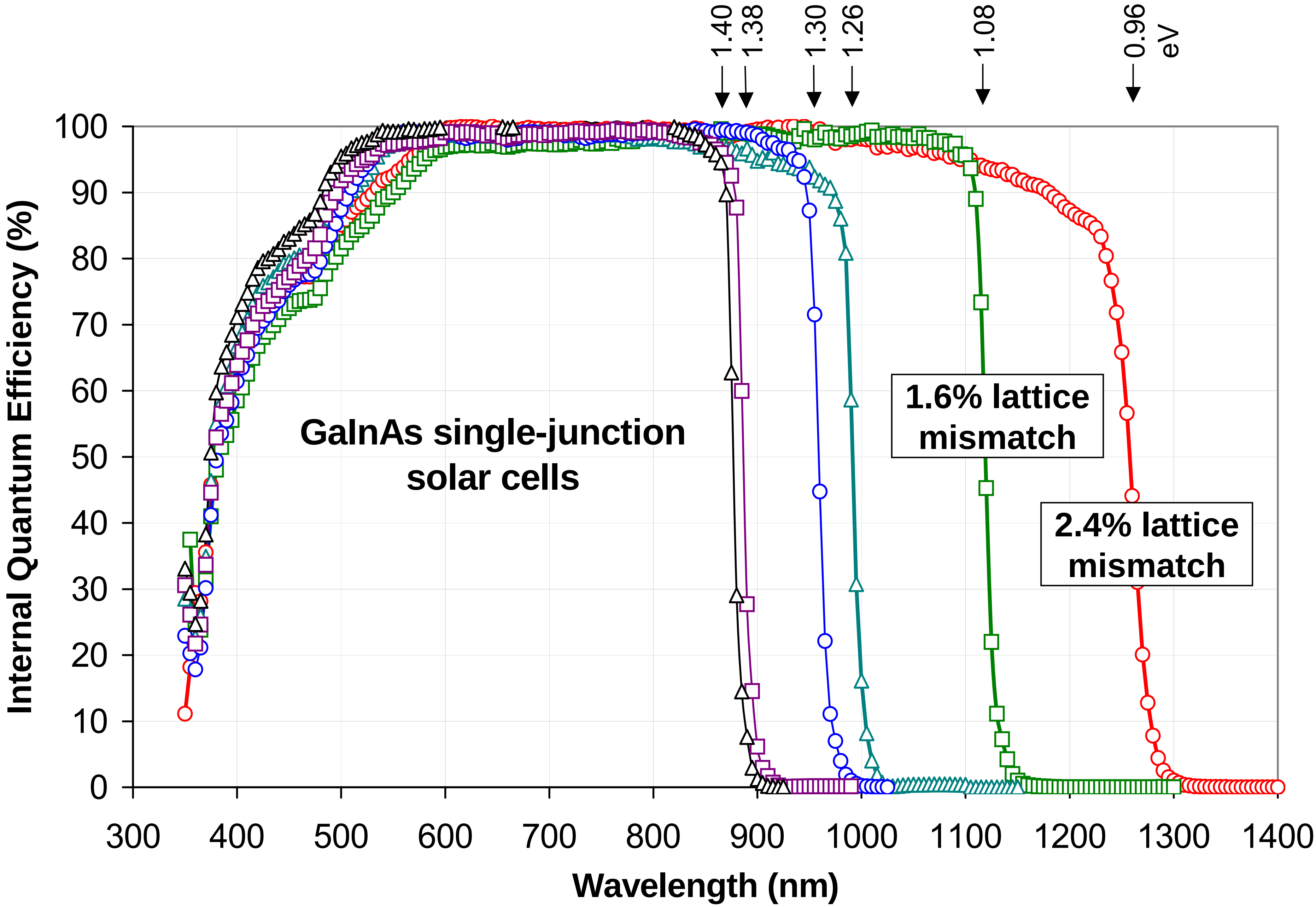
Courtesy J. Geisz – NREL

Bandgap vs. Lattice Constant



R. R. King, Stanford Photonics Research Center Symposium, Stanford, CA, Sep. 14-16, 2009

Internal QE of Metamorphic GaInAs Cells on Ge



R. R. King, Stanford Photonics Research Center Symposium, Stanford, CA, Sep. 14-16, 2009

SPECTROLAB
A BOEING COMPANY

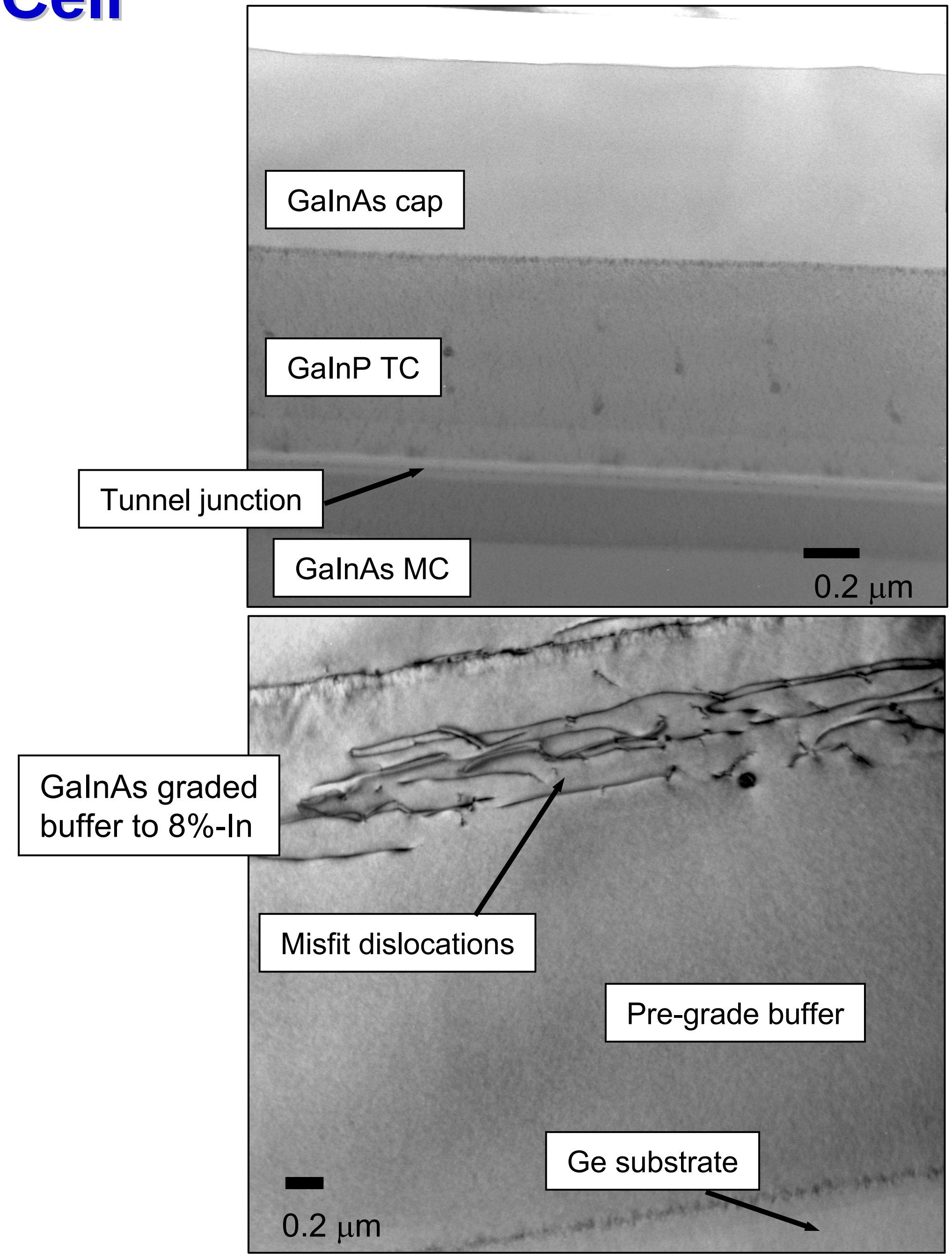
BOEING

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

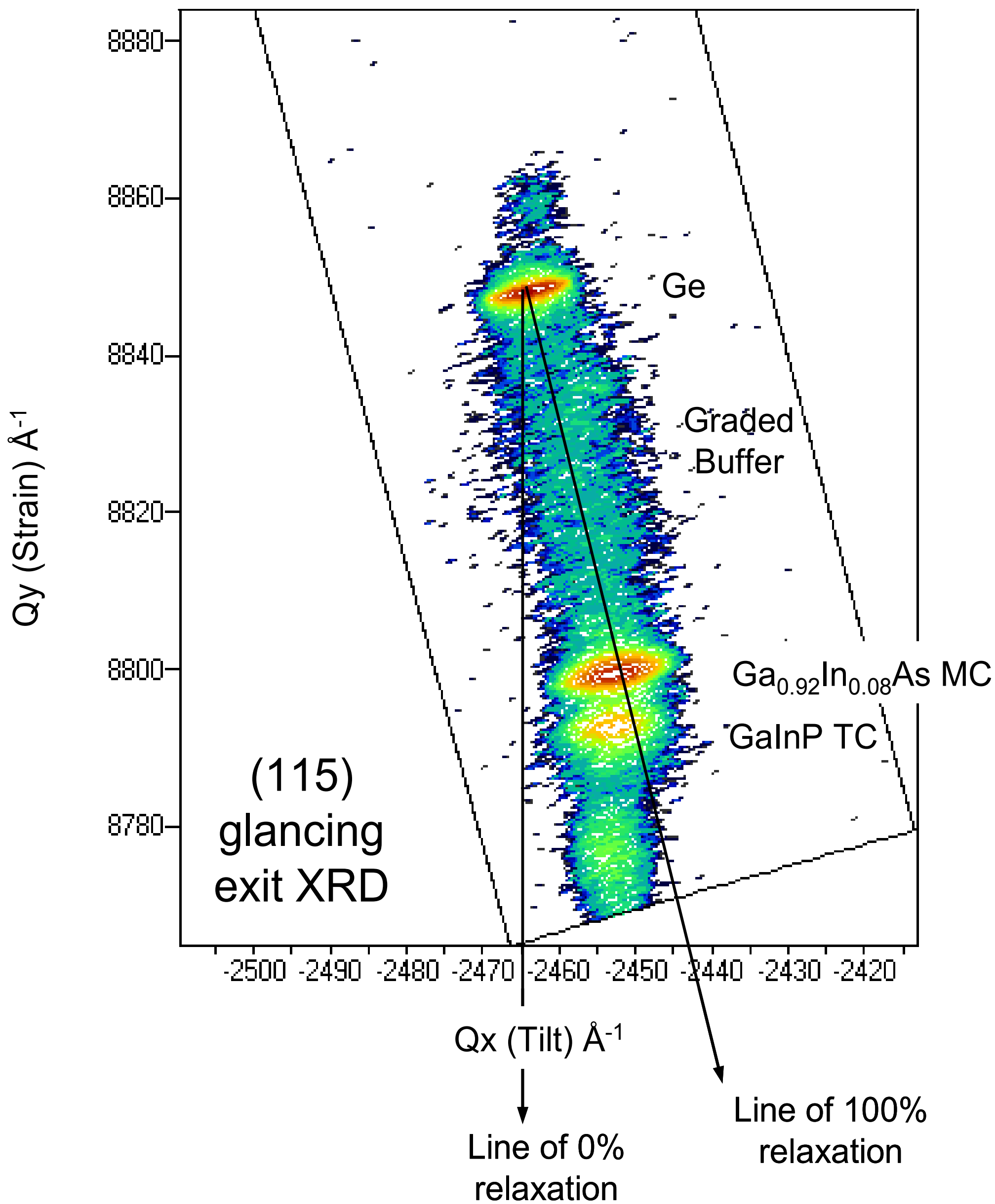
- Low dislocation density in active cell layers in top portion of epilayer stack:

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

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

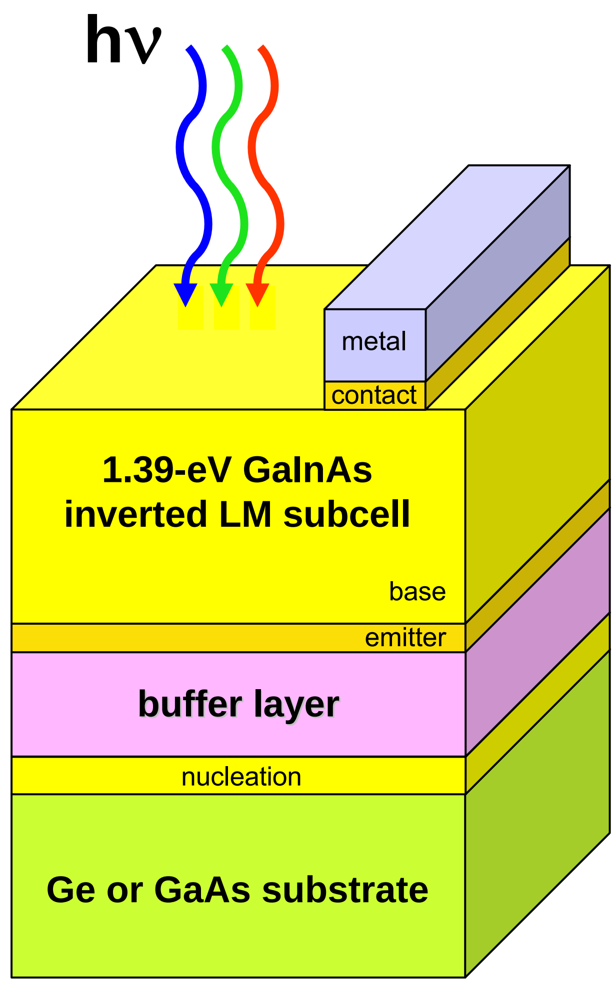


High-Resolution XRD Reciprocal Space Map (RSM)



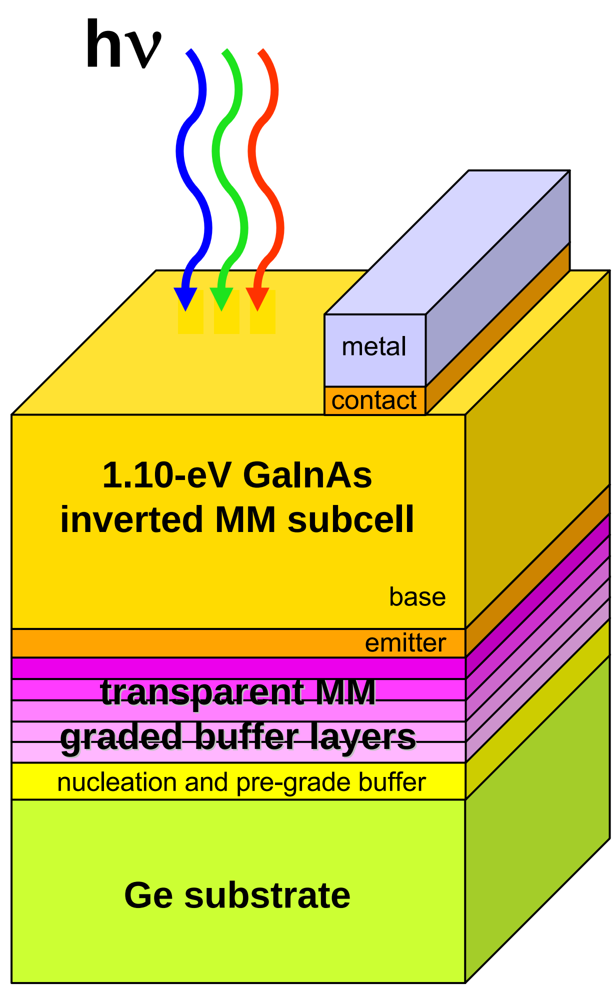
- GaInP/ 8%-In GaInAs/ Ge metamorphic (MM) cell structure
- Nearly 100% relaxed step-graded buffer → removes driving force for dislocations to propagate into active cell layers
- 56%-In GaInP top cell pseudomorphic with respect to GaInAs middle cell

Inverted Lattice-Matched (LM) 1.39-eV GaInAs Subcell



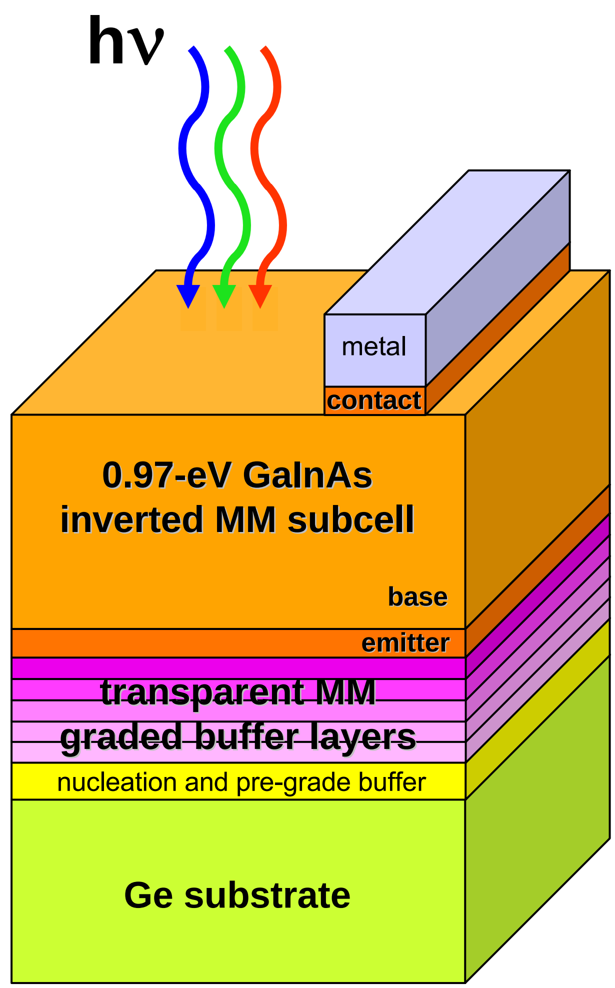
Growth on Ge or GaAs substrate,
followed by substrate removal from sunward surface

Metamorphic (MM) 3-Junction Cells –– Inverted 1.10-eV GaInAs Subcell



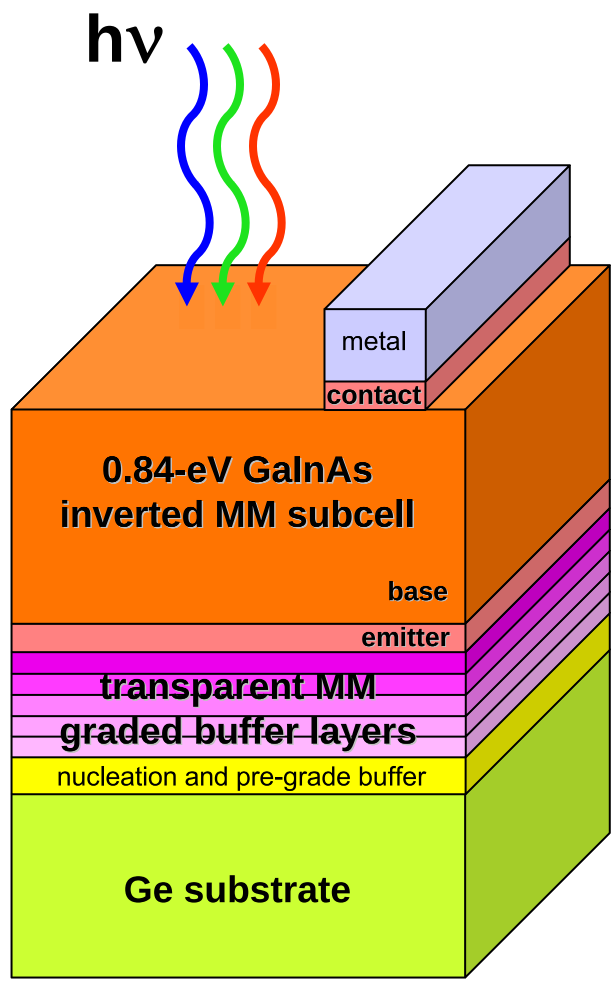
Growth on Ge or GaAs substrate,
followed by substrate removal from sunward surface

Metamorphic (MM) 3-Junction Cells –– Inverted 0.97-eV GaInAs Subcell



Growth on Ge or GaAs substrate, followed by substrate removal from sunward surface

Metamorphic (MM) 3-Junction Cells –– Inverted 0.84-eV GaInAs Subcell

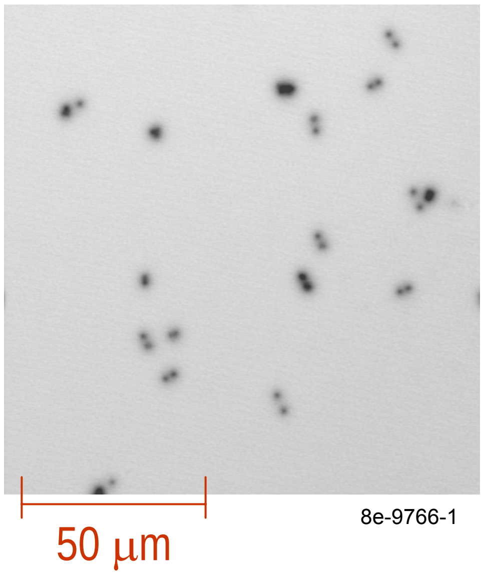


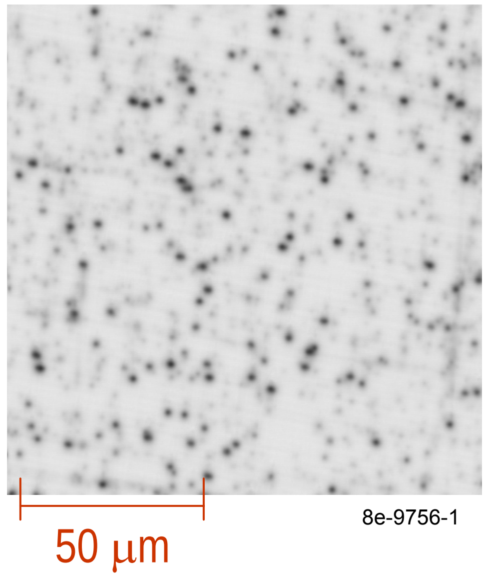
Growth on Ge or GaAs substrate,
followed by substrate removal from sunward surface

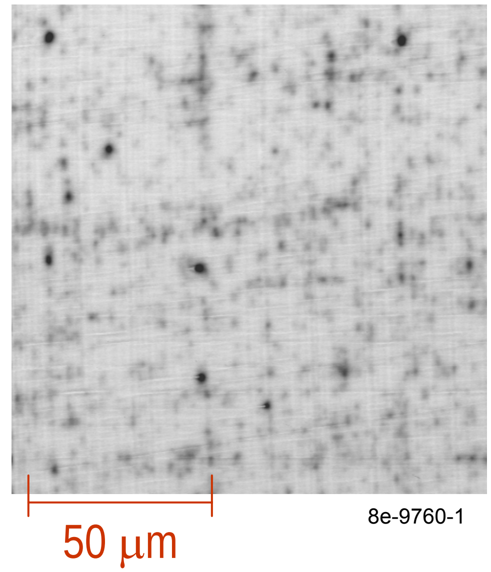
SPECTROLAB
A BOEING COMPANY

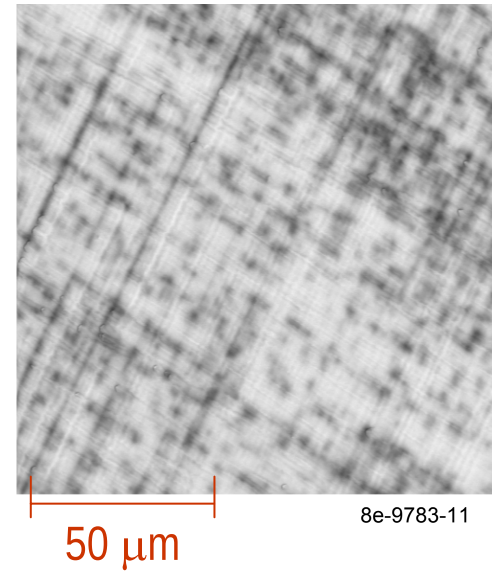
BOEING

Dislocations in Inverted Metamorphic Cells – EBIC

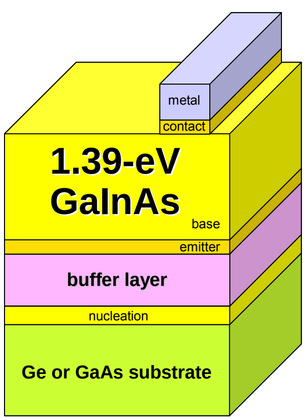


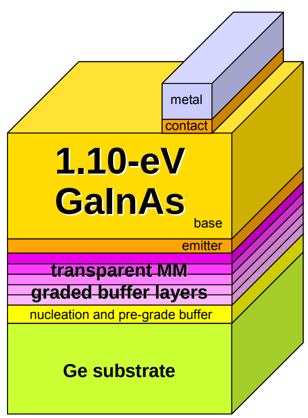


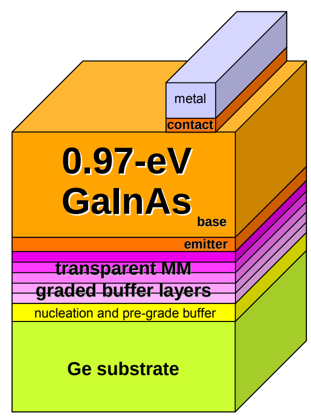


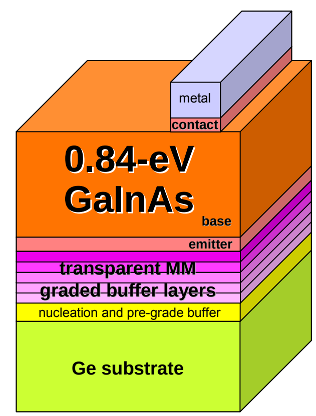


	1.39-eV ILM subcell	**1.10-eV IMM subcell**	**0.97-eV IMM subcell**	**0.84-eV IMM subcell**
GaInAs comp.	2% In	23% In	33% In	44% In
Latt. mismatch	0.1%	1.6%	2.3%	3.1%
Disloc. density	2.5 x 10^5 cm^{-2}	3.9 x 10^6 cm^{-2}	5.0 x 10^6 cm^{-2}	6.3 x 10^6 cm^{-2}



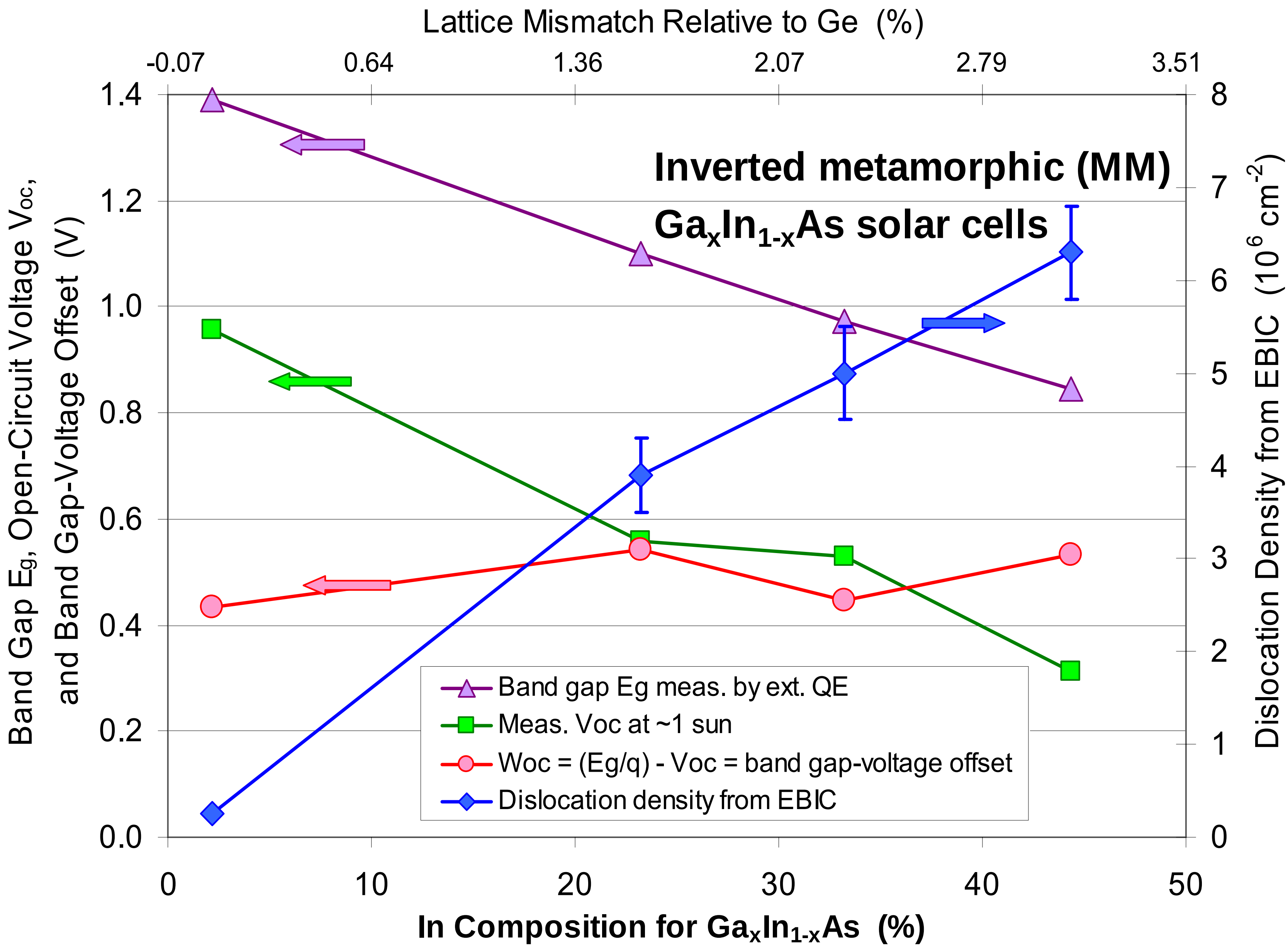




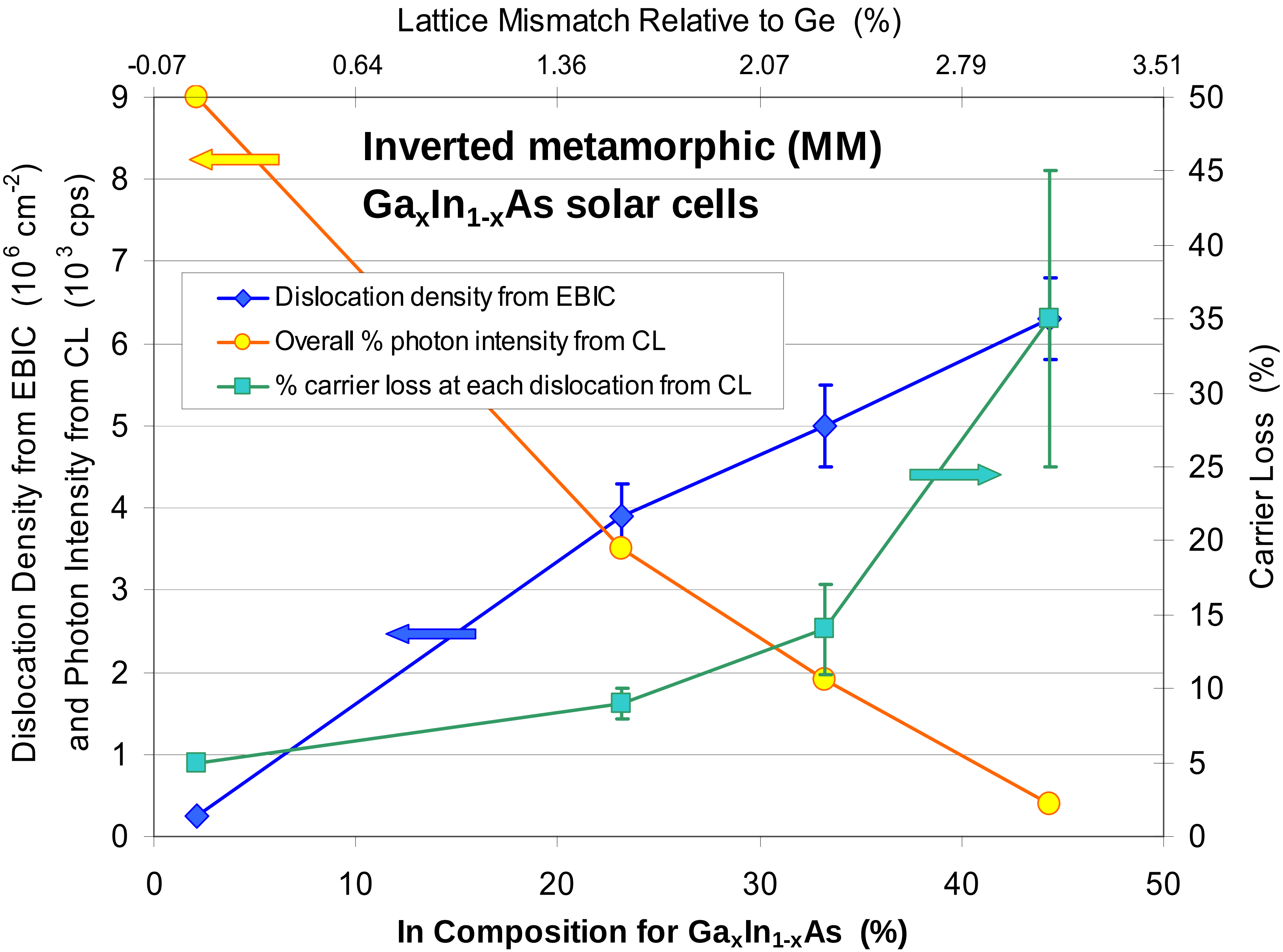


EBIC images and dislocation density of inverted metamorphic cell test structures

Dislocations in Inverted Metamorphic Cells



Dislocations in Inverted Metamorphic Cells



R. R. King, Stanford Photonics Research Center Symposium, Stanford, CA, Sep. 14-16, 2009

SPECTROLAB
A BOEING COMPANY

BOEING

Solar Cell Voltage

Voltage depends on non-equilibrium concentrations of electrons and holes

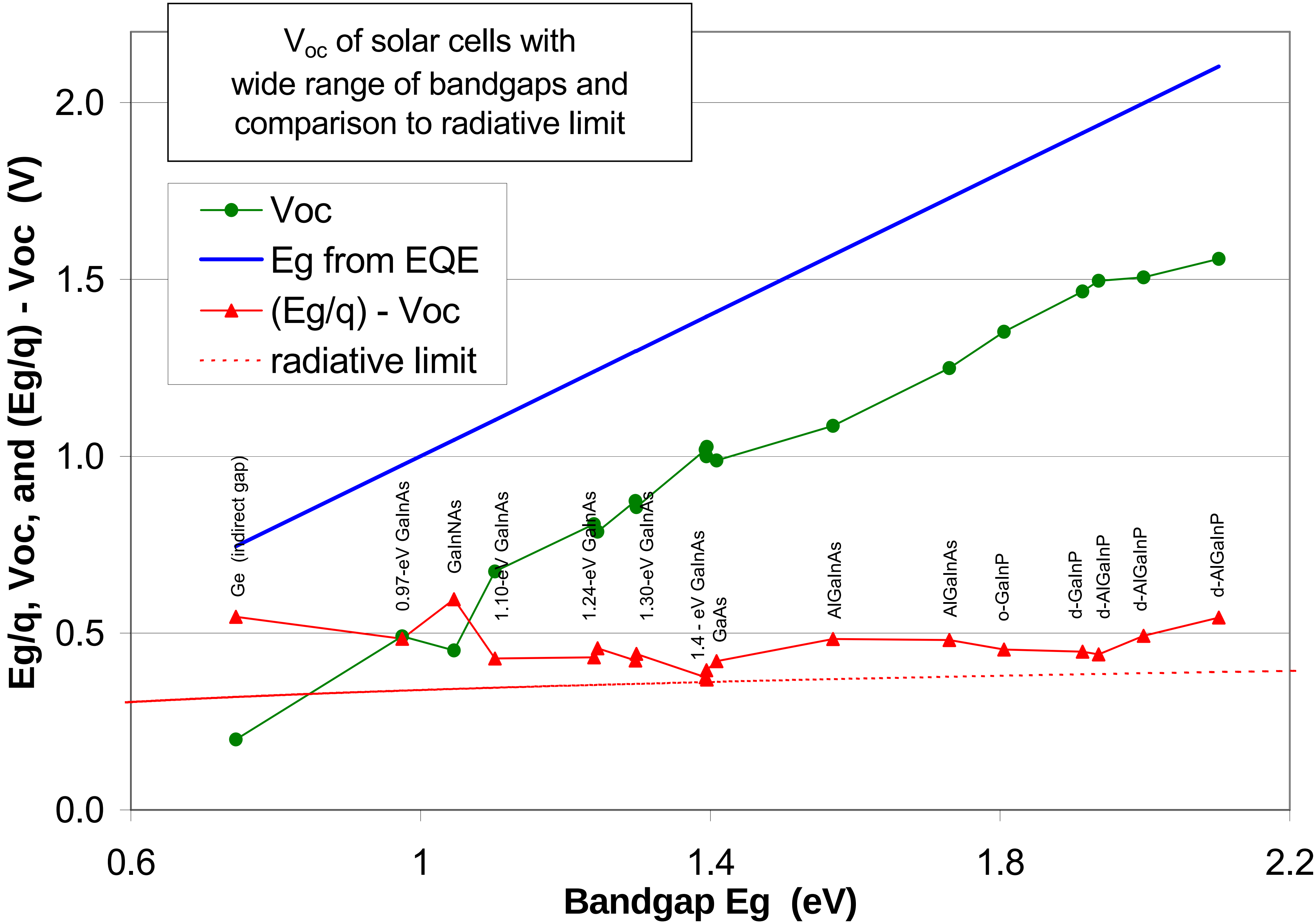
$$pn = n_i^2 e^{qV/kT}$$

$$n_i^2 = N_C N_V e^{-E_g/kT} \qquad pn = N_C N_V e^{-(E_g - qV)/kT} = N_C N_V e^{-qW/kT}$$

$$V = \frac{kT}{q}\ln\left(\frac{pn}{n_i^2}\right) \qquad W \equiv \left(E_g/q\right) - V = \frac{kT}{q}\ln\left(\frac{N_C N_V}{pn}\right)$$

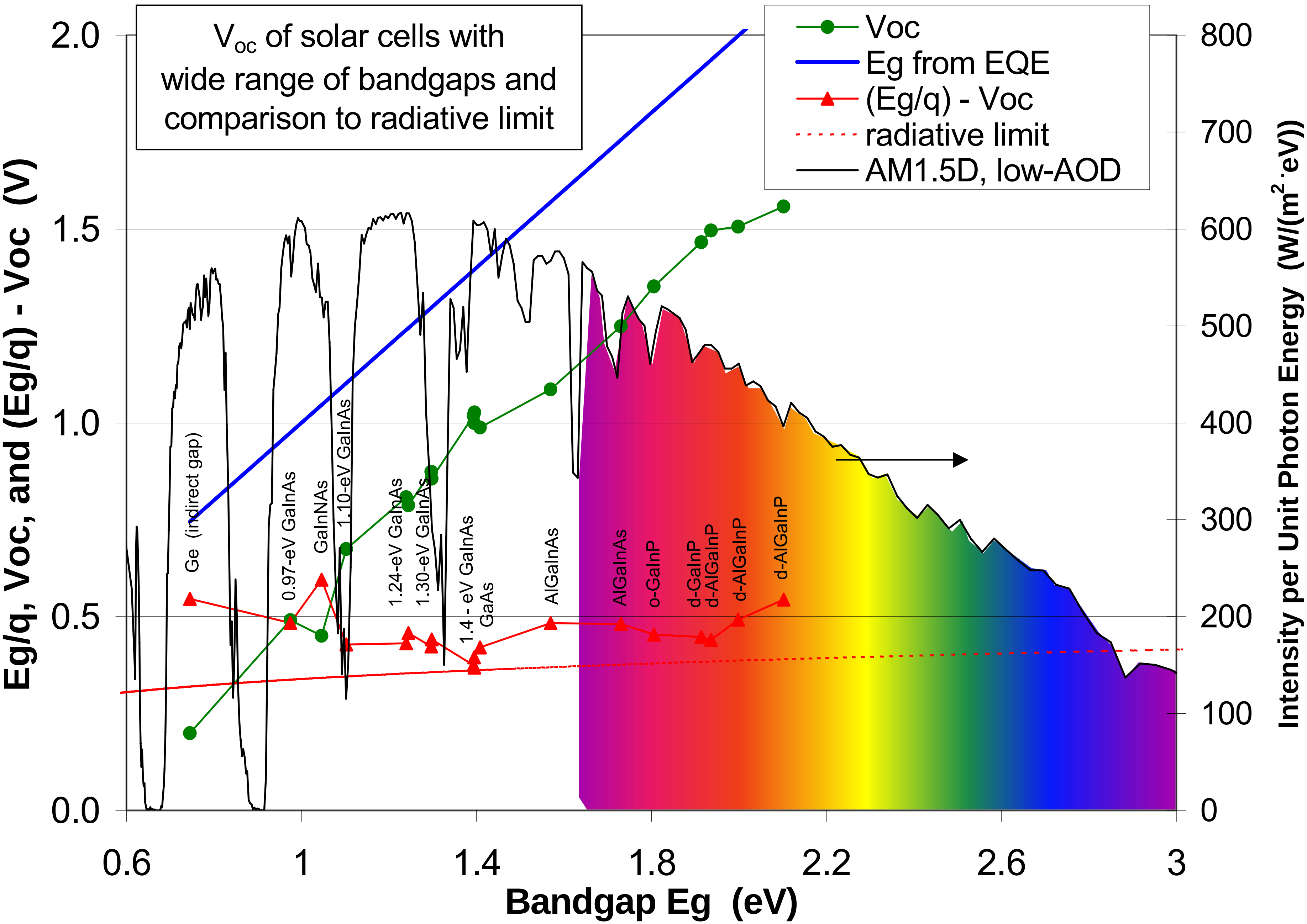
- Bandgap-voltage offset $W \equiv (E_g/q) - V$ is a useful parameter for gauging solar cell quality, especially when dealing with semiconductors of many different bandgaps
- Basically a measure of how close electron and hole quasi-Fermi levels are to conduction and valence band edges

Band gap - Voltage Offset (E_g/q) - V_{oc} for Single-Junction Solar Cells



R. R. King, Stanford Photonics Research Center Symposium, Stanford, CA, Sep. 14-16, 2009

Band gap - Voltage Offset (E_g/q) - V_{oc} for Single-Junction Solar Cells



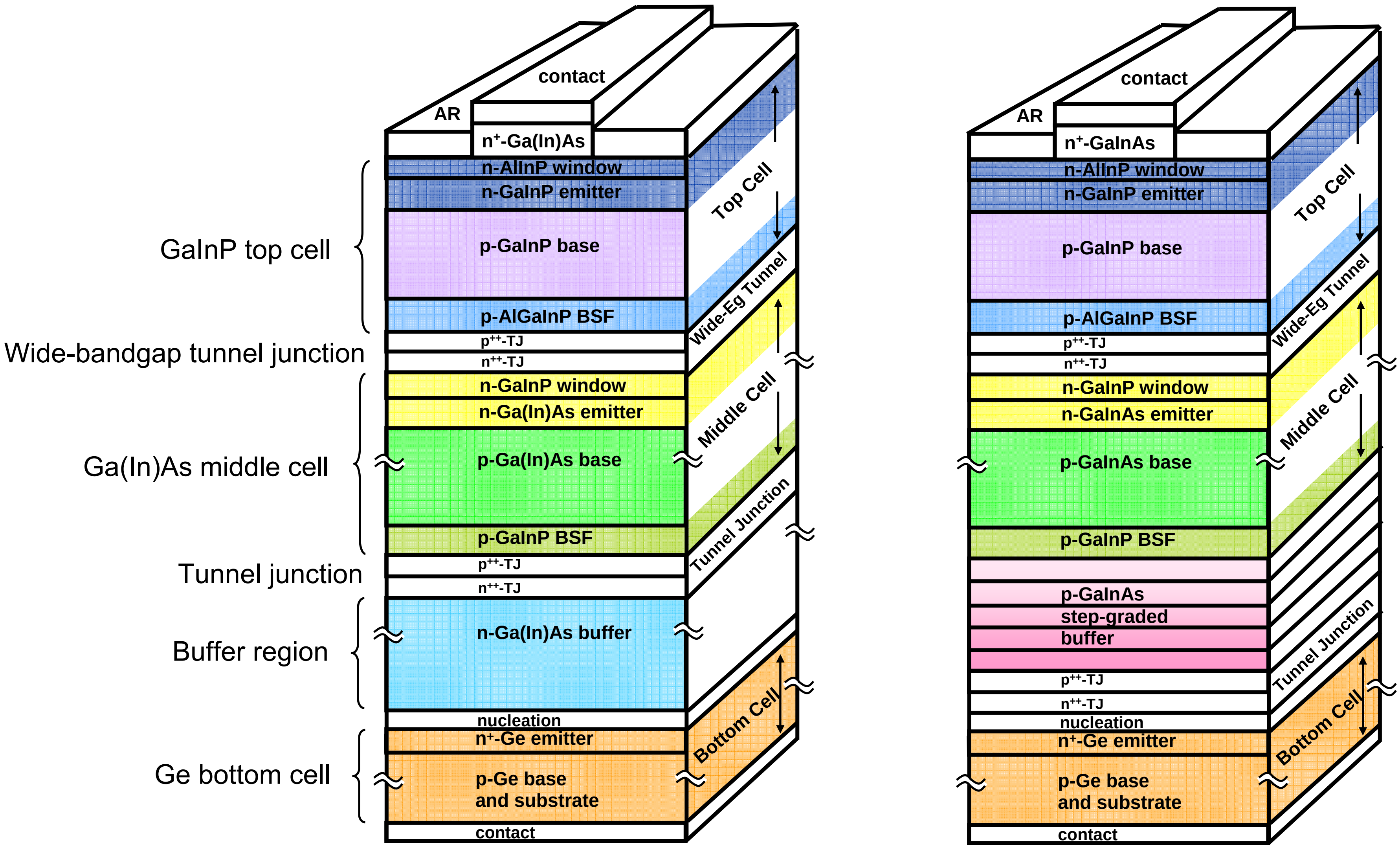
R. R. King, Stanford Photonics Research Center Symposium, Stanford, CA, Sep. 14-16, 2009

High-Efficiency
Multijunction Cells

SPECTROLAB
A BOEING COMPANY

LM and MM 3-Junction Cell Cross-Section

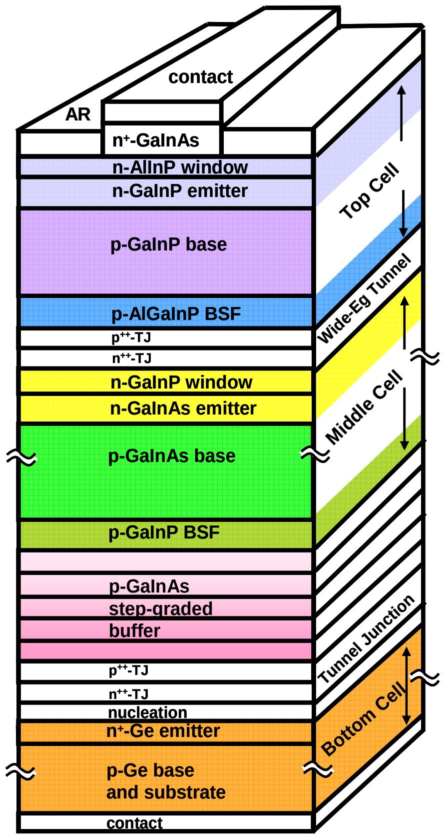
BOEING



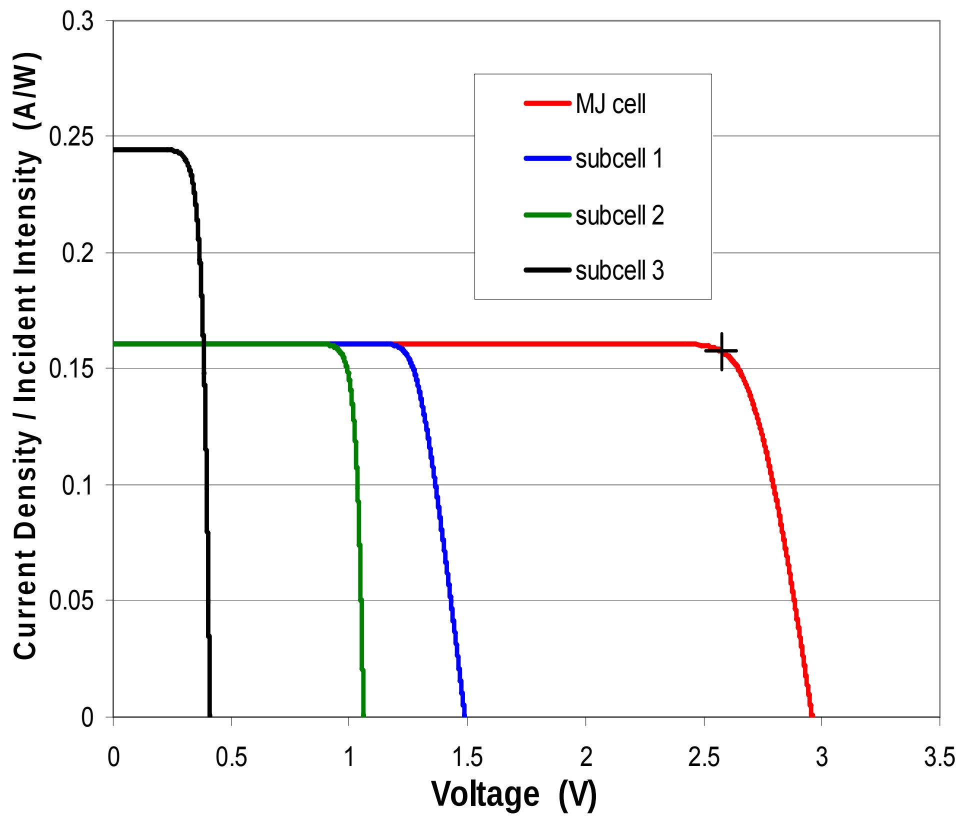
Lattice-Matched (LM)

Lattice-Mismatched or Metamorphic (MM)

Metamorphic (MM) 3-Junction Solar Cell

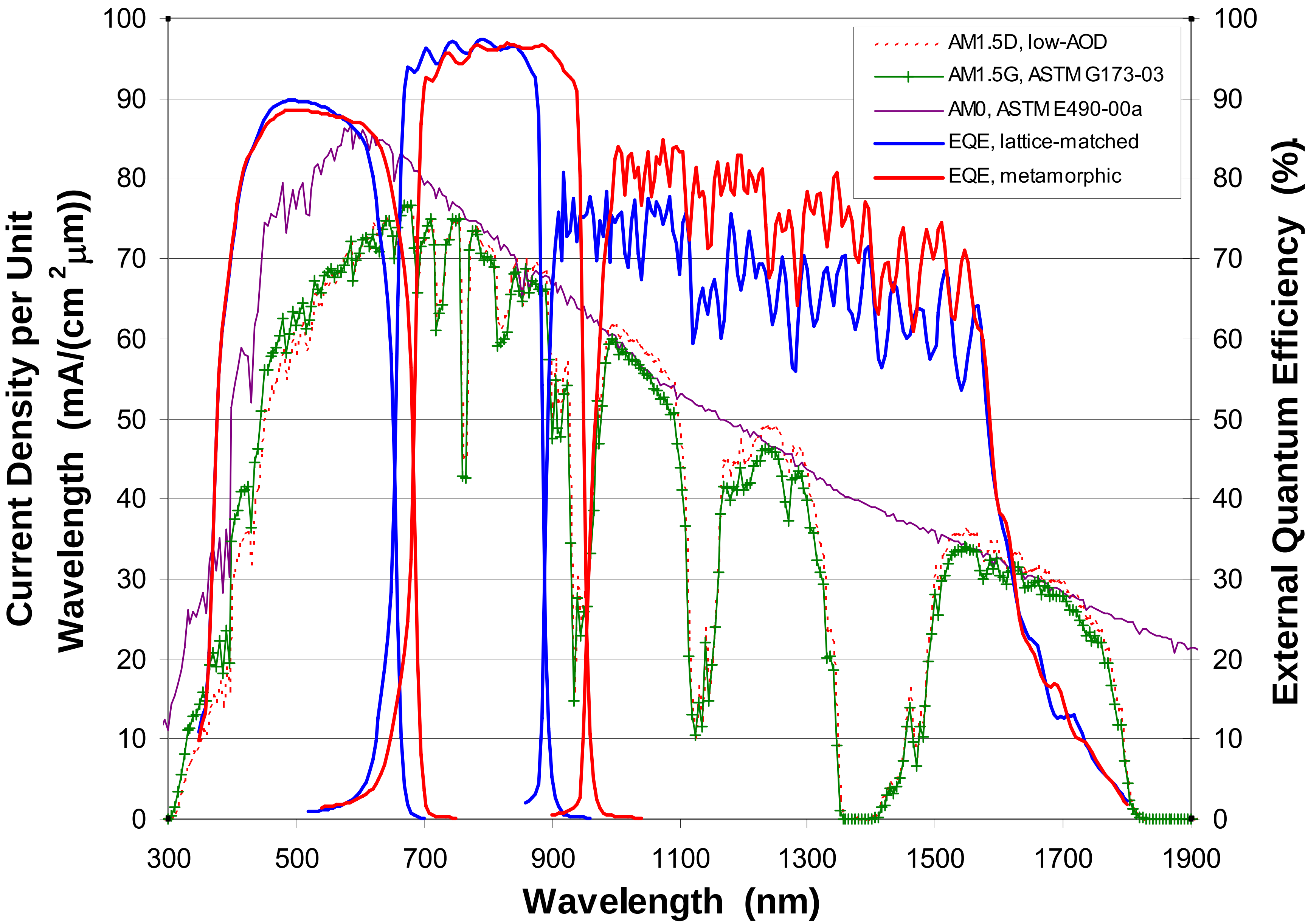


Lattice-Mismatched or Metamorphic (MM)



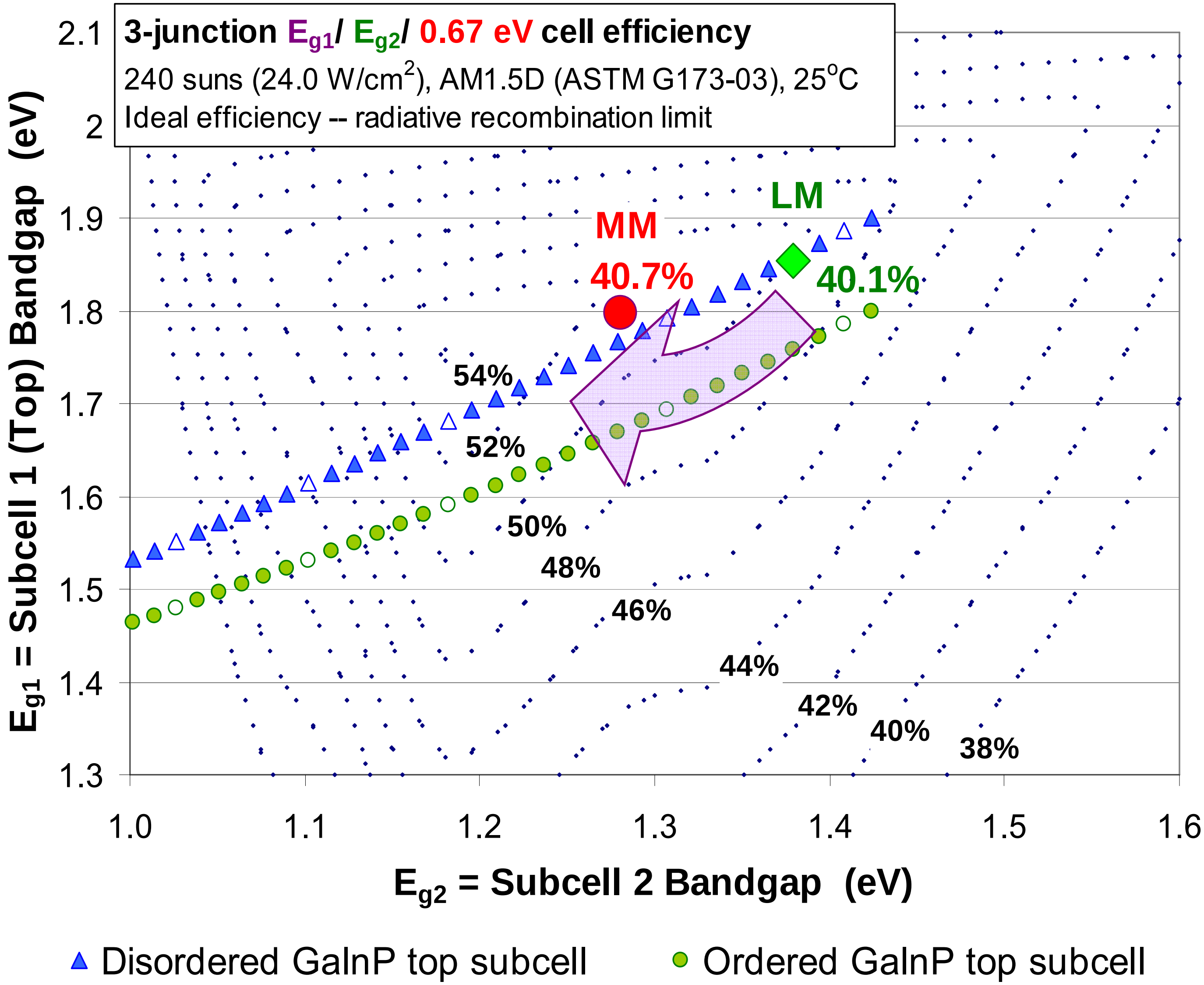
- Metamorphic growth of upper two subcells, GaInAs and GaInP

External QE of LM and MM 3-Junction Cells



R. R. King, Stanford Photonics Research Center Symposium, Stanford, CA, Sep. 14-16, 2009

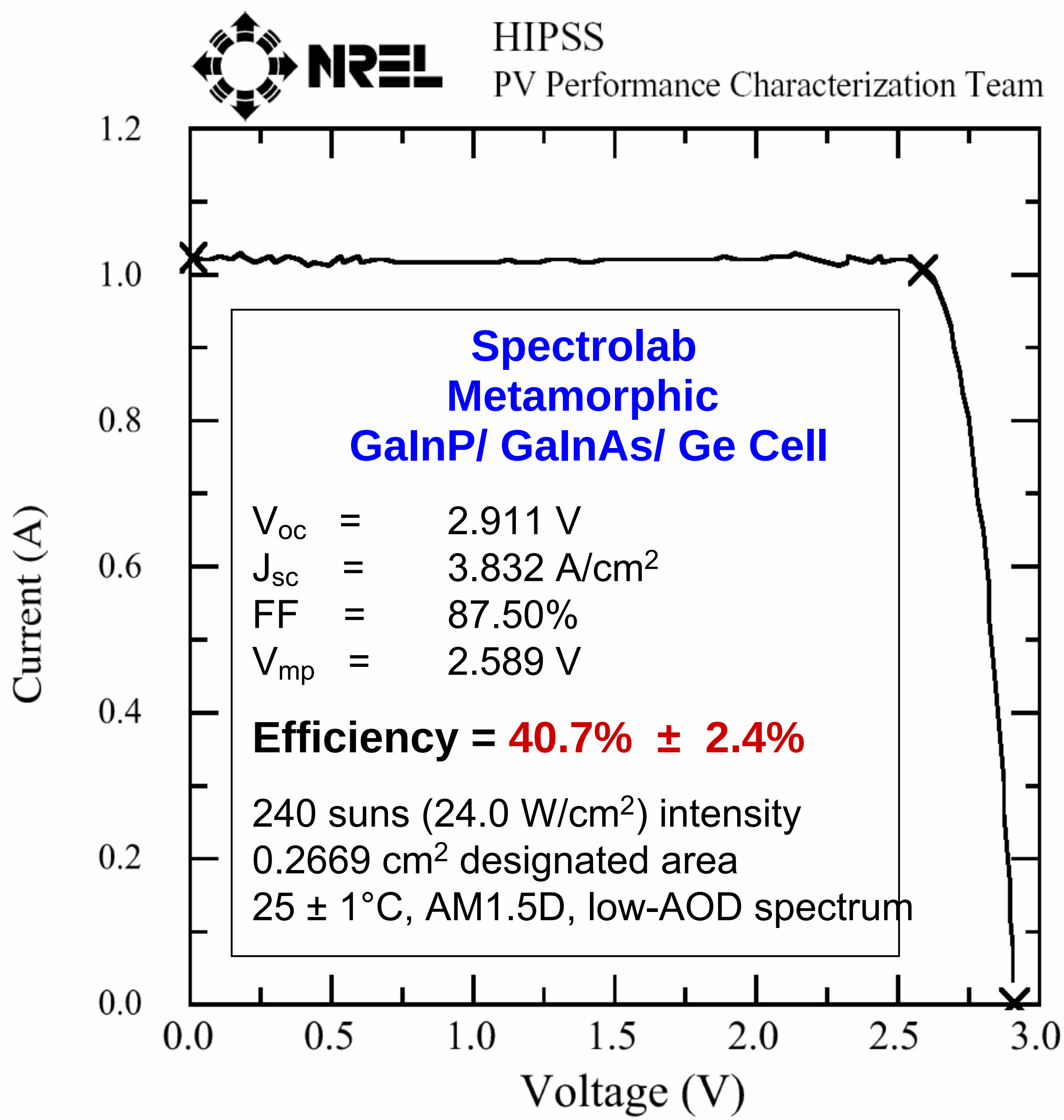
Metamorphic (MM) 3-Junction Solar Cell



- Metamorphic GaInAs and GaInP subcells bring band gap combination closer to theoretical optimum

R. R. King, Stanford Photonics Research Center Symposium, Stanford, CA, Sep. 14-16, 2009

Record 40.7%-Efficient Concentrator Solar Cell

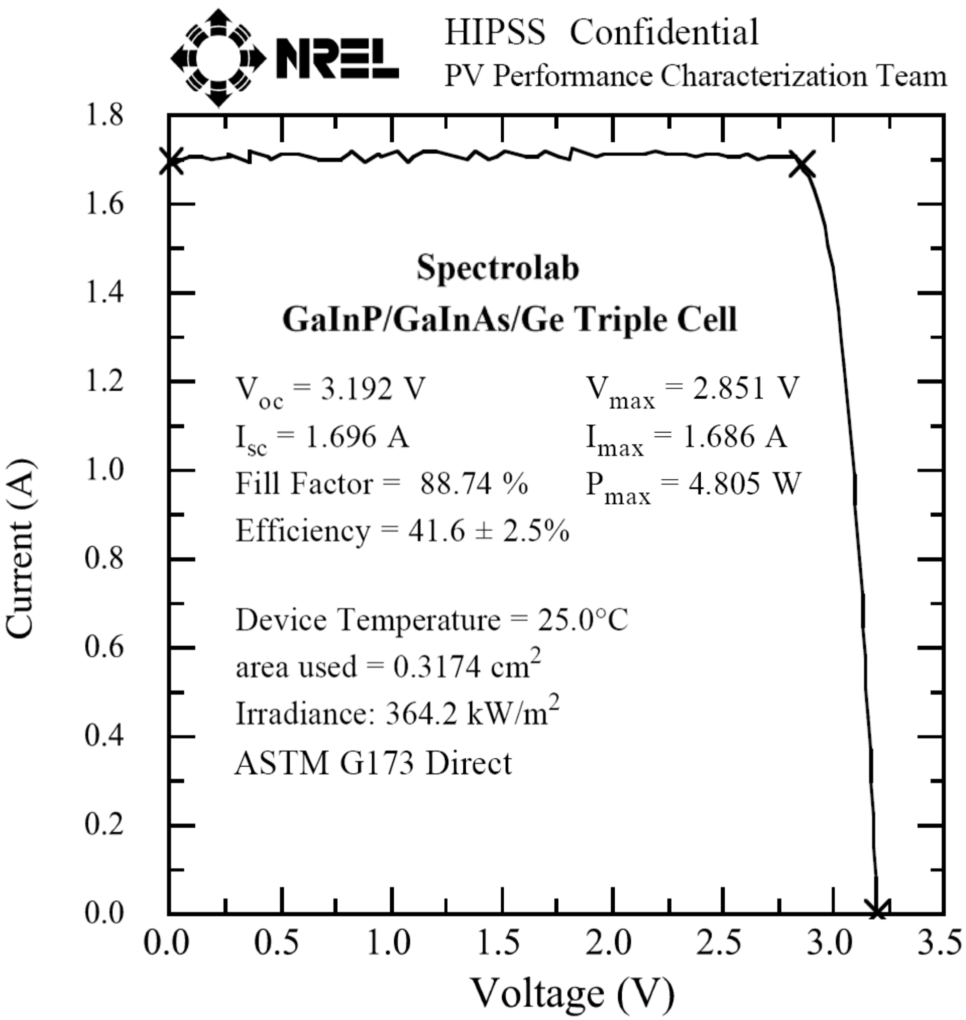


- **First solar cell of any type to reach over 40% efficiency**

Ref.: R. R. King et al., *"40% efficient metamorphic GaInP / GaInAs / Ge multijunction solar cells,"*
Appl. Phys. Lett., ***90****, 183516, 4 May 2007.*

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

New World Record
41.6% Multijunction Solar Cell



Ref.: R. R. King et al., 24th European Photovoltaic Solar Energy Conf., *Hamburg, Germany, Sep. 21-25, 2009.*

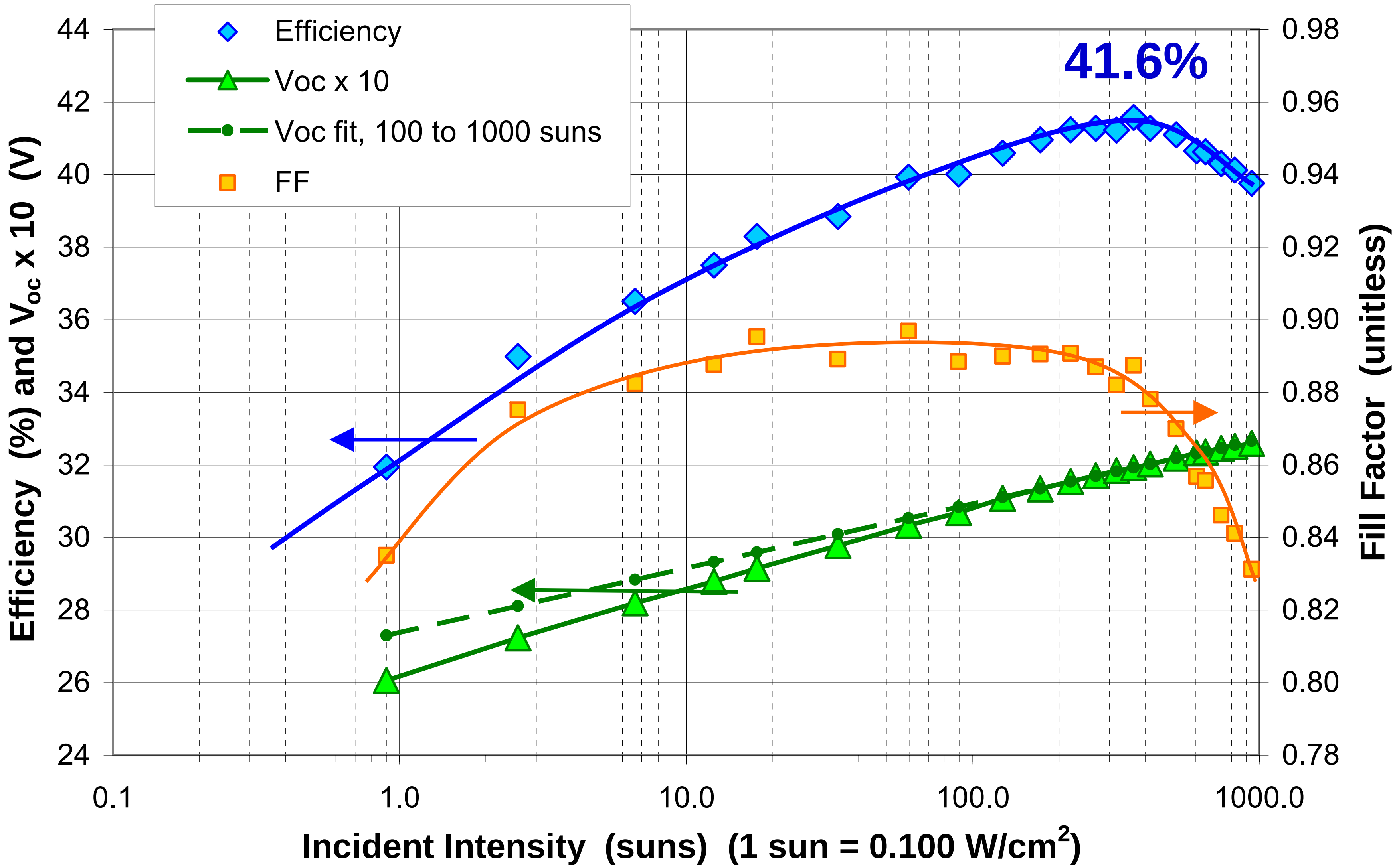
- **41.6% efficiency demonstrated for 3J lattice-matched Spectrolab cell, a new world record**
- **Highest efficiency for any type of solar cell measured to date**
- **Independently verified by National Renewable Energy Laboratory (NREL)**
- **Standard measurement conditions (25°C, AM1.5D, ASTM G173 spectrum) at 364 suns (36.4 W/cm²)**
- **Lattice-matched cell structure similar to C3MJ cell, with reduced grid shadowing as planned for C4MJ cell**
- **Incorporating high-efficiency 3J metamorphic cell structure + further improvements in grid design**
  → strong potential to reach 42-43% champion cell efficiency

Concentrator cell light I-V and efficiency independently verified by C. Osterwald, K. Emery – NREL

SPECTROLAB
A BOEING COMPANY

41.6% Solar Cell
Eff., Voc vs. Concentration

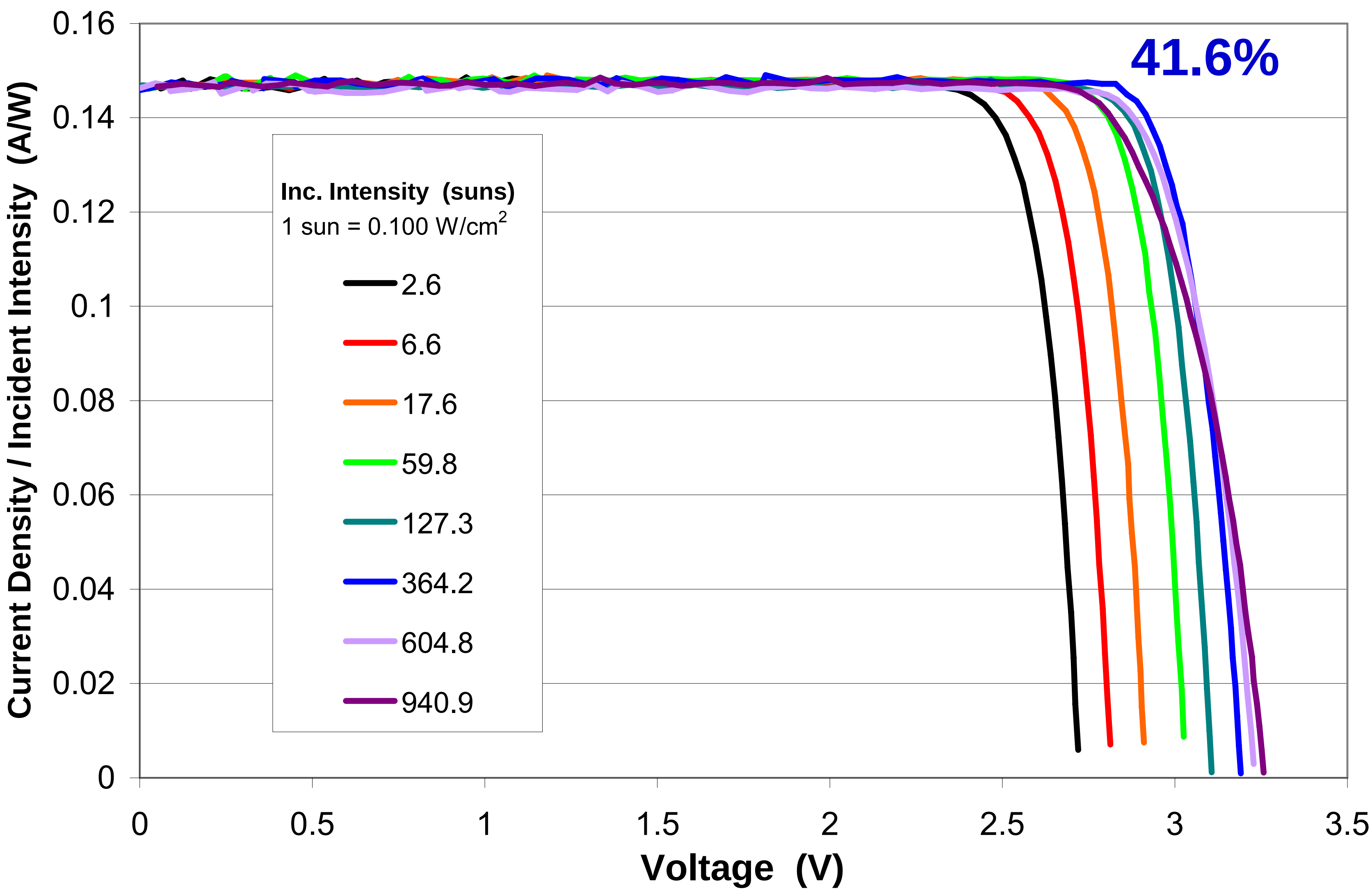
BOEING



- **At peak 41.6% efficiency → 364 suns, Voc = 3.192 V, FF = 0.887**
- **Efficiency still >40% at 820 suns, at 940 suns efficiency is 39.8%**
- **Diode ideality factor of 1.0 for all 3 junctions fits V_{oc} well from 100 to 1000 suns**

R. R. King, Stanford Photonics Research Center Symposium, Stanford, CA, Sep. 14-16, 2009

41.6% Solar Cell LIV Curves vs. Concentration



- **At peak 41.6% efficiency → 364 suns, Voc = 3.192 V, FF = 0.887**
- **Series resistance causes drop in V_{mp} above 400 suns, V_{oc} continues to increase**
- **Efficiency still >40% at 820 suns, at 940 suns efficiency is 39.8%**

Best Research Cell Efficiencies

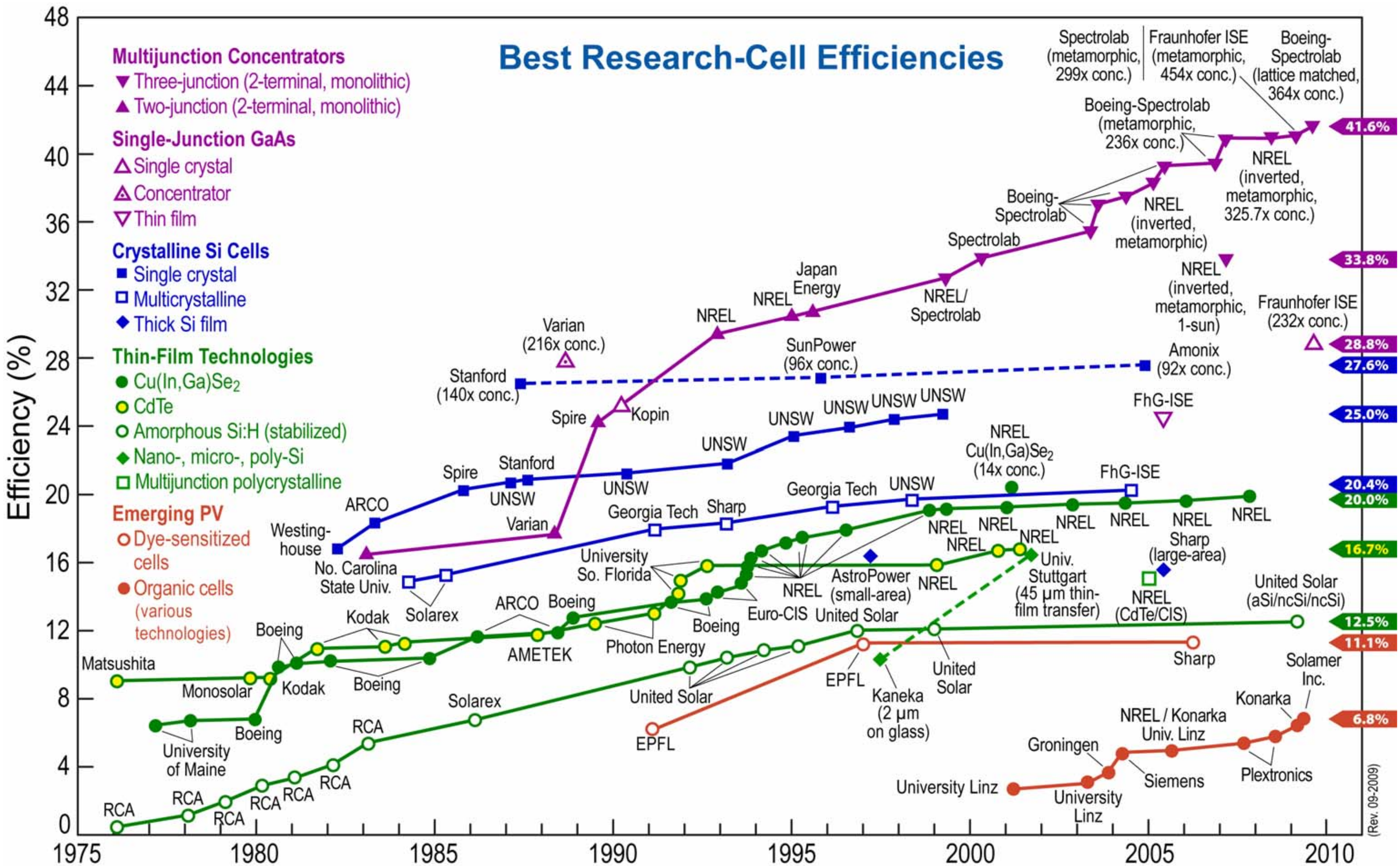
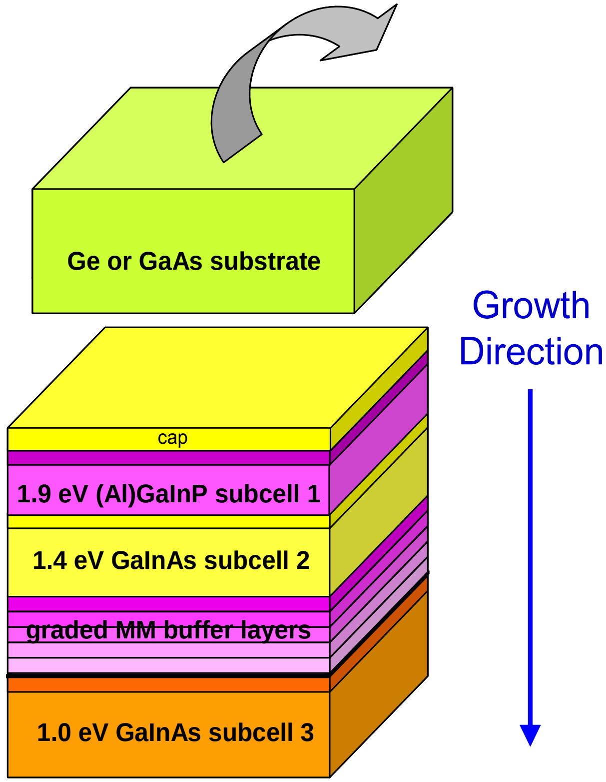
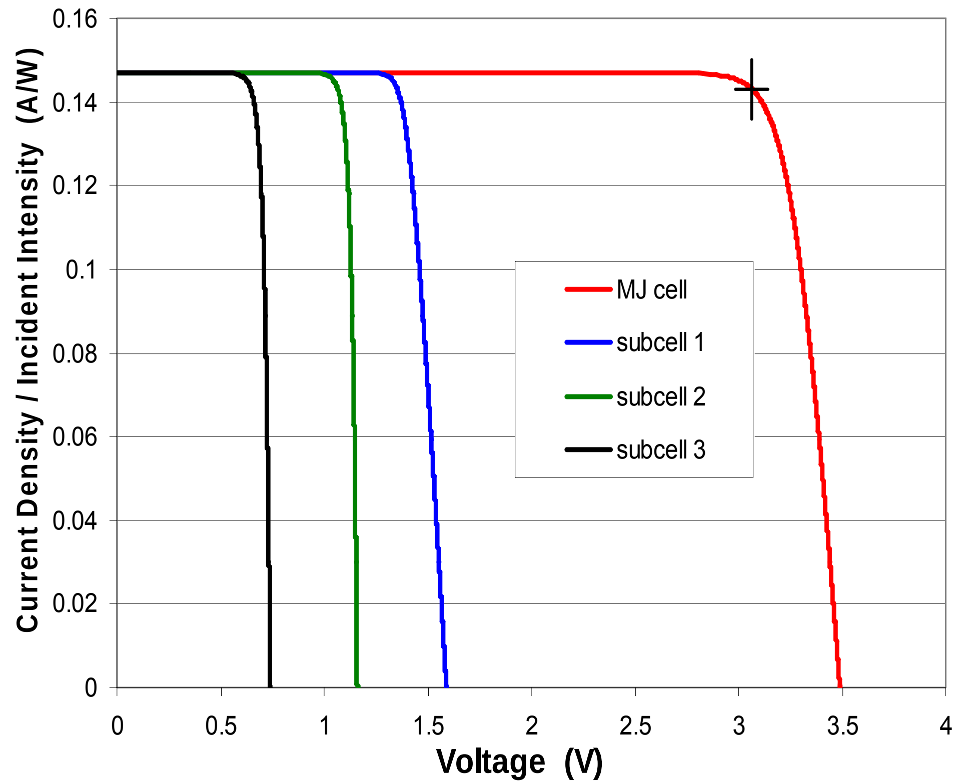


Chart courtesy of Larry Kazmerski, NREL

Inverted Metamorphic (IMM) 3-Junction Cell



Growth on Ge or GaAs substrate, followed by substrate removal from sunward surface

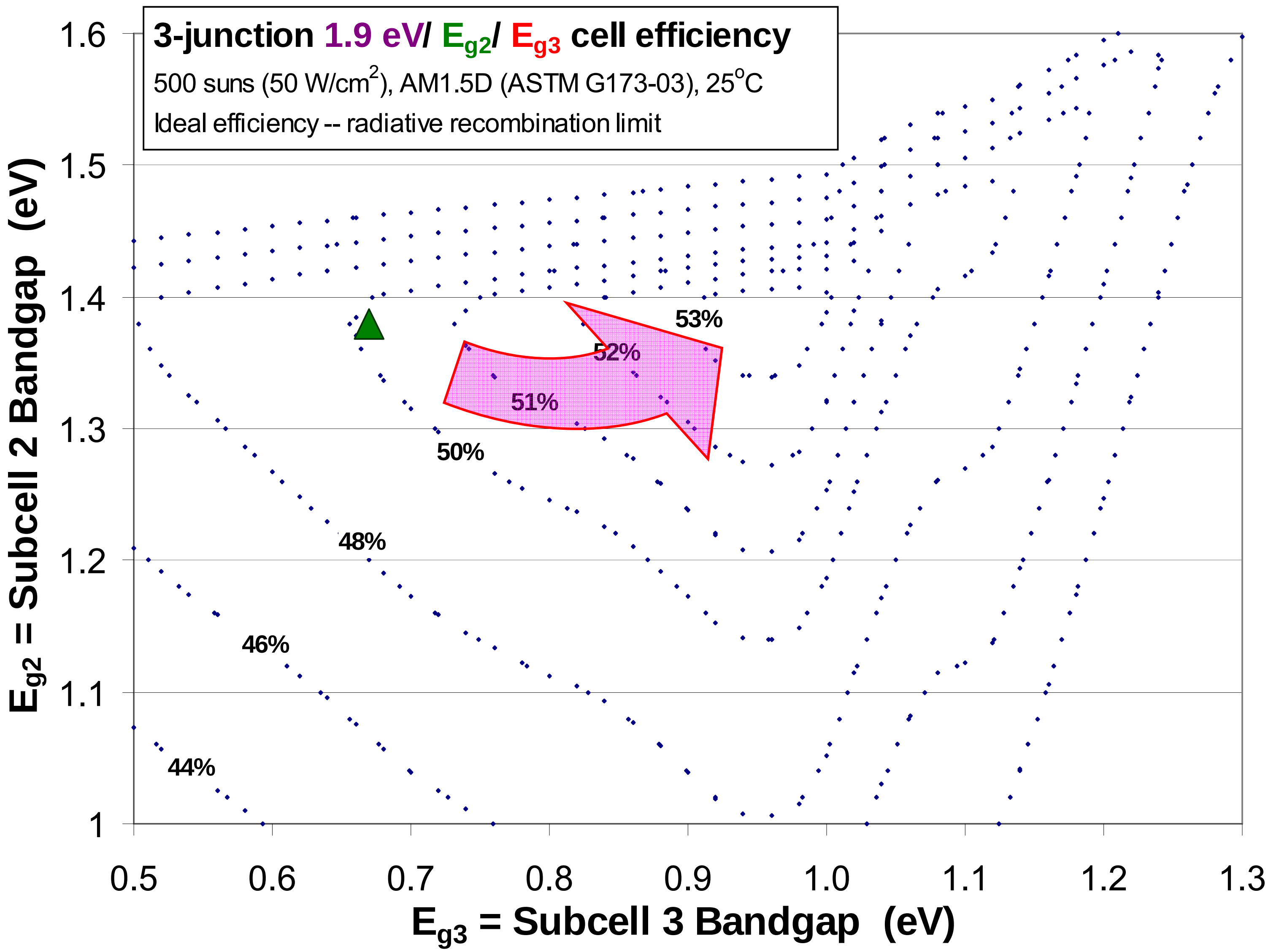


- Bottom ~1-eV GaInAs subcell is inverted and metamorphic (IMM)
- Upper two GaInAs and GaInP subcells are inverted and lattice matched (ILM)

Inverted Metamorphic (IMM) 3-Junction Cell

SPECTROLAB
A BOEING COMPANY

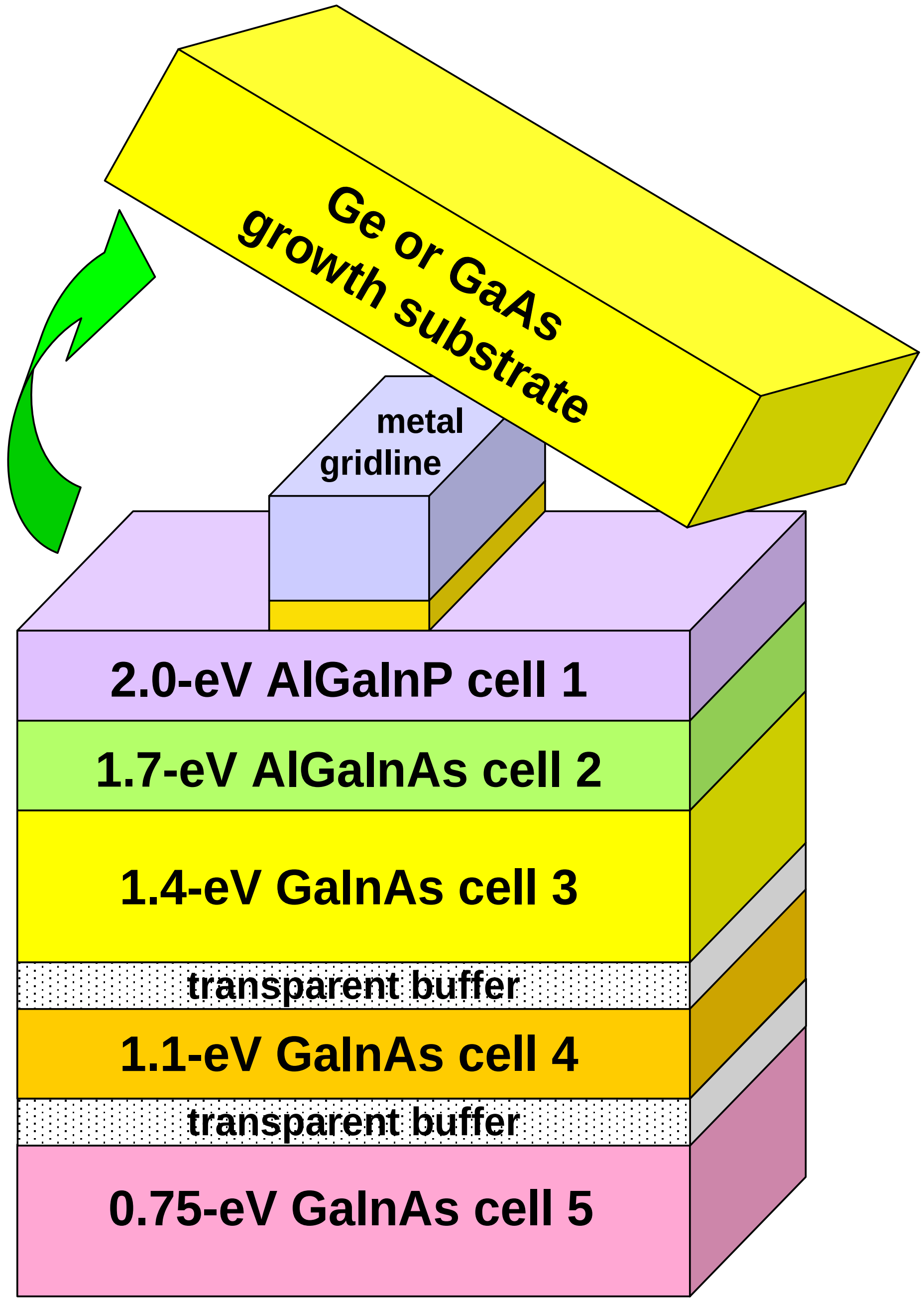
BOEING



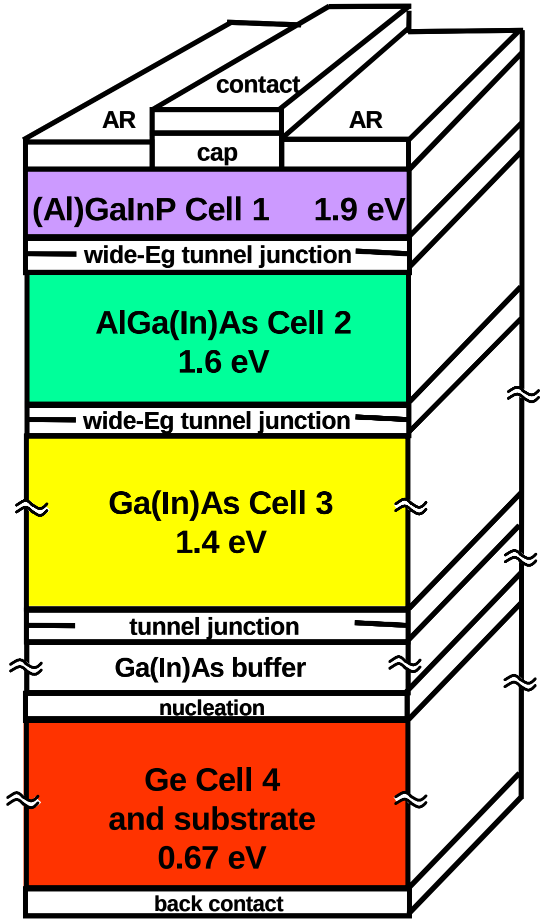
- Raising band gap of bottom cell from 0.67 for Ge to ~1.0 eV for IMM GaInAs raises theoretical 3J cell efficiency

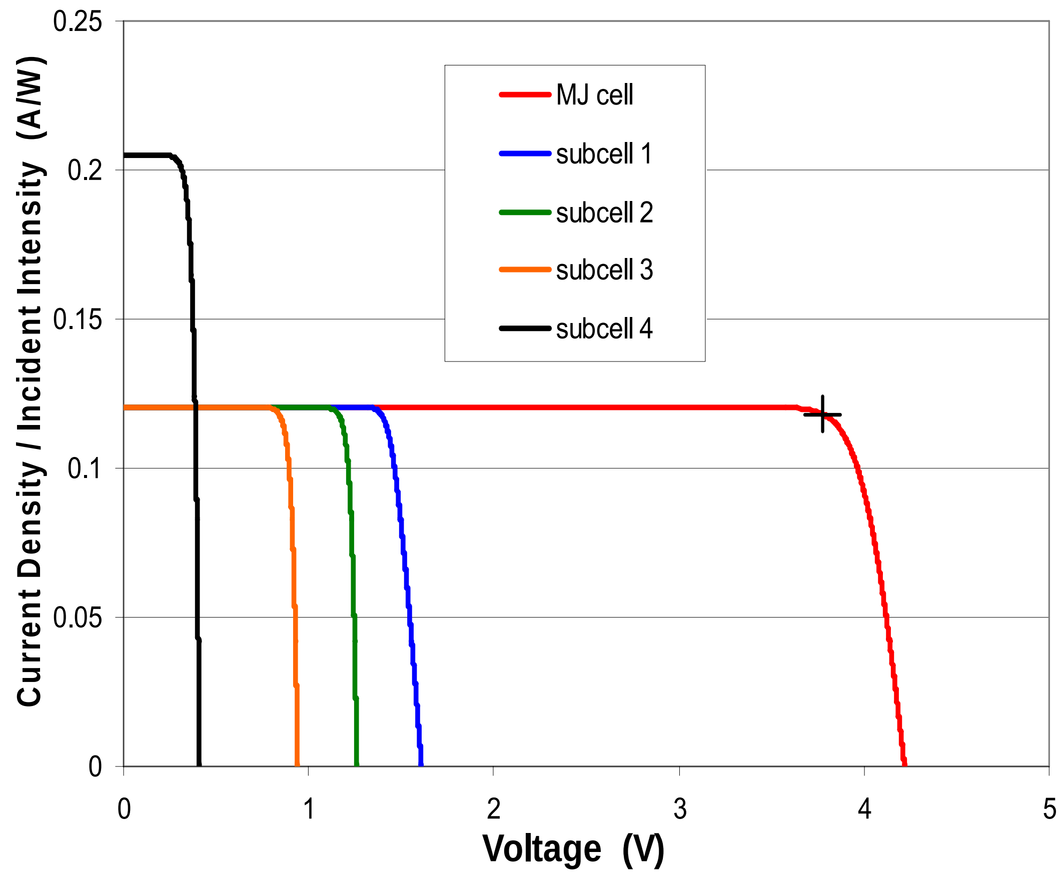
R. R. King, Stanford Photonics Research Center Symposium, Stanford, CA, Sep. 14-16, 2009

5-Junction Inverted Metamorphic (IMM) Cells



4-Junction Lattice-Matched Cell

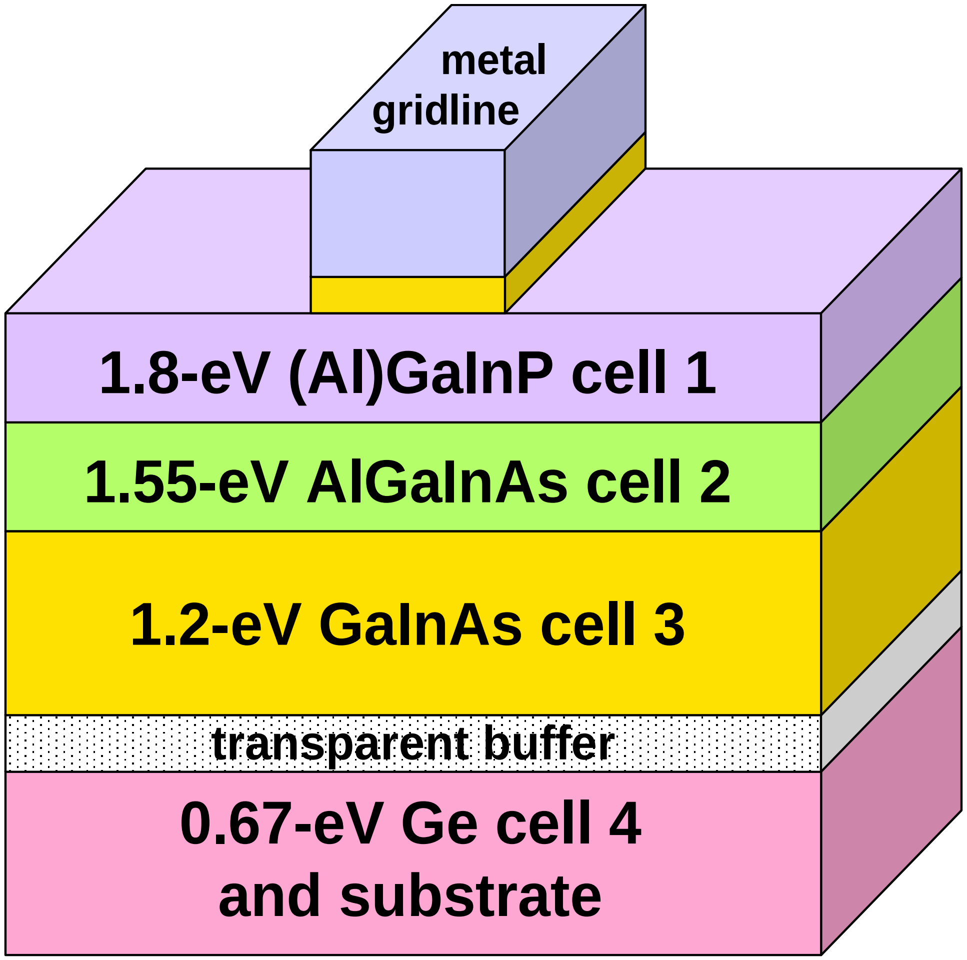




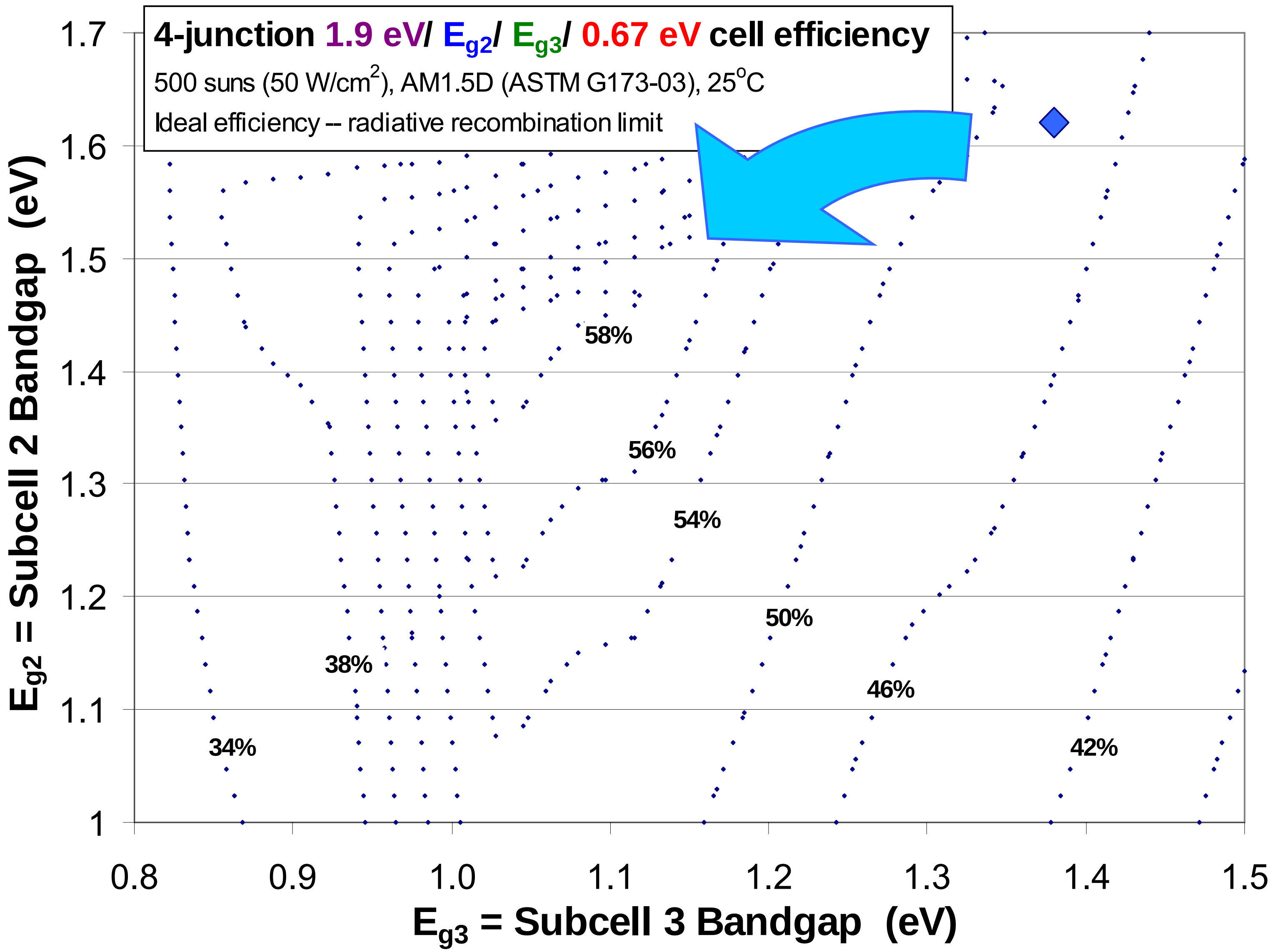
- Current density in spectrum above Ge cell 4 is divided 3 ways among GaInAs, AlGa(In)As, GaInP cells

- Lower current and I^2R resistive power loss

4-Junction Upright Metamorphic (MM) Terrestrial Concentrator Cell



4-Junction Cell
Optimum Band Gap Combinations

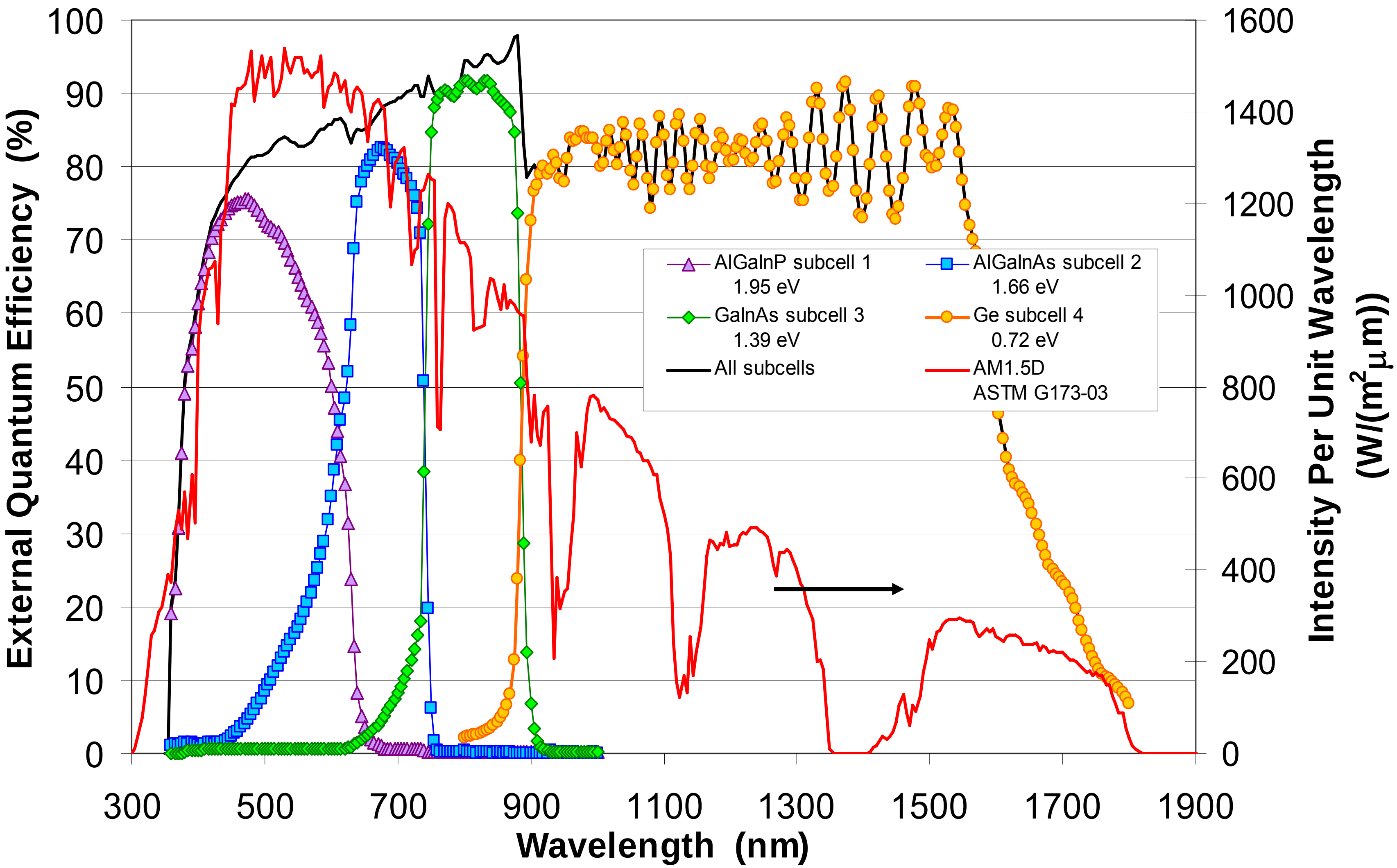


- Lowering band gap of subcells 2 and 3, e.g., with MM materials, gives higher theoretical 4J cell efficiency

Measured 4-Junction Cell Quantum Efficiency

SPECTROLAB
A BOEING COMPANY

BOEING

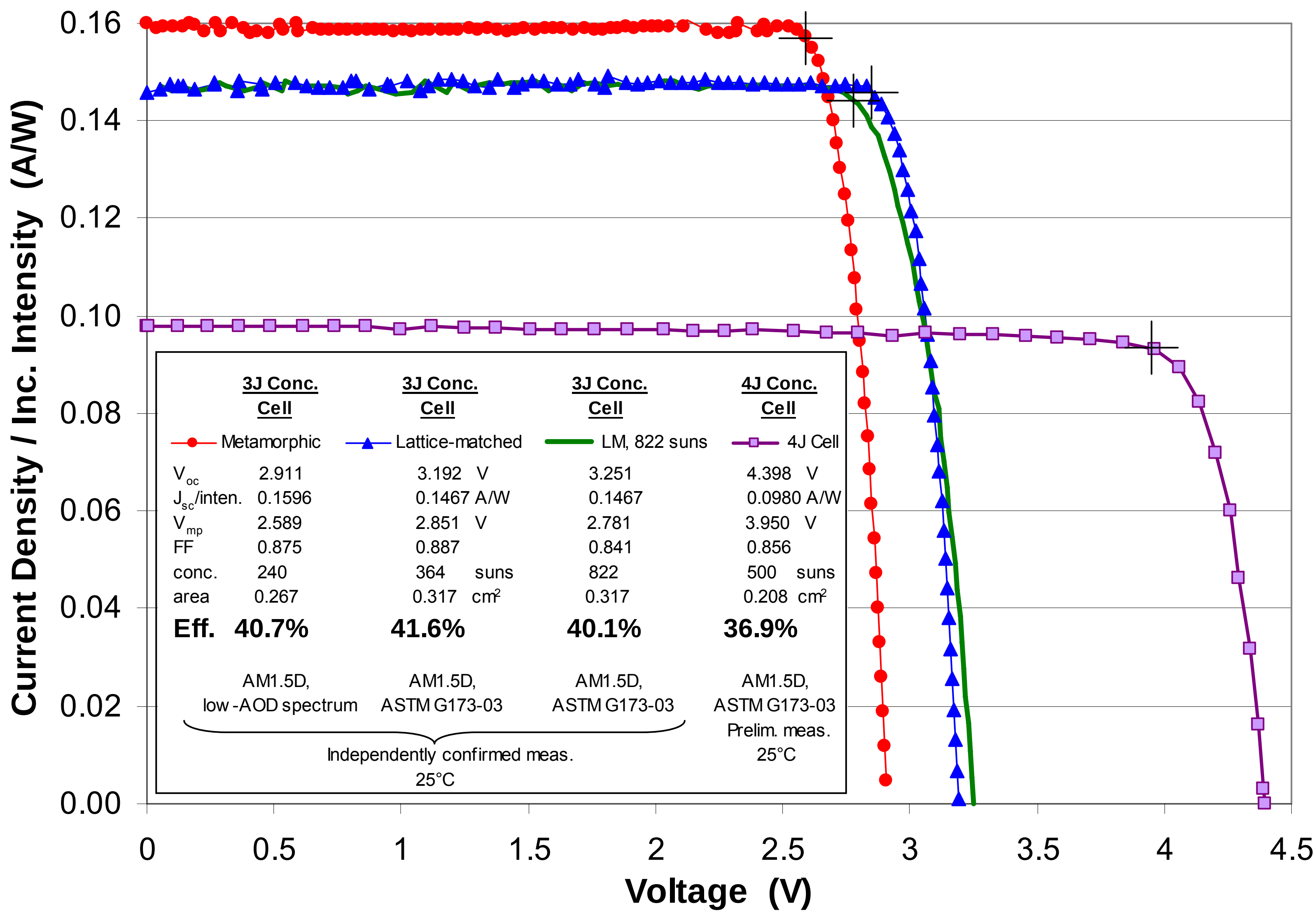


R. R. King, Stanford Photonics Research Center Symposium, Stanford, CA, Sep. 14-16, 2009

SPECTROLAB
A BOEING COMPANY

Light I-V Curves
Record Efficiency Cells

BOEING

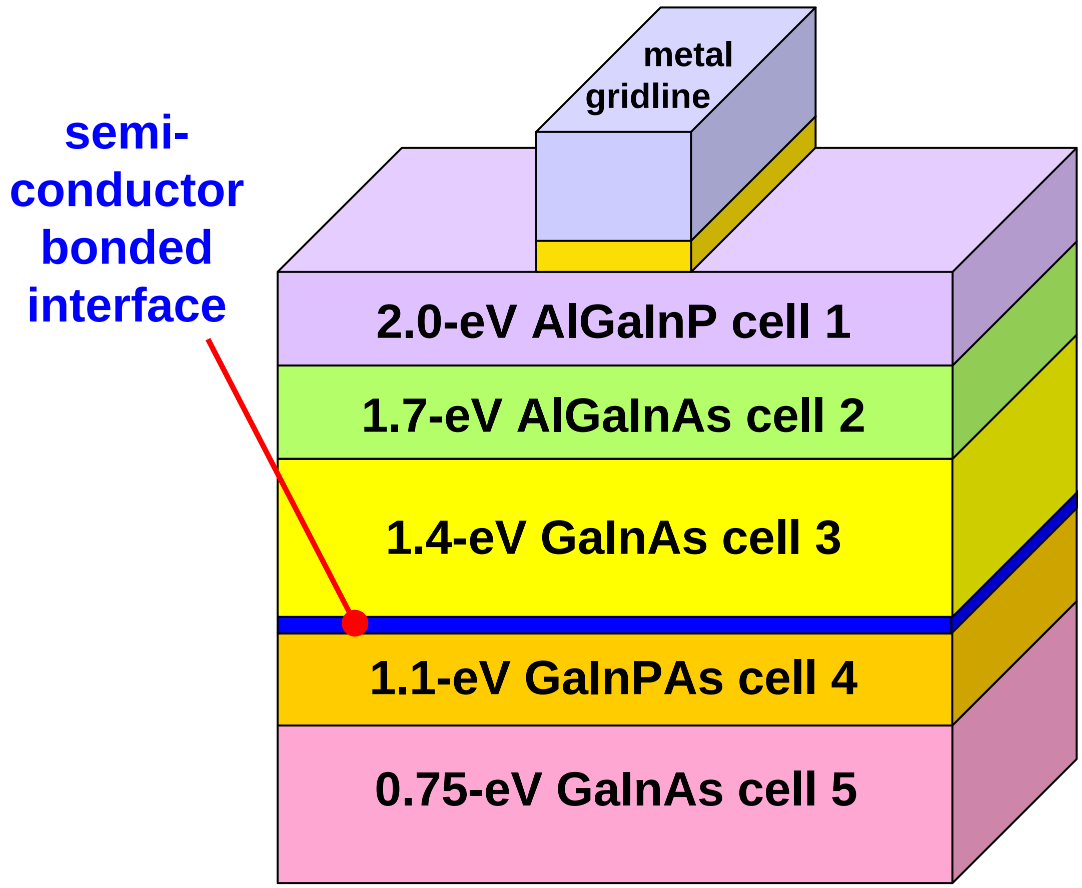


- Light I-V curves for 3-junction upright MM (40.7%), 3J lattice-matched (41.6%), 3J lattice-matched at 822 suns (39.1%), and 4J lattice-matched cell (36.9%)

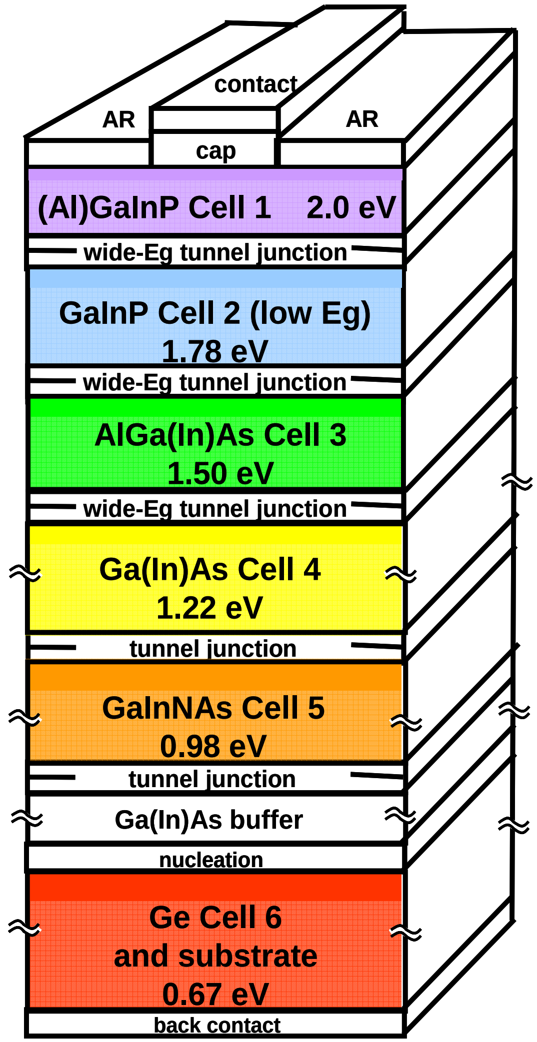
R. R. King, Stanford Photonics Research Center Symposium, Stanford, CA, Sep. 14-16, 2009

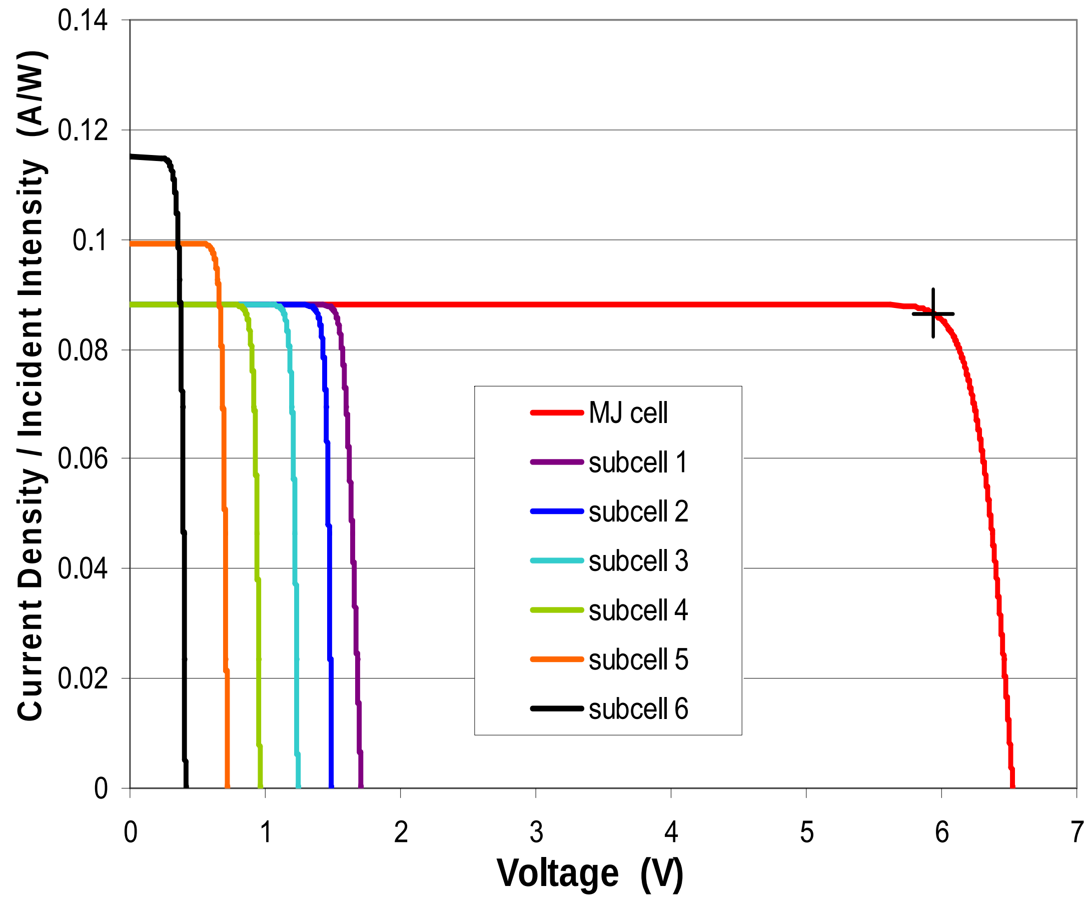
Semiconductor-Bonded Technology (SBT) Terrestrial Concentrator Cell

- **Wafer bonding for multijunction solar cells**
  - Low band gap cells for MJ cells using high-quality, lattice-matched materials
  - Epitaxial exfoliation and substrate removal
  - Formation of lattice-engineered substrate for later MJ cell growth
  - Bonding of high-band-gap and low-band-gap cells after growth
  - Electrical conductance of semiconductor-bonded interface
  - Surface effects for semiconductor-to-semiconductor bonding



6-Junction Solar Cells

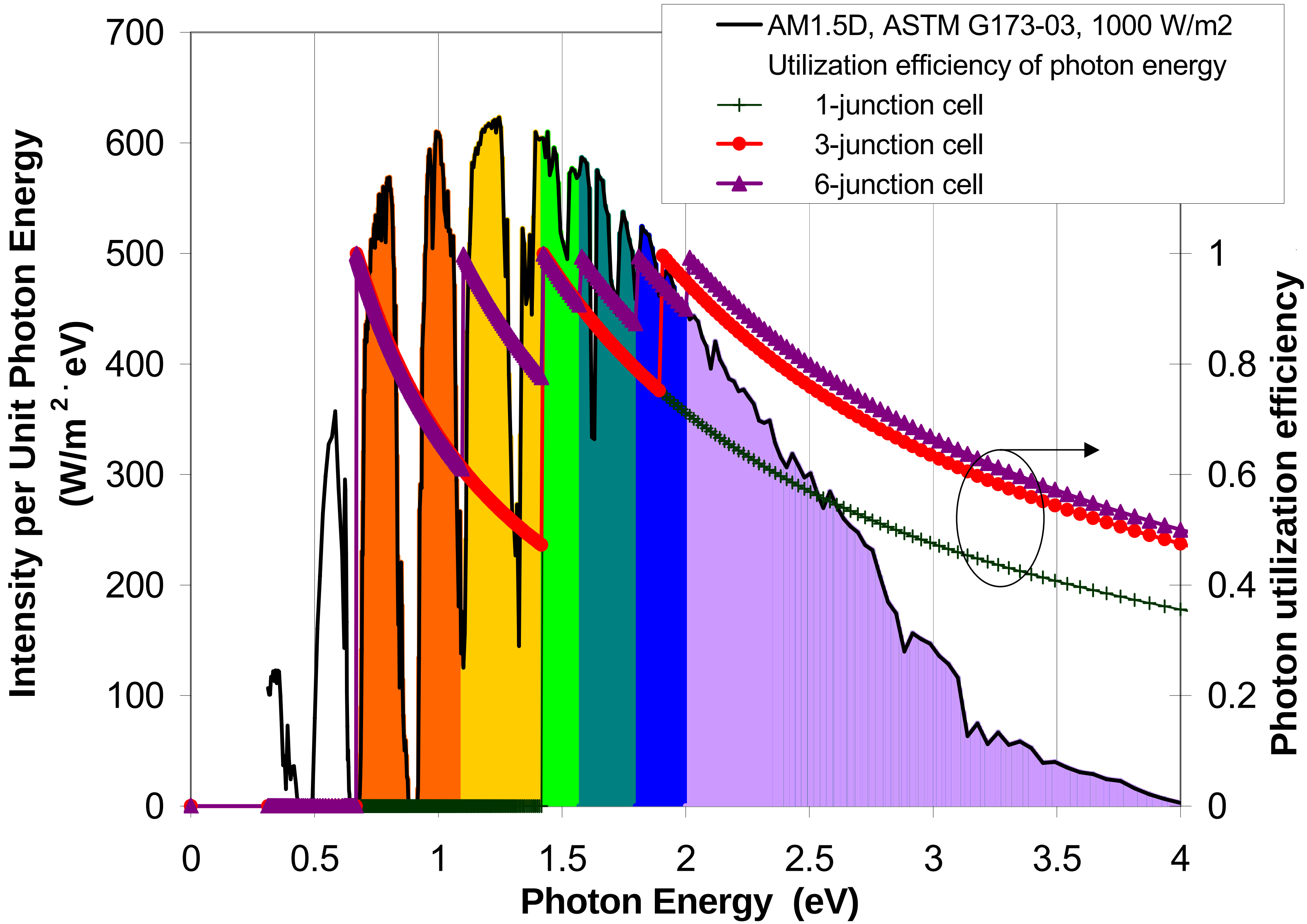




R. R. King, Stanford Photonics Research Center Symposium, Stanford, CA, Sep. 14-16, 2009

Photon Utilization Efficiency
6-Junction Solar Cells

SPECTROLAB
A BOEING COMPANY
BOEING



R. R. King, Stanford Photonics Research Center Symposium, Stanford, CA, Sep. 14-16, 2009

Concentrator Photovoltaic (CPV) Systems

and

Economics

SPECTROLAB

A BOEING COMPANY

Concentrator PV Systems with Multijunction Cells

BOEING

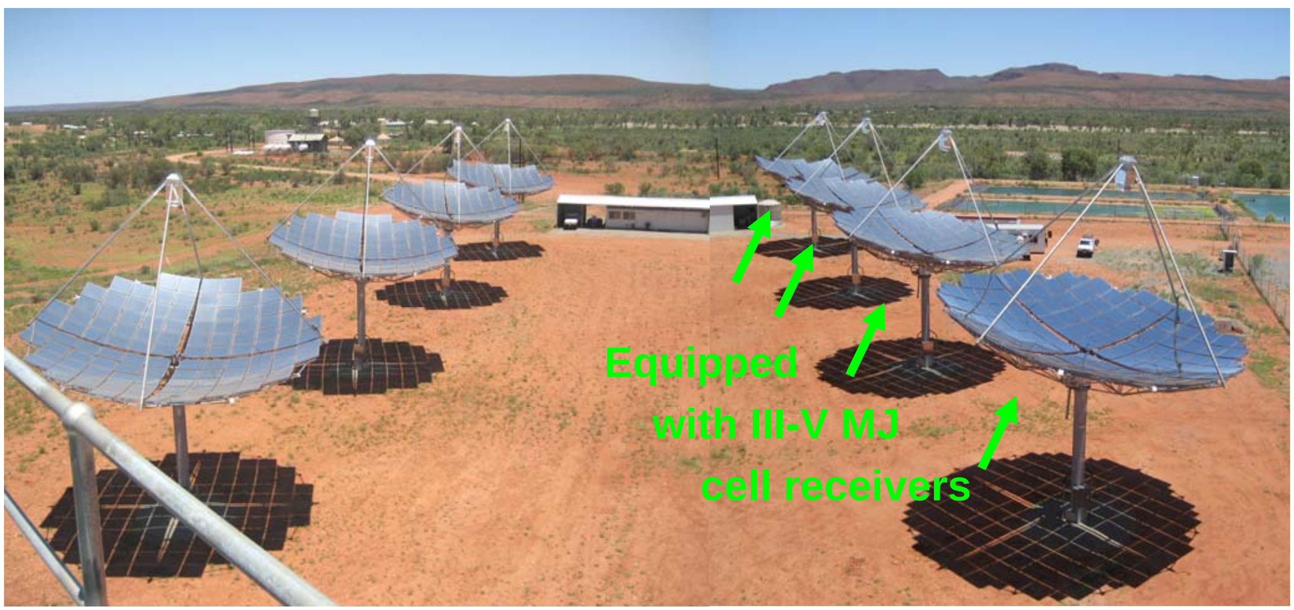
- 1 football field of ~ 17% solar cells at 1-sun produces ~ 500 kW.
- By using MJ cells (> 35%) at concentration of 500 suns, same power is produced from smaller semiconductor area (or the football field produces 500 MW).

Combination of high efficiency & 500X concentration boosts output per semiconductor area by a factor of 1000.

MJ cells are replaced by less expensive optics and common materials.

Leads to reduced cost of energy despite paying extra for tracking & cooling.

Solar Systems, Australia
Hermannsburg Power Station



Courtesy of Solar Systems Pty. Ltd., Australia

- **III-V MJ cells give 56% measured improvement in module efficiency relative to Si concentrator cells**

Balance of System Costs

Courtesy of Solar Systems Pty. Ltd., Australia

Optics

Cooling

Tracking

Structure

Operation and Maintenance

SPECTROLAB
A BOEING COMPANY

Economics for Device Physicists

BOEING

Continuity equation:

$$\frac{\partial \rho}{\partial t} = qG - qR - \nabla \cdot J$$

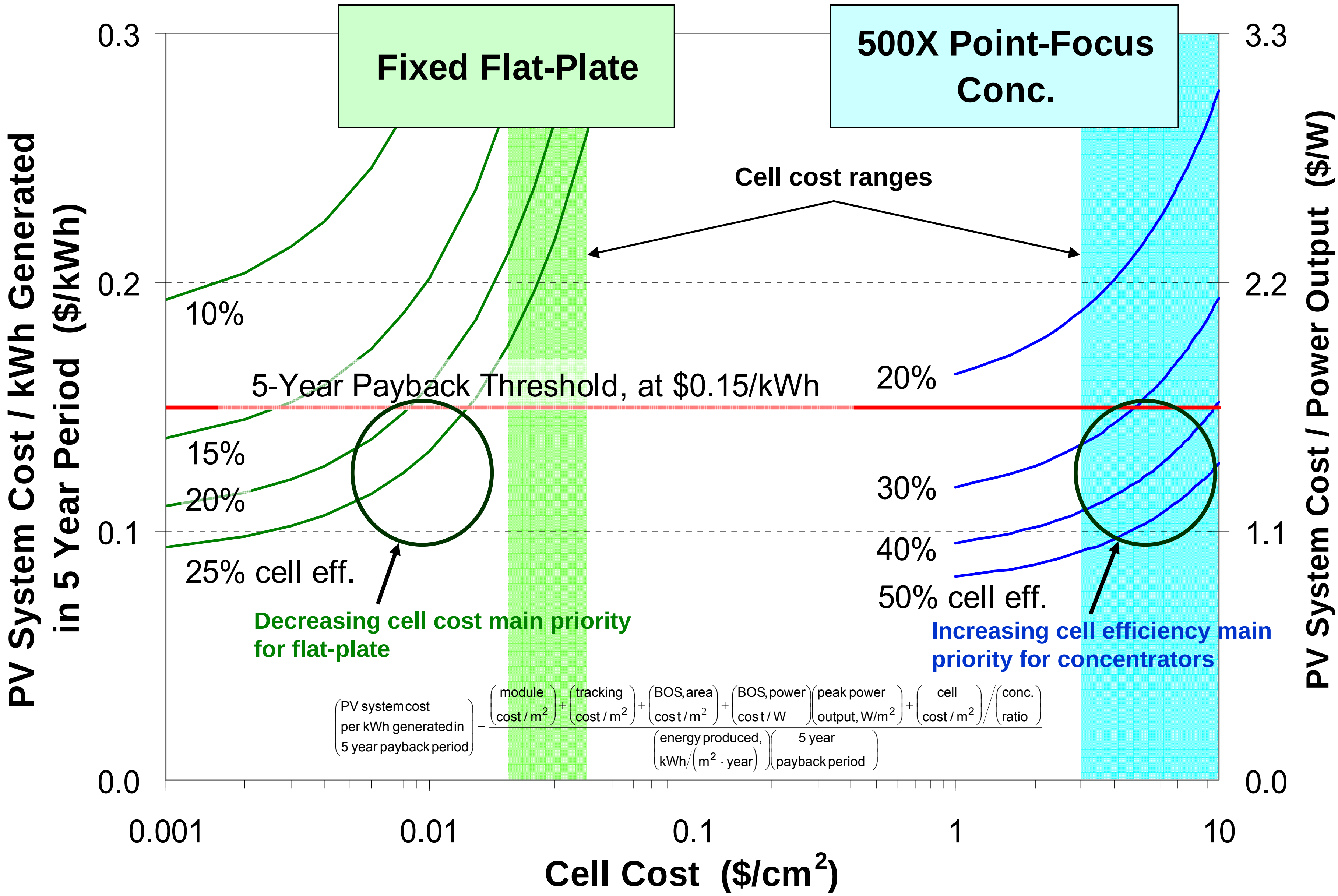
...in $$ rather than charge carriers:

$$\frac{\partial \$\$}{\partial t} = \$\$_{gen} - \$\$_{exp} - \nabla \cdot F_{\$\$}$$

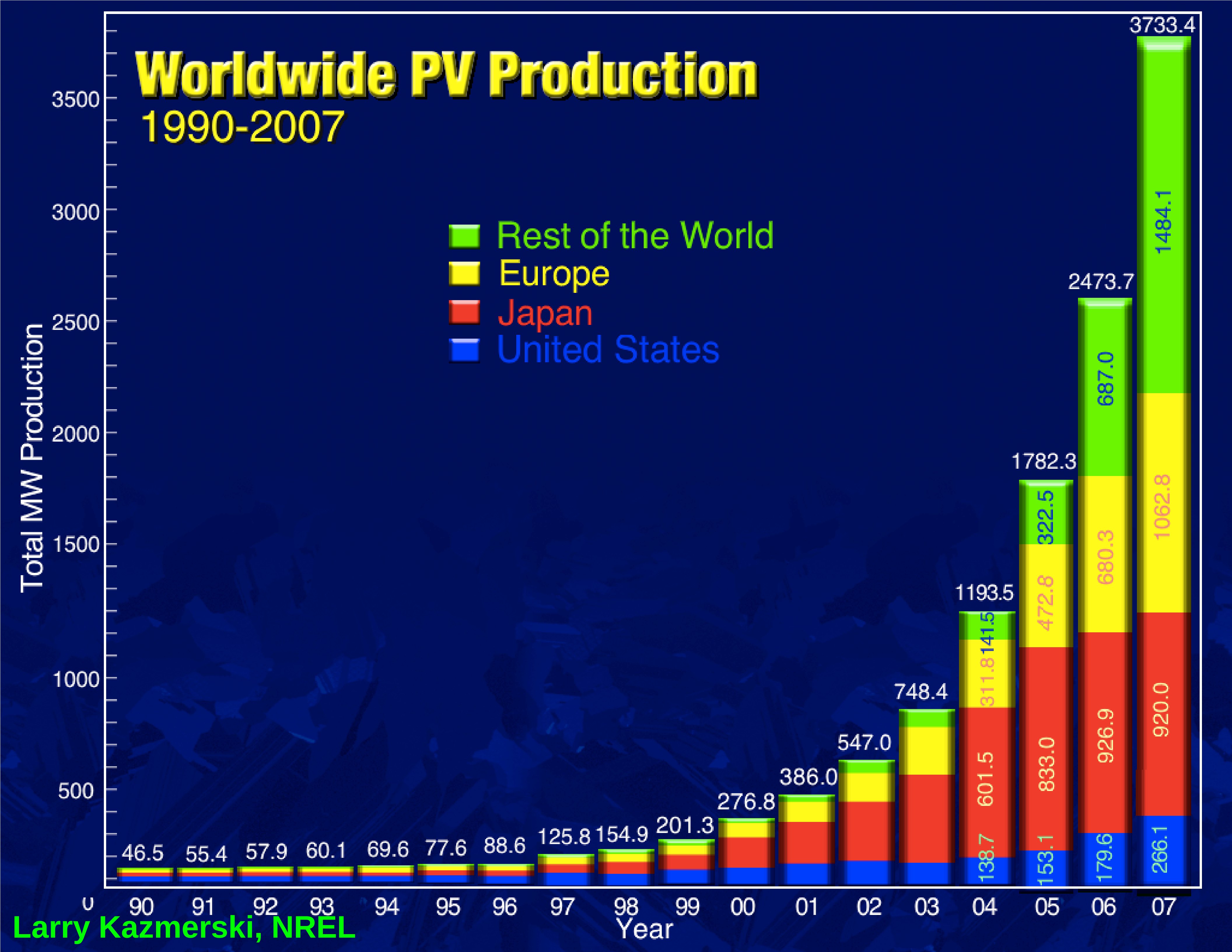
change in value of PV system (profit or loss)	=	value of kWhr generated by PV system	–	operating expenses for PV system	–	funds paid out to bank for interest and principal on loan to buy PV system

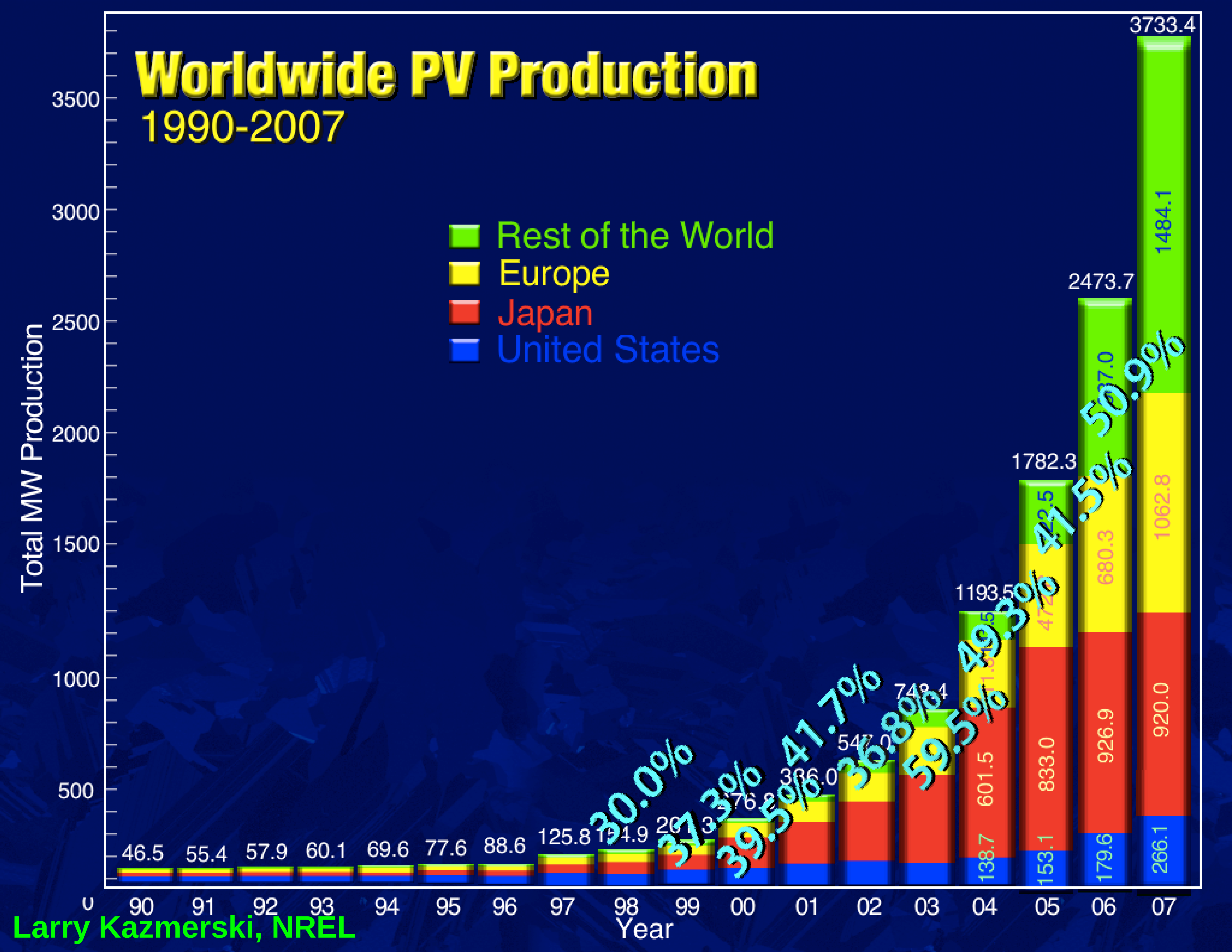
$$\rightarrow \begin{pmatrix} \text{PV system cost} \\ \text{per kWh generated in} \\ \text{5 year payback period} \end{pmatrix} = \frac{\left[\begin{pmatrix} \text{module} \\ \text{cost / m}^2 \end{pmatrix} + \begin{pmatrix} \text{tracking} \\ \text{cost / m}^2 \end{pmatrix} + \begin{pmatrix} \text{BOS, area} \\ \text{cost / m}^2 \end{pmatrix} + \begin{pmatrix} \text{BOS, power} \\ \text{cost / W} \end{pmatrix}\begin{pmatrix} \text{peak power} \\ \text{output, W/m}^2 \end{pmatrix} + \begin{pmatrix} \text{cell} \\ \text{cost / m}^2 \end{pmatrix} \Big/ \begin{pmatrix} \text{conc.} \\ \text{ratio} \end{pmatrix}\right]}{\begin{pmatrix} \text{energy produced,} \\ \text{kWh}/\left(\text{m}^2 \cdot \text{year}\right) \end{pmatrix}\begin{pmatrix} \text{5 year} \\ \text{payback period} \end{pmatrix}}$$

Terrestrial PV System Cost vs. Cell Cost

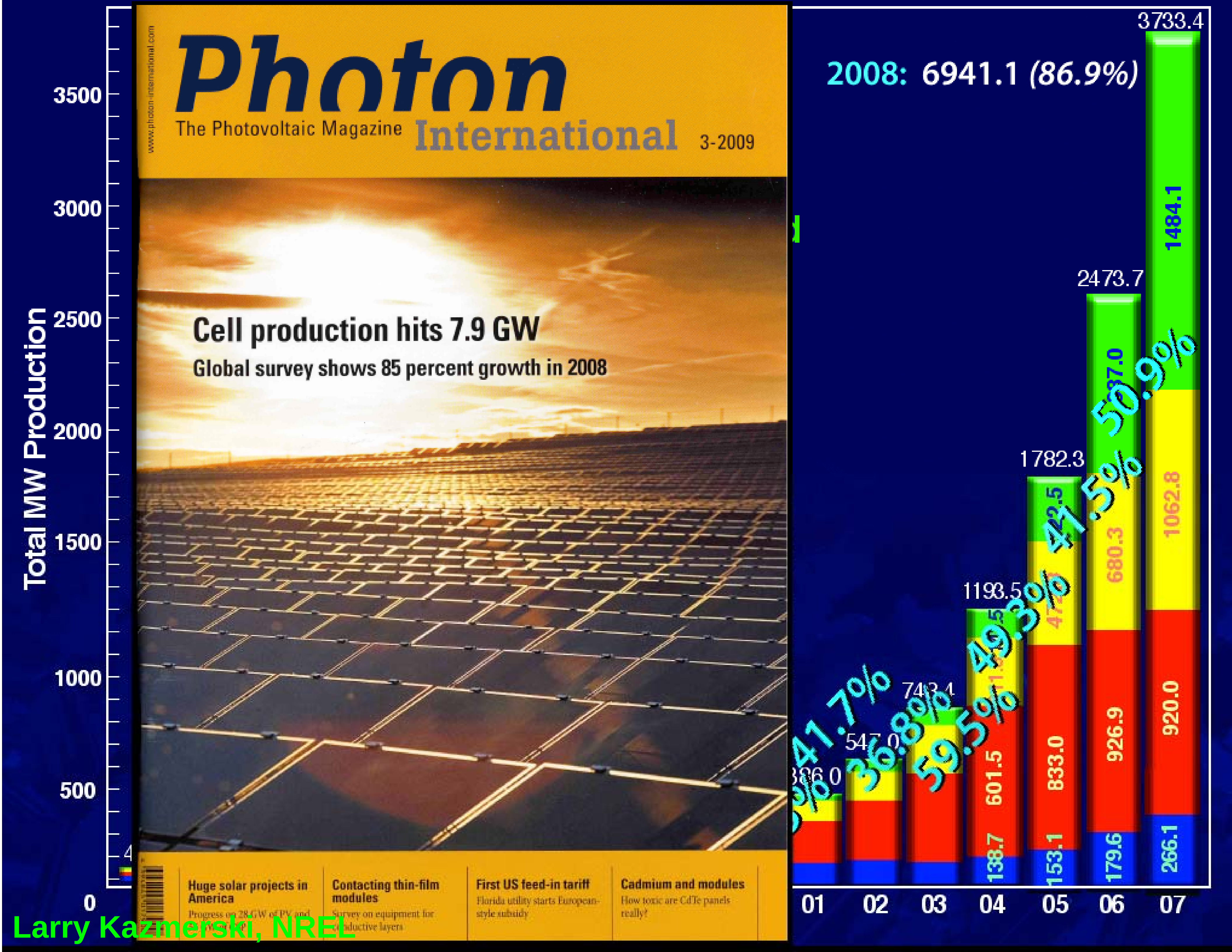


R. R. King et al.*, 3rd Int'l. Conf. on Solar Concentrators (ICSC-3), *Scottsdale, AZ, May 2005


Worldwide PV Production
1990-2007
Rest of the World
Europe
Japan
United States
Total MW Production
3500
3000
2500
2000
1500
1000
500
0
46.5
55.4
57.9
60.1
69.6
77.6
88.6
125.8
154.9
201.3
276.8
386.0
547.0
748.4
1193.5
1782.3
2473.7
3733.4
138.7
601.5
311.8
141.5
153.1
833.0
472.8
322.5
179.6
926.9
680.3
687.0
266.1
920.0
1062.8
1484.1
90
91
92
93
94
95
96
97
98
99
00
01
02
03
04
05
06
07
Year
Larry Kazmerski, NREL



Worldwide PV Production
1990-2007
Rest of the World
Europe
Japan
United States
Total MW Production
Year
500
1000
1500
2000
2500
3000
3500
90
91
92
93
94
95
96
97
98
99
00
01
02
03
04
05
06
07
46.5
55.4
57.9
60.1
69.6
77.6
88.6
125.8
386.0
1193.5
1782.3
2473.7
3733.4
30.0%
37.3%
39.5%
41.7%
36.8%
59.5%
49.3%
41.5%
50.9%
138.7
601.5
153.1
833.0
179.6
926.9
680.3
266.1
920.0
1062.8
1484.1
Larry Kazmerski, NREL



Photon
The Photovoltaic Magazine
International
3-2009
www.photon-international.com
Cell production hits 7.9 GW
Global survey shows 85 percent growth in 2008
Huge solar projects in America
Contacting thin-film modules
Survey on equipment for conductive layers
First US feed-in tariff
Florida utility starts European-style subsidy
Cadmium and modules
How toxic are CdTe panels really?
Total MW Production
0
500
1000
1500
2000
2500
3000
3500
2008: 6941.1 (86.9%)
01
02
03
04
05
06
07
547.0
743.4
1193.5
1782.3
2473.7
3733.4
41.7%
36.8%
59.5%
49.3%
41.5%
50.9%
601.5
138.7
833.0
153.1
926.9
179.6
680.3
1062.8
920.0
266.1
1484.1
Larry Kazmerski, NREL

Summary

- **Urgent global need to address carbon emission, climate change, and energy security concerns → renewable electric power can help**
- **Theoretical solar conversion efficiency**
  - Examining built-in assumptions points out opportunities for higher PV efficiency
  - Multijunction architectures, up/down conversion, quantum structures, intermediate bands, hot-carrier effects, solar concentration → higher η
  - Theo. solar cell **η > 70%,** practical **η > 50%** achievable
- **Metamorphic multijunction cells have begun to realize their promise**
  - Metamorphic semiconductors offer vastly expanded **palette** of band gaps
  - **40.7%** metamorphic GaInP/ GaInAs/ Ge 3J cells demonstrated
  - First solar cells of any type to reach over 40% efficiency
- **New world record efficiency of 41.6% demonstrated**
  - Highest efficiency yet measured for any type of solar cell
  - 41.6% efficiency independently verified at NREL (364 suns, 25°C, AM1.5D)
- **Solar cells with efficiencies in this range can transform the way we generate most of our electricity, and make the PV market explode**