New Frontiers in Solar Cell Conversion Efficiency

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Acknowledgments

- Spectrolab has a 52-year company heritage and has been a leader in solar technology throughout the entire history of the solar industry
- The recent achievement of >40% conversion efficiency is the result of those decades of effort and the work of a collaborative development team including:
  - Richard King, Nasser Karam, Kent Barbour, Hector Cotal, Dhananjay Bhusari, Mark Takahashi, Andrey Masalykin, and the entire multijunction solar cell team at Spectrolab
  - Martha Symko-Davies, Fannie Posey-Eddy, Robert McConnell, Larry Kazmerski, Keith Emery, James Kiehl, Tom Moriarty – NREL
  - Rosina Bierbaum – University of Michigan, Ann Arbor

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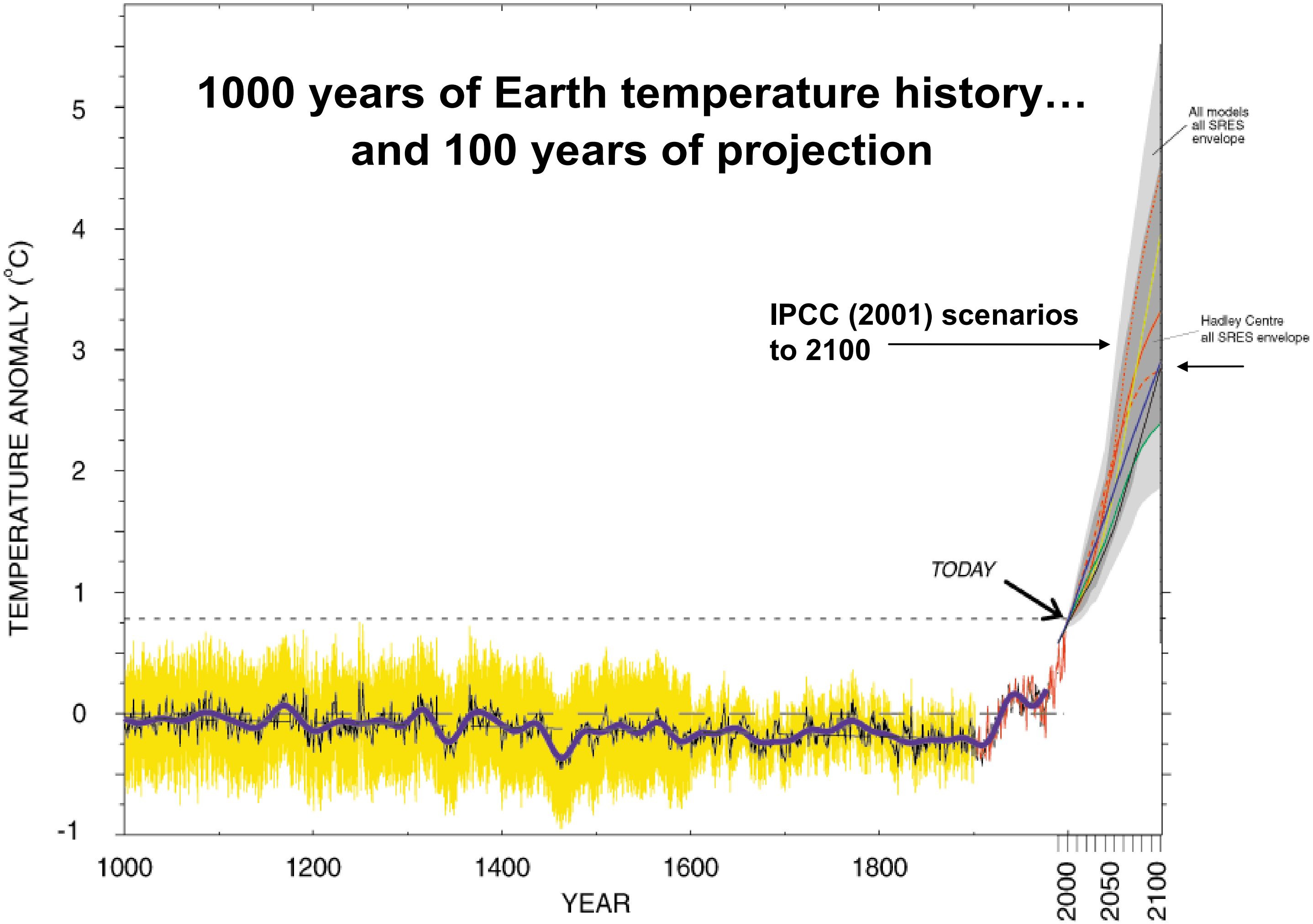
Thank You !

Temperature Anomaly by Year



Rosina Bierbaum, Univ. of Michigan, IPCC

R. R. King, 51st Electronic Materials Conf., University Park, Pennsylvania, June 24-26, 2009

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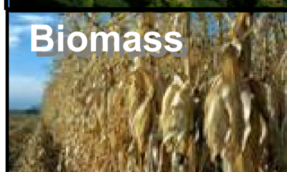
Renewable Energy Solutions are Technology-Driven

Today:
Renewables (other than hydro) are 2% of world electricity generation

Tomorrow:
Technology and market forces will transform renewables from niche to mainstream

- ✓ High capital cost but zero fuel cost
- × Limited availability

- ✓ High capital cost but zero fuel cost
- × Limited availability



- × Land and H_2O intensive
- × Subject to drought
- ✓ Produces liquid fuels for mobility

- ✓ Historically high but rapidly falling cost
- ✓ Ubiquitous and abundant

Aerospace technologies
- **Airfoils**
- **Efficient motors**

Oil & Gas Technology
- **Drilling**
- **Heat injection**

Biotechnology
- **Agricultural**
- **Genetic engineering**

Electronics technologies
- **Semiconductors**
- **Optics**

Climate change and the end of cheap oil are forces transforming the energy economy from an era where waste was often the most economical solution to one in which efficiency is an economic driver

PV Technology Options

Flat plates

~94% of today's market

Crystalline silicon
- Single crystal
- Polycrystalline

Thin films
- CdTe
- Amorphous Si
- $CuInGaSe_2$

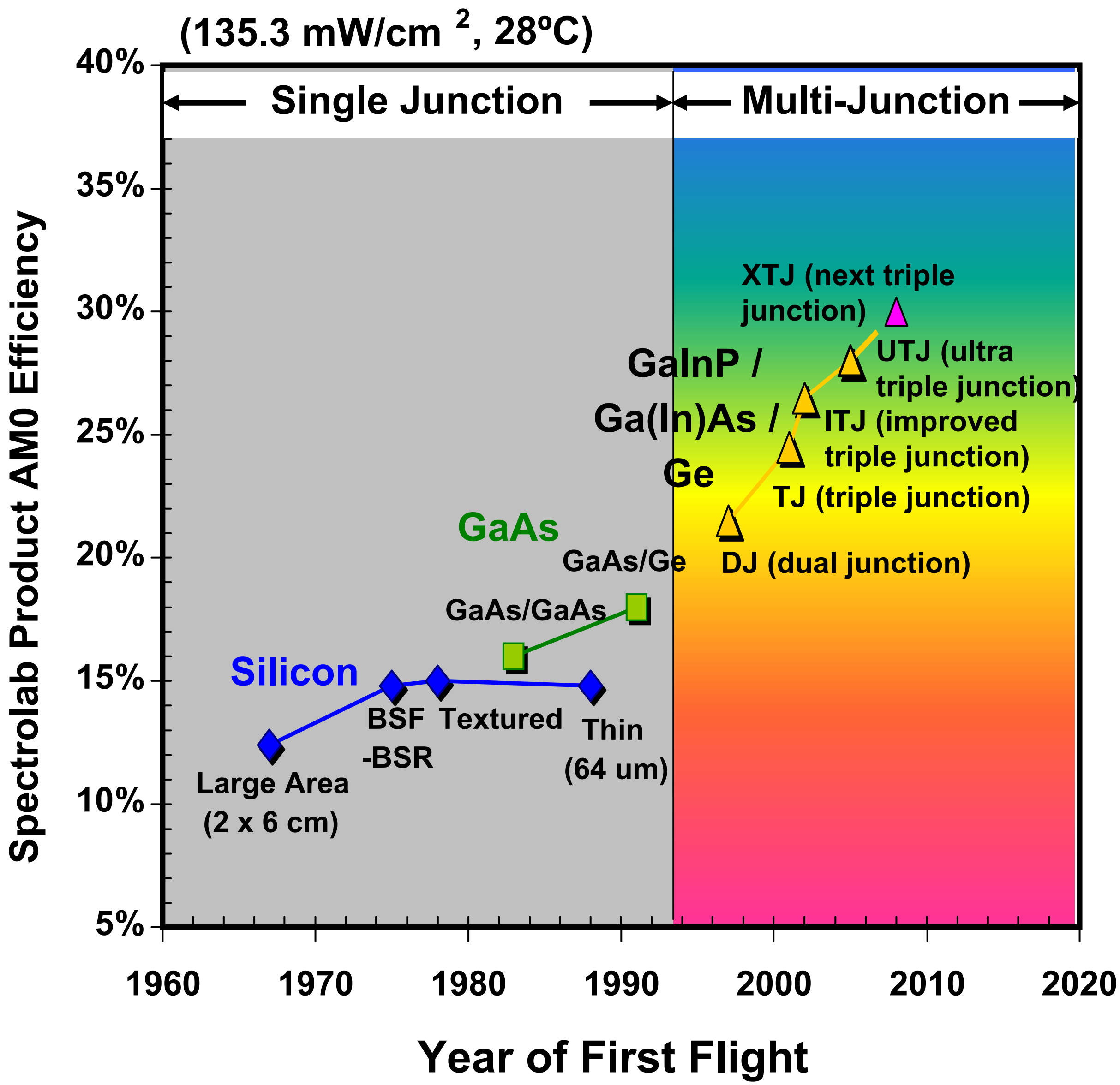
New technologies
- Organic
- Multiple others

Concentrators

Silicon
- Linear focus
- Point focus
- 2–200x

Multijunctions (III-Vs)
- Point focus
- 250 to >1000x

Spectrolab Space PV Leadership



- Key early work charted the course toward the current III-V-based technology
  - Kamath (HRL, ~1977) — GaAs and AlGaAs
  - Bedair, et al (North Carolina State Univ, ~1978-1981) — AlGaAs/GaAs dual junction
  - Peter Iles and Frank Ho (Tecstar, ~1983–1990) — GaAs on Ge substrate
  - Yang (Rockwell, ~1979) — early TJ experiments
  - Jerry Olsen (NREL, ~1987) — GaInP/GaAs dual junction
  - Tobin & Lillington (Spire, Spectrolab ~1990) — GaAs/Ge dual junction
- Spectrolab retooled in the early 1990's to focus exclusively on the new multi-junction technology

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Best Research Cell Efficiencies

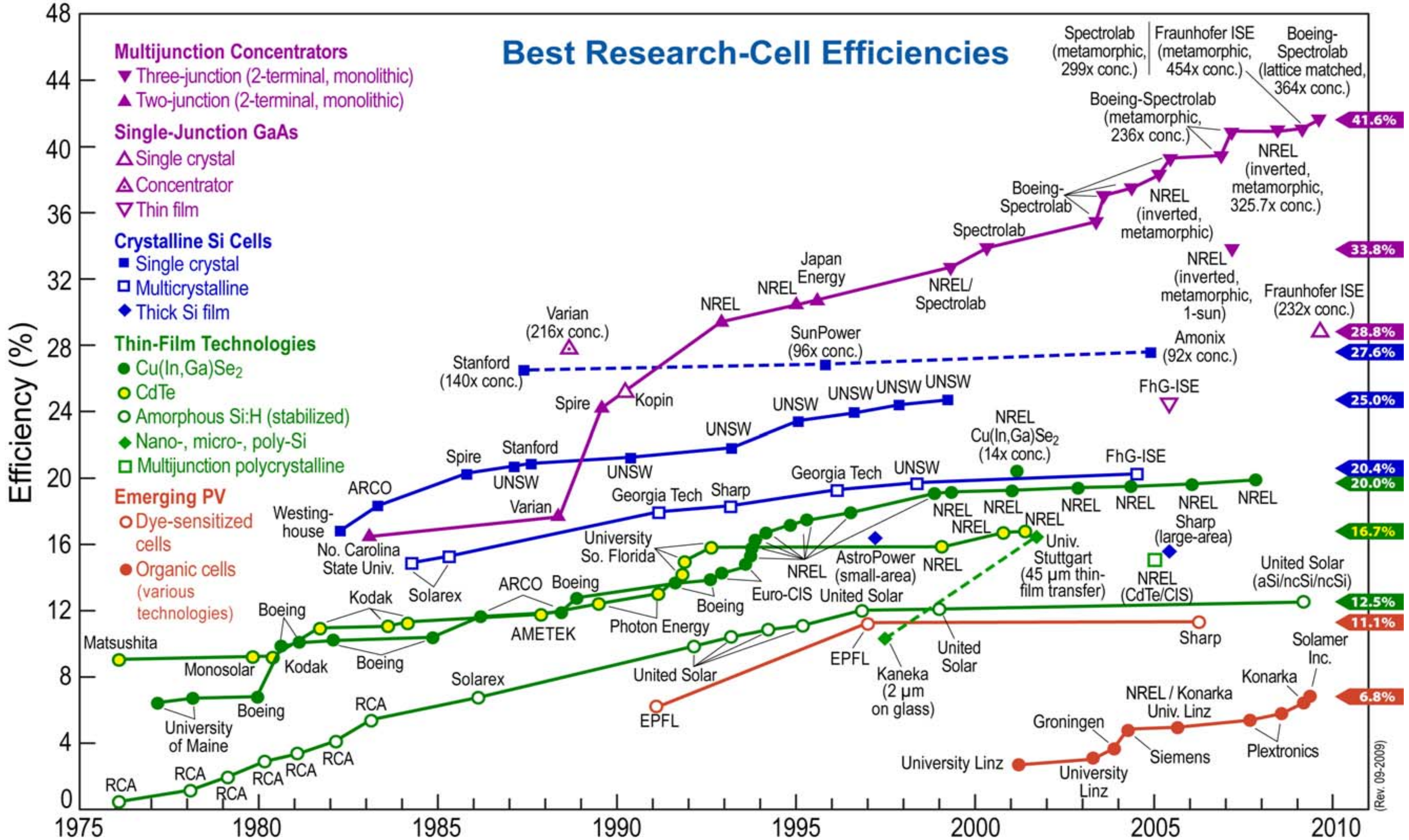
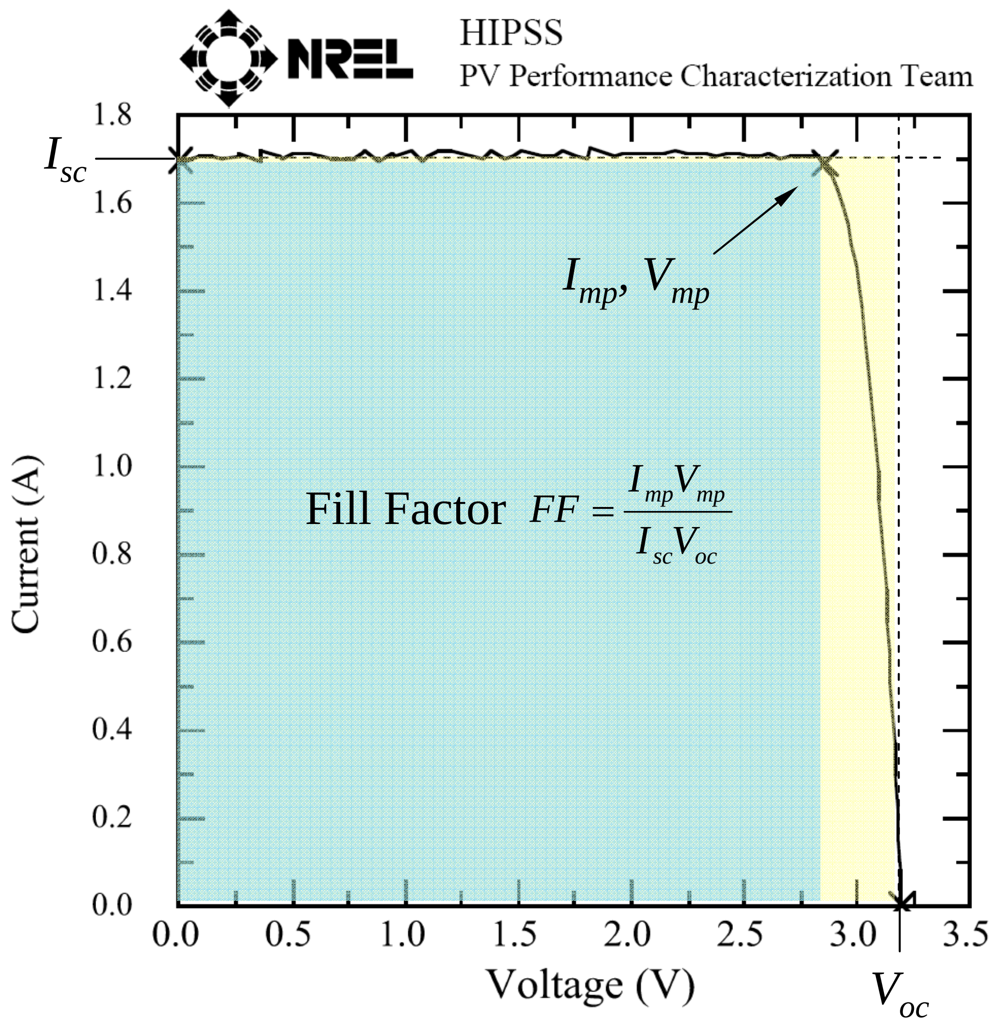


Chart courtesy of Larry Kazmerski, NREL

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

Record 41.6%-Efficient Concentrator Solar Cell



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

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Record Efficiency
GaInP/ GaInAs/ Ge Cell

V_{oc}	=	3.192 V
I_{sc}	=	1.696 A
FF	=	88.74%
V_{mp}	=	2.851 V
I_{mp}	=	1.686 A
P_{mp}	=	4.805 W

Efficiency = 41.6% ± 2.5%

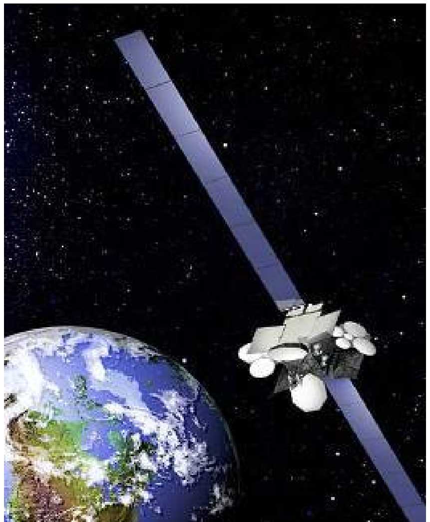
364.2 suns (36.42 W/cm^2) intensity
0.3174 cm^2 designated area
25°C, AM1.5D,
ASTM G173-03 spectrum

- Device fabricated February 2008
- Independent validation August 2009

Highest efficiency achieved to date for any solar cell

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

Space and Terrestrial Similarities



Space Photovoltaics

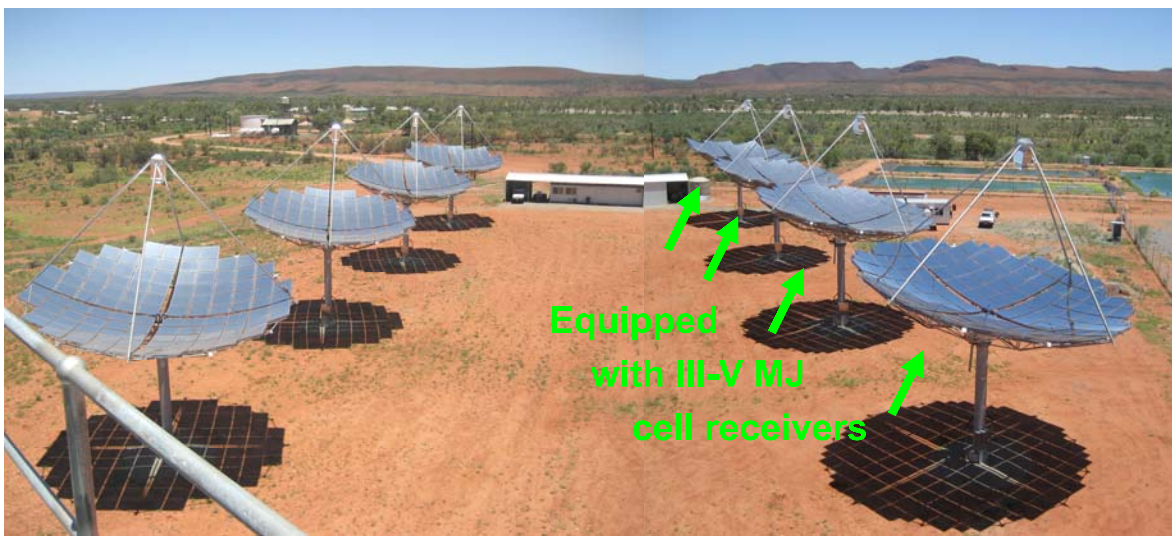
- Off-grid at 38,000 km altitude — very high reliability required
- Space customers demand highest efficiency triple junction cells available
- Cells are expensive compared to alternative technologies (i.e., silicon)
- … but are nevertheless the lowest cost option for the system (rather high shipping cost, ~US$20,000 per lb)

Terrestrial Photovoltaics

- Concentrator system customers demand highest efficiency triple junction cells available
- Return on investment demands very high reliability
- Cells are expensive compared to alternative technologies (i.e., silicon, thin film)
- … but are nevertheless the lowest cost option for the system (leveraging investment in balance of plant)

High efficiency cells enable lower cost systems for space and terrestrial (utility-scale) solar power

Real Impact of Multijunction Solar Cells vs. Silicon

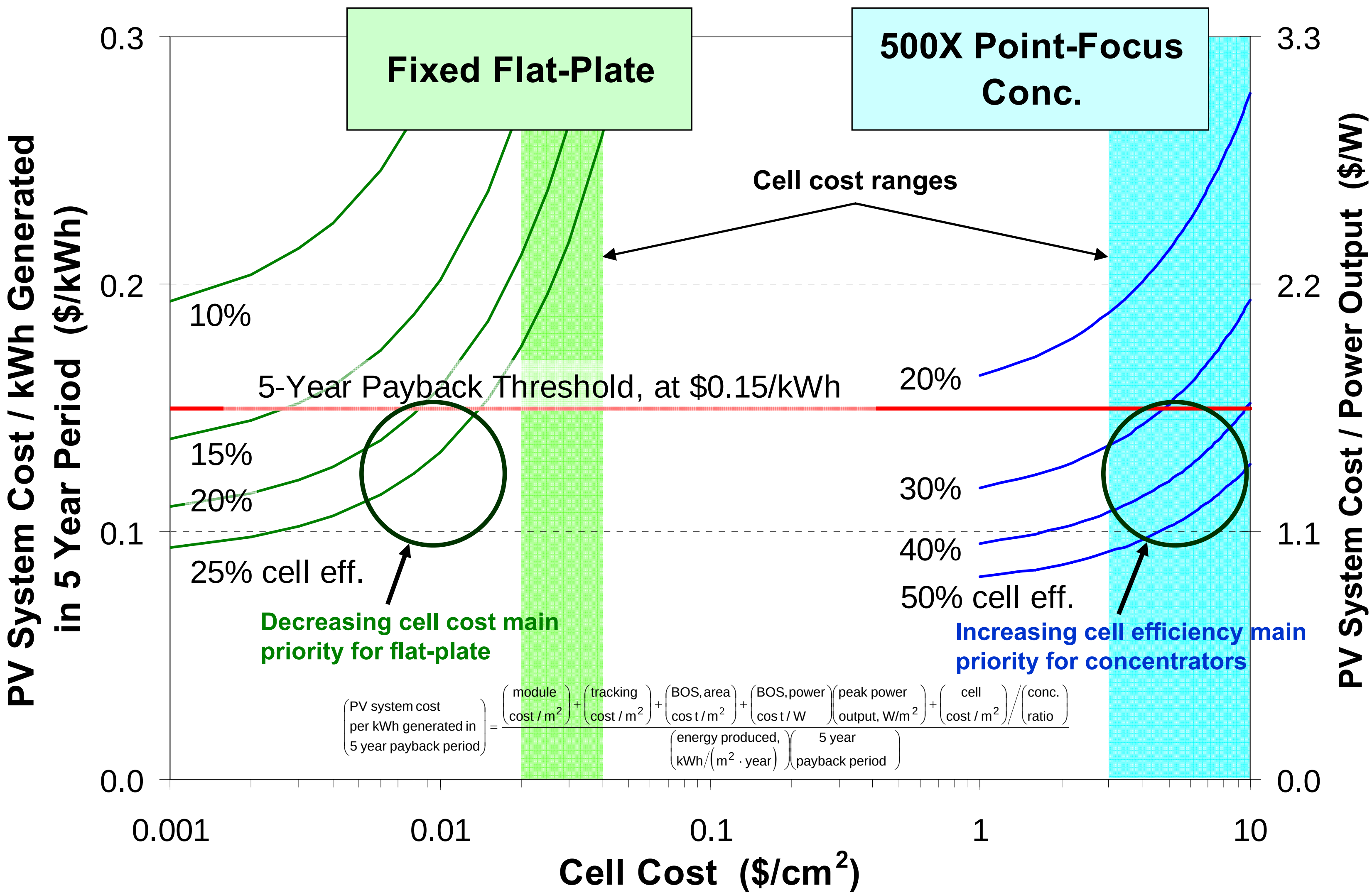


- **III-V MJ cells give 56% measured improvement in module efficiency relative to Si concentrator cells**

Courtesy of Solar Systems Pty. Ltd., Australia

R. R. King, 51st Electronic Materials Conf., University Park, Pennsylvania, June 24-26, 2009

Terrestrial PV System Cost vs. Cell Cost



Ref.: R. R. King et al., 3rd Int'l. Conf. on Solar Concentrators (ICSC-3), Scottsdale, AZ, May 1-5, 2005

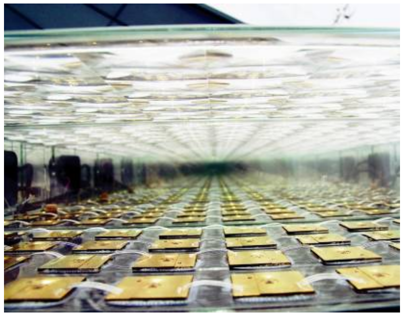
Spectrolab's Cells under Sun

Amonix
Since October 2000

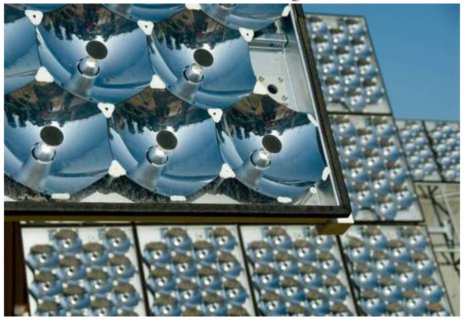
APS – CTEK
Since May 2004

Solar Systems
since February 2006

Concentrix Solar GmbH
Since October 2006



SolFocus
Since February 2007



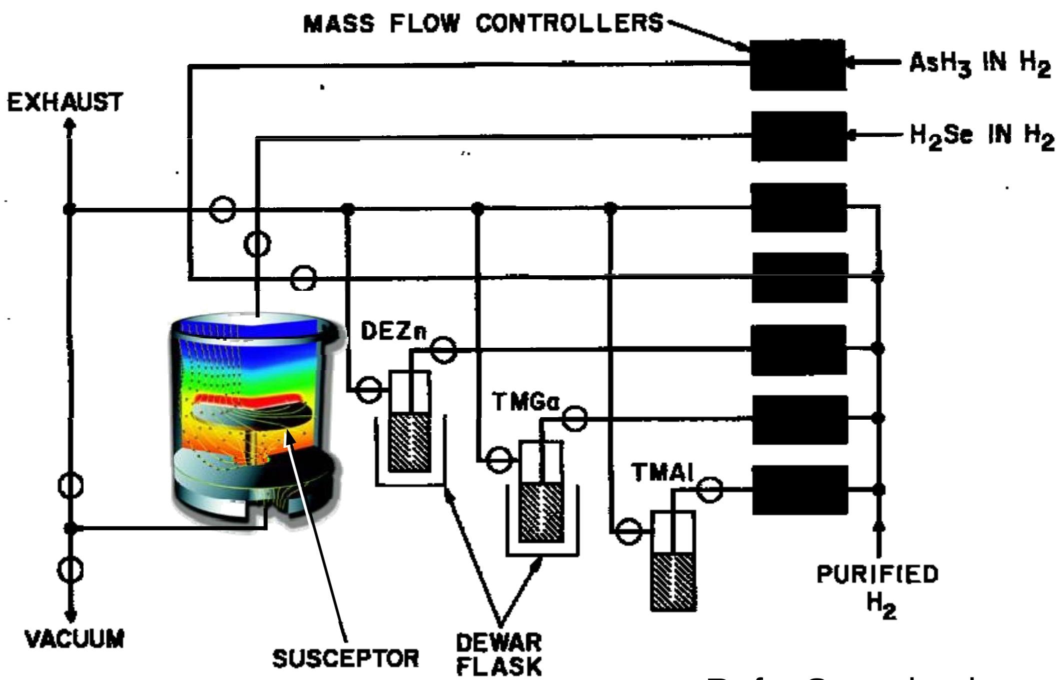
Energy Innovations
Since May 2007

Boeing Phantom Works
Since August 2007

OPEL, Inc.
Since February 2008

- Spectrolab terrestrial product applications are multiplying and maturing
- Growing field experience, space reliability heritage, and rigorous in-house qualification for terrestrial use are establishing the cost-effectiveness of the technology

Metal-Organic Vapor-Phase Epitaxy (MOVPE)



- **Also referred to as Organo-metallic Vapor-Phase-Epitaxy (OMVPE) or Metal-Organic Chemical Vapor Deposition (MOCVD)**
  - Offers high growth rates
  - Excellent crystal quality without requiring ultra-high vacuum
  - Typical parameters

Growth temperature	600 -750°C
Growth rate	10 - 200 nm/min
Pressure	0.1 - 1 atm.
Inlet V/III ratio	10 - 500

  - Typical sources (in palladium-diffused H_2 carrier)

trimethyl gallium (TMGa)
trimethyl indium (TMIn)
trimethyl aluminum (TMAl)
diethyl zinc (DEZn)
arsine (t-butyl arsine)
phosphine (t-butyl phosphine)
disilane (silane) (in H_2 or N_2)
hydrogen selenide (in H_2 or N_2)

Ref.: Swaminathan and Macrander

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Maximum Solar Cell Efficiencies

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Measured **Theoretical**

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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).

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)

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%**

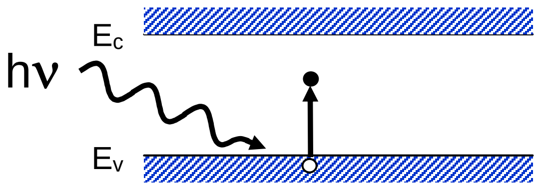
3-gap GaInP/GaAs/GaInAs cell at 1 sun (NREL) **33.8%**

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%**

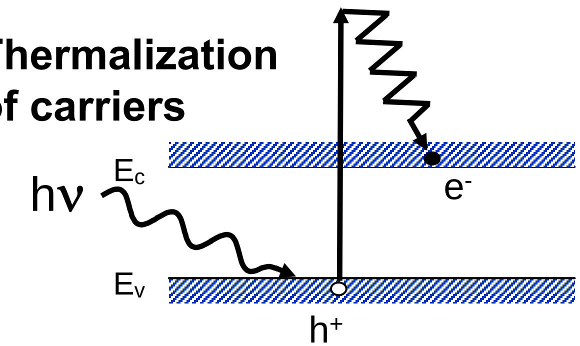
R. R. King et al., 24th European Photovoltaic Solar Energy Conf., Hamburg, Germany, Sep. 21-25, 2009

Fundamental Conversion Loss Mechanisms

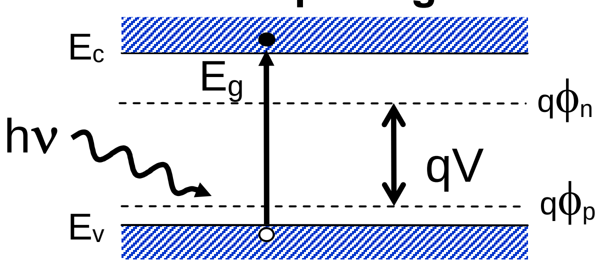
Insufficient energy to reach E_c

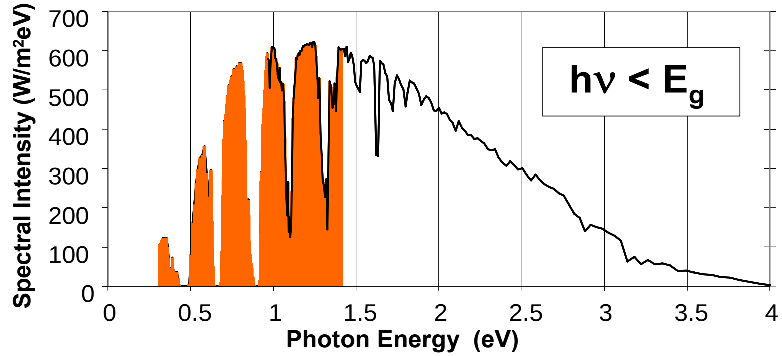


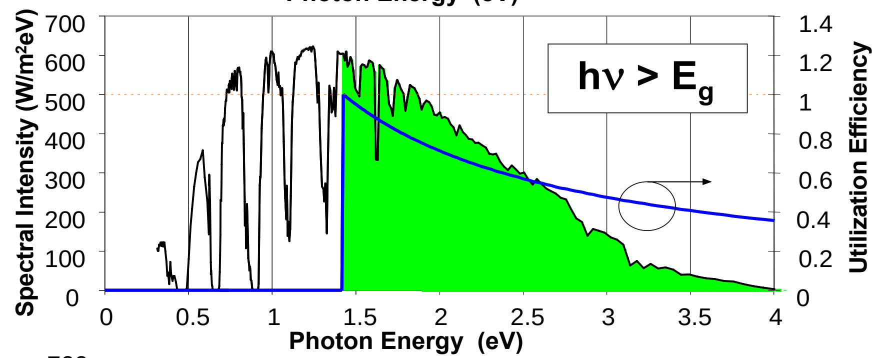
Thermalization of carriers

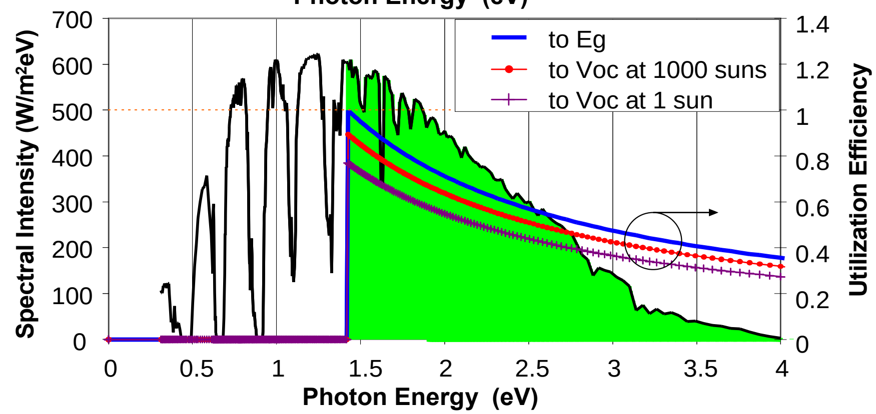


Quasi-Fermi level splitting



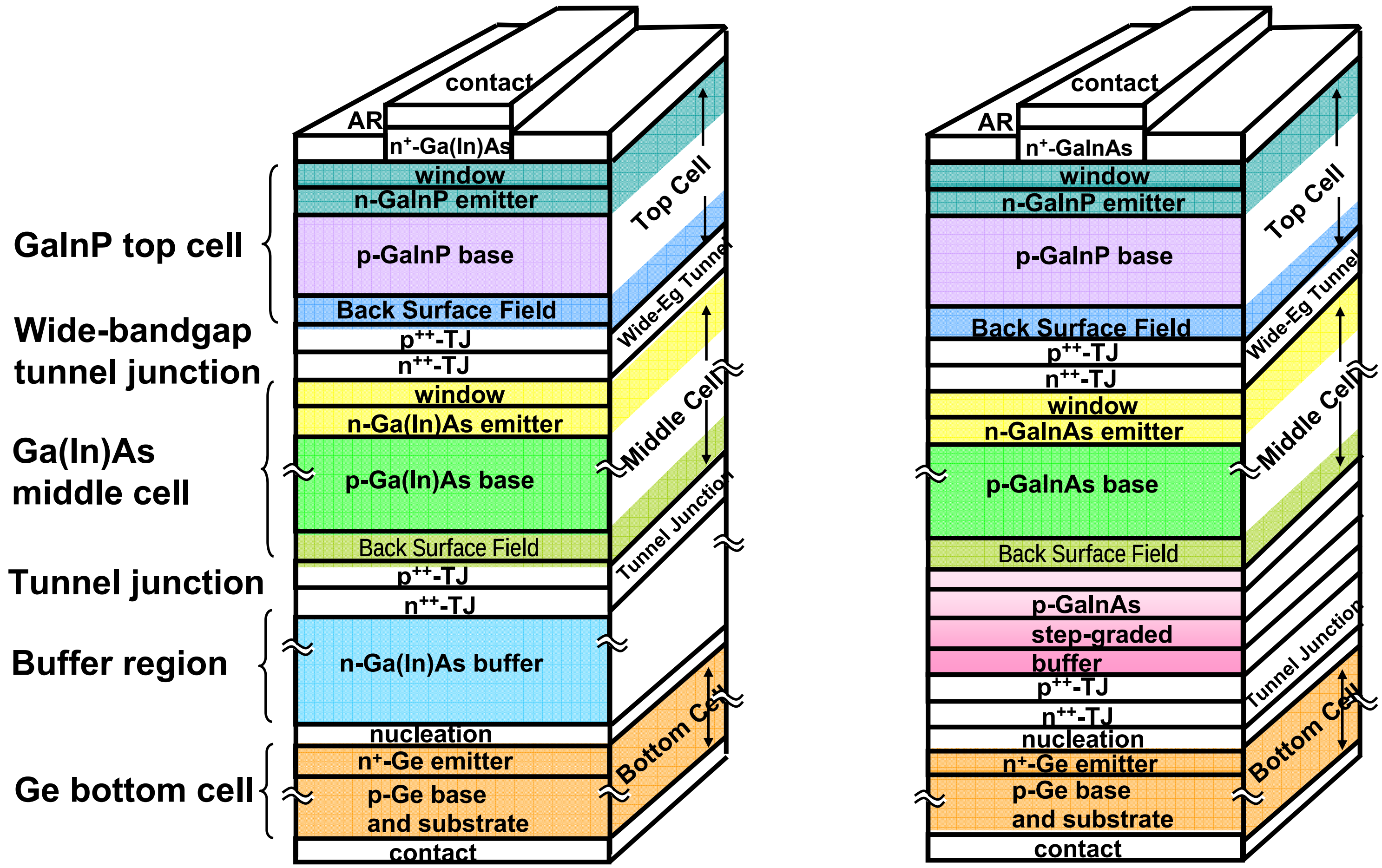






R. R. King, III-V Tutorial, 4th World Conf. on Photovoltaic Energy Conversion, Waikoloa, Hawaii, May 7, 2006

LM and MM 3-Junction Cell Cross-Section

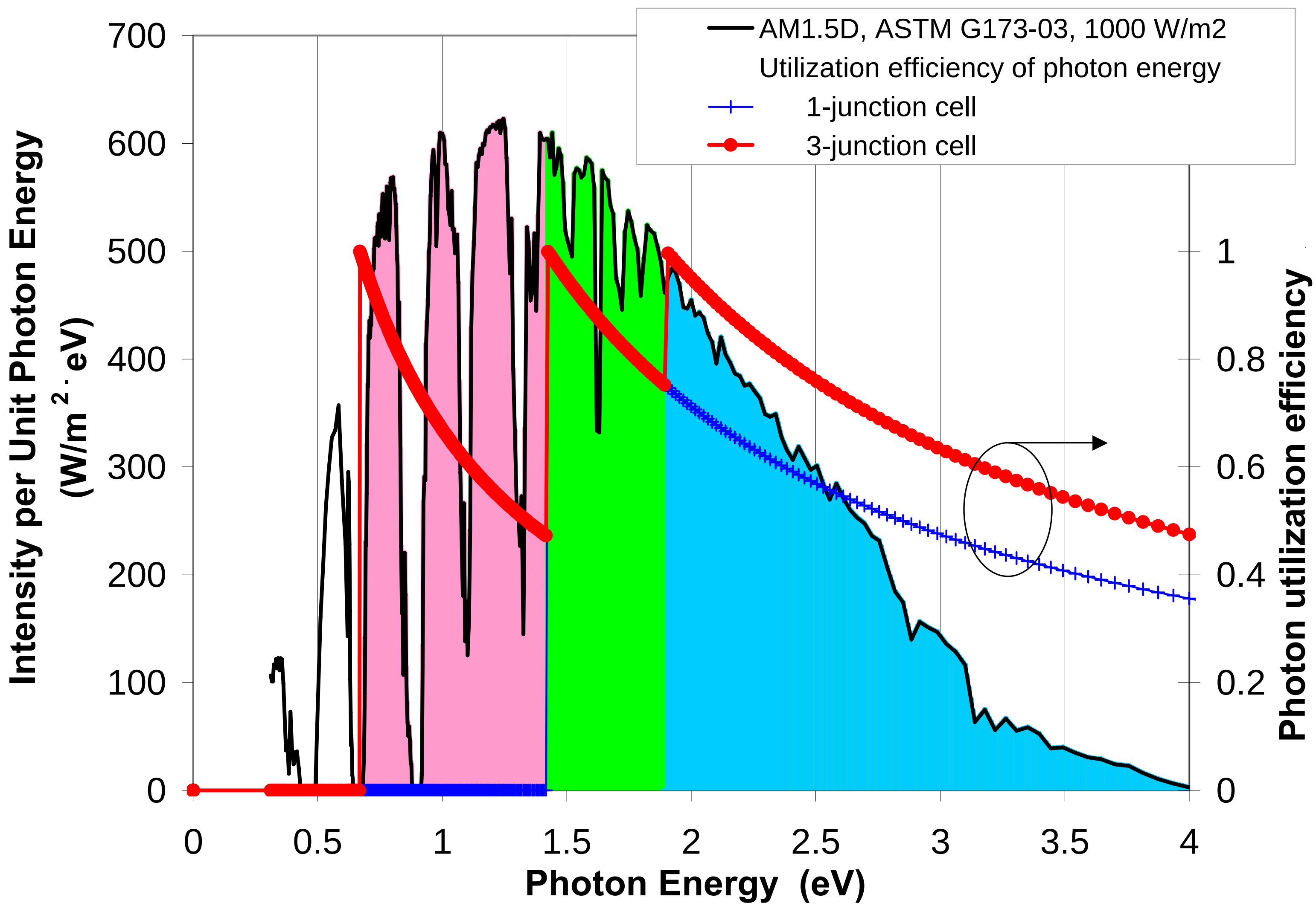


Lattice-Matched (LM)

Lattice-Mismatched or Metamorphic (MM)

R. R. King et al., 29th IEEE Photovoltaic Specialists Conf., New Orleans, Louisiana, May 20-24, 2002

Photon Utilization Efficiency 3-Junction Solar Cells



R. R. King, III-V Tutorial, 4th World Conf. on Photovoltaic Energy Conversion, Waikoloa, Hawaii, May 7, 2006

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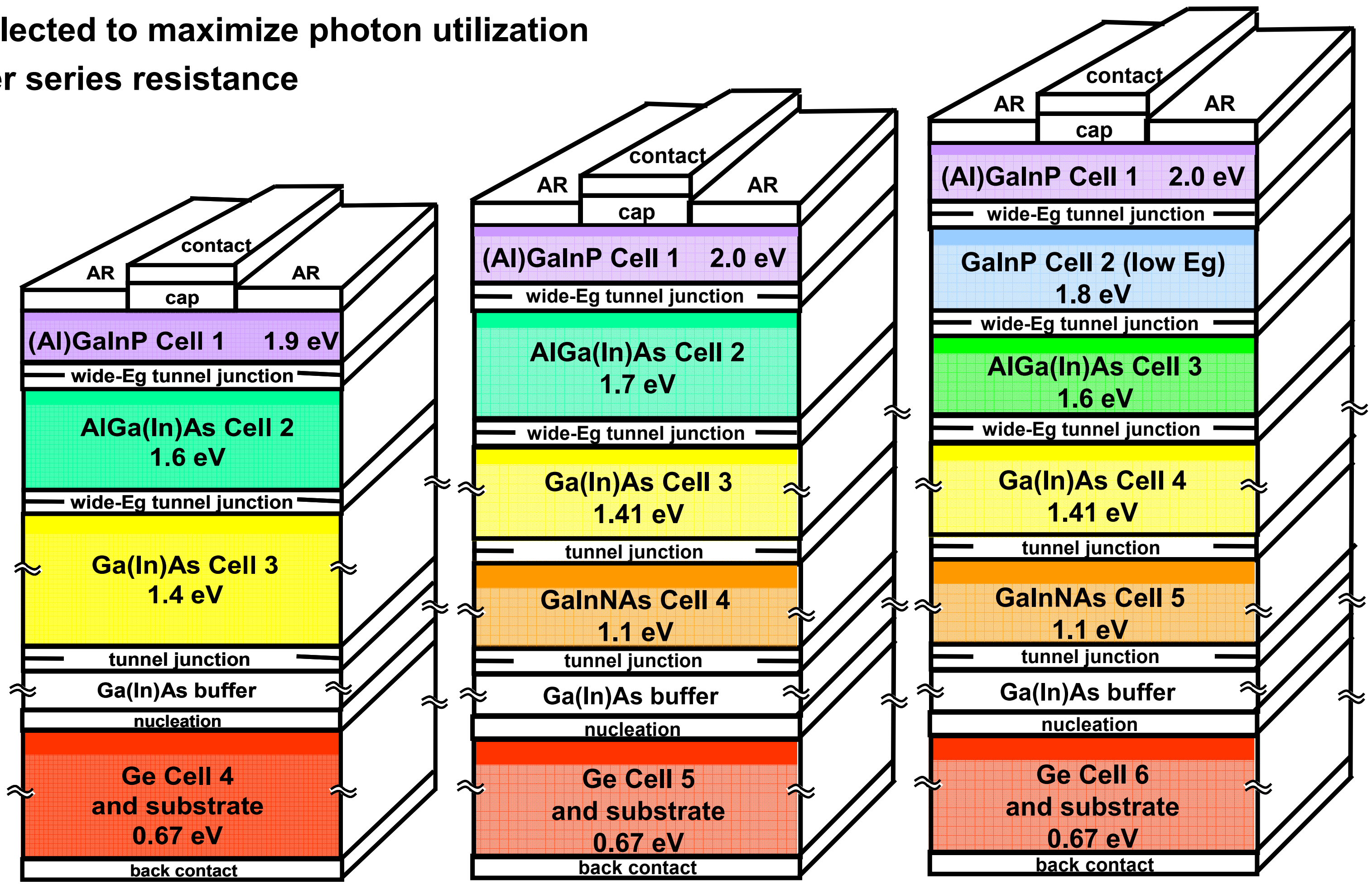
Solar Cell Efficiency Improvement Strategies

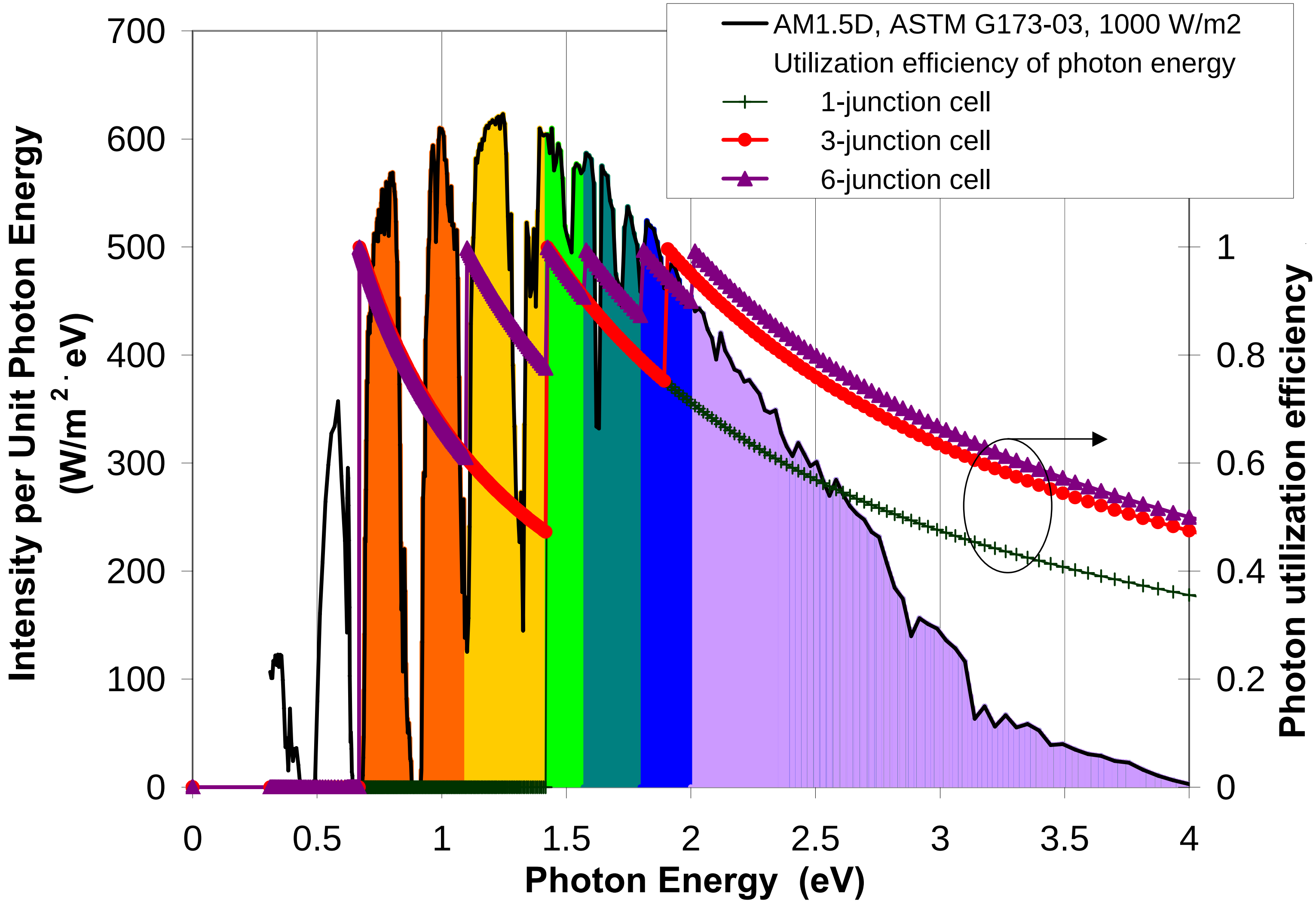
- Ge substrate provides high quality growth platform
- Divide available current among more subcells, matched in each
- E_g selected to maximize photon utilization
- Lower series resistance



R. R. King et al., 19th European Photovoltaic Solar Energy Conf., Paris, France, June 7-11, 2004, & 21st EU PVSEC, Sep. 4-8, 2006

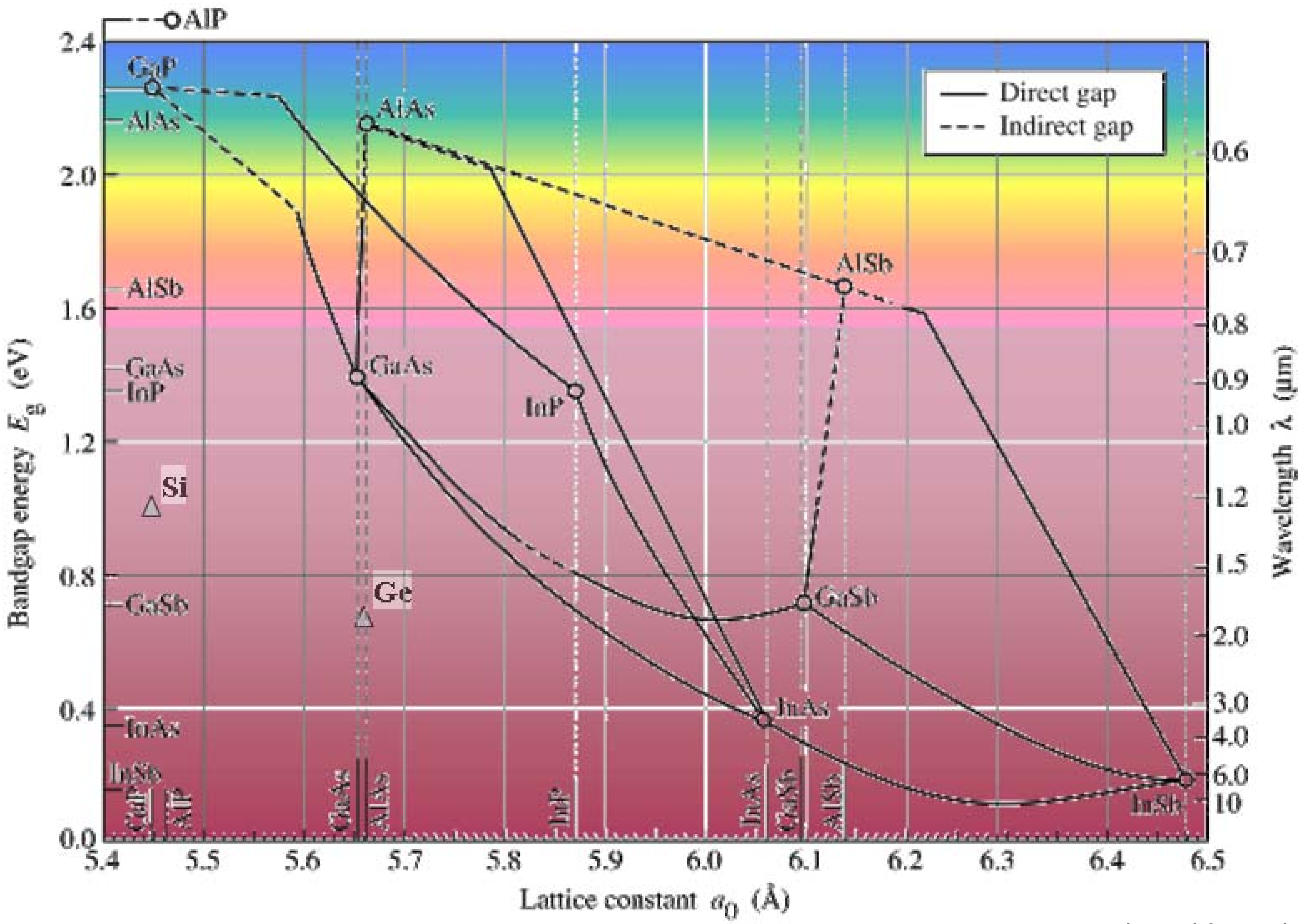
Ref.: U.S. Pat. No. 6,316,715, Spectrolab, Inc., filed 3/15/00, issued 11/13/01.

Photon Utilization Efficiency
6-Junction Solar Cells



R. R. King, III-V Tutorial, 4th World Conf. on Photovoltaic Energy Conversion, Waikoloa, Hawaii, May 7, 2006

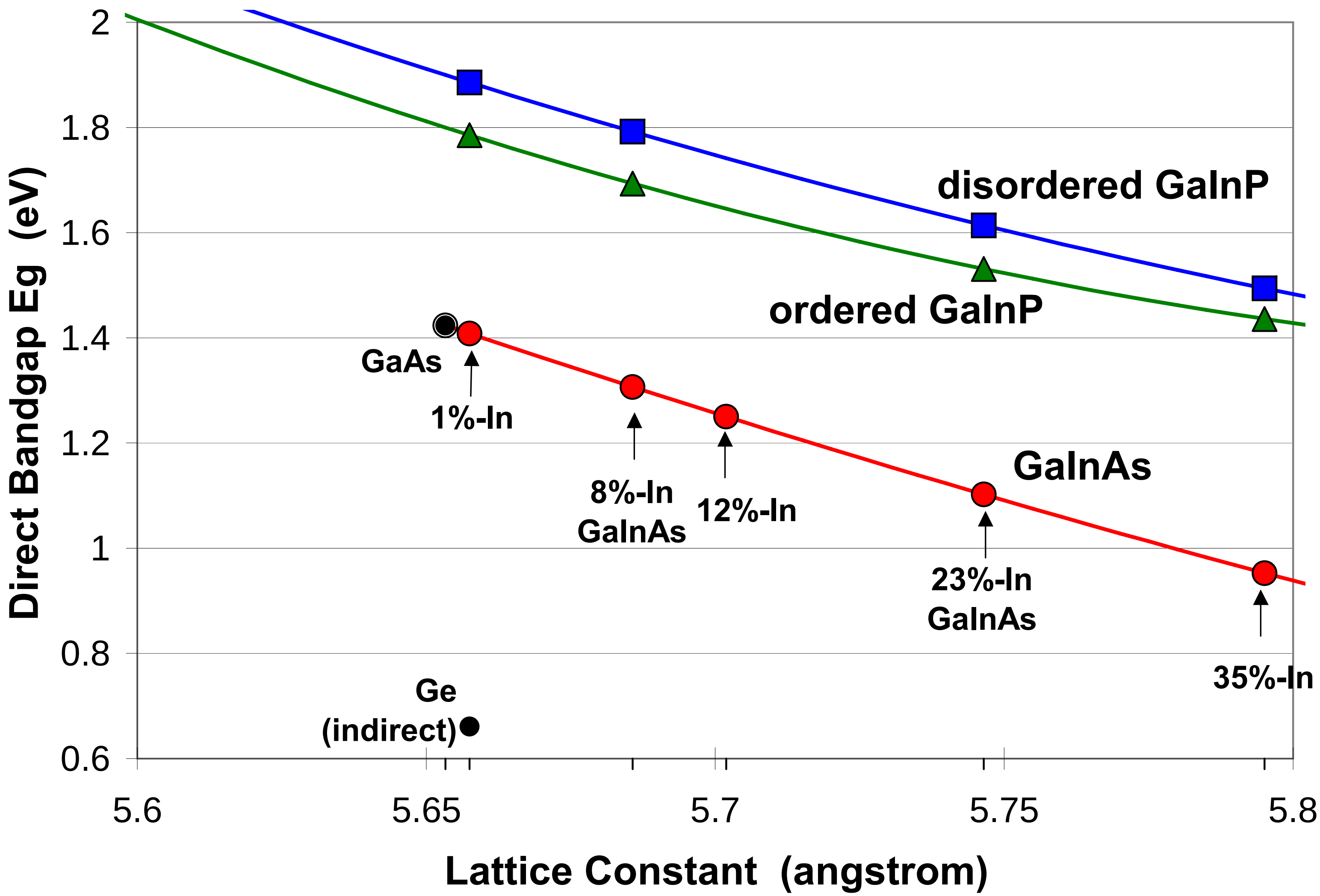
Bandgap vs. Lattice Constant



Adopted from Tien, 1988

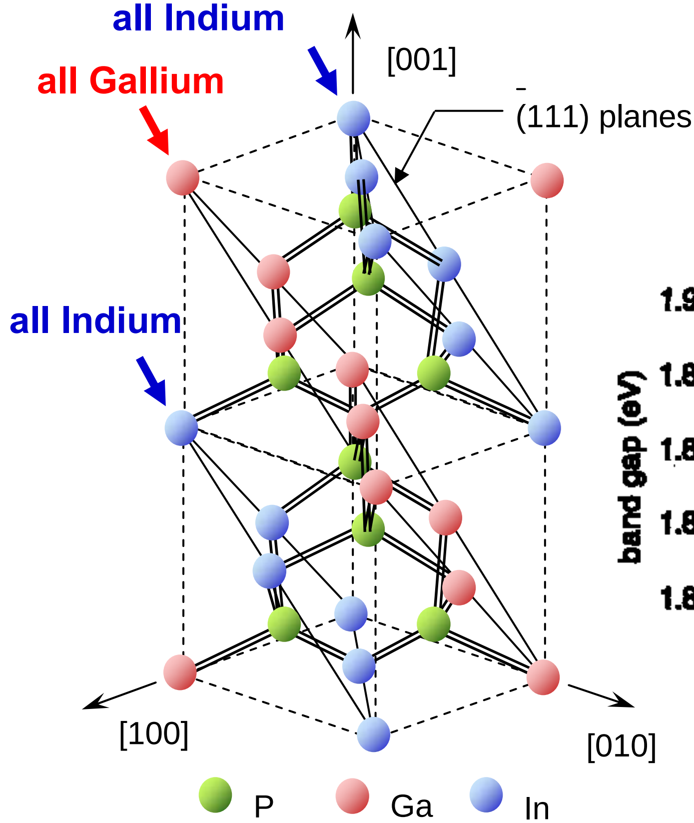
III-V semiconductors offer flexible bandgap combinations

Bandgap vs. Lattice Constant



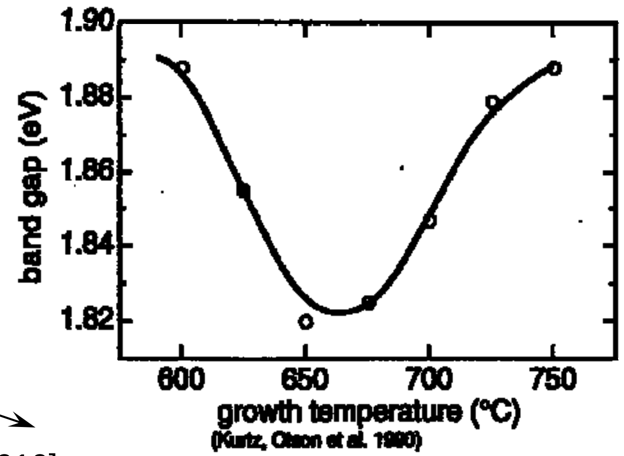
R. R. King et al., 19th European Photovoltaic Solar Energy Conf., Paris, France, June 7-11, 2004

Group-III Sublattice Ordering in $Ga_{0.5}In_{0.5}P$

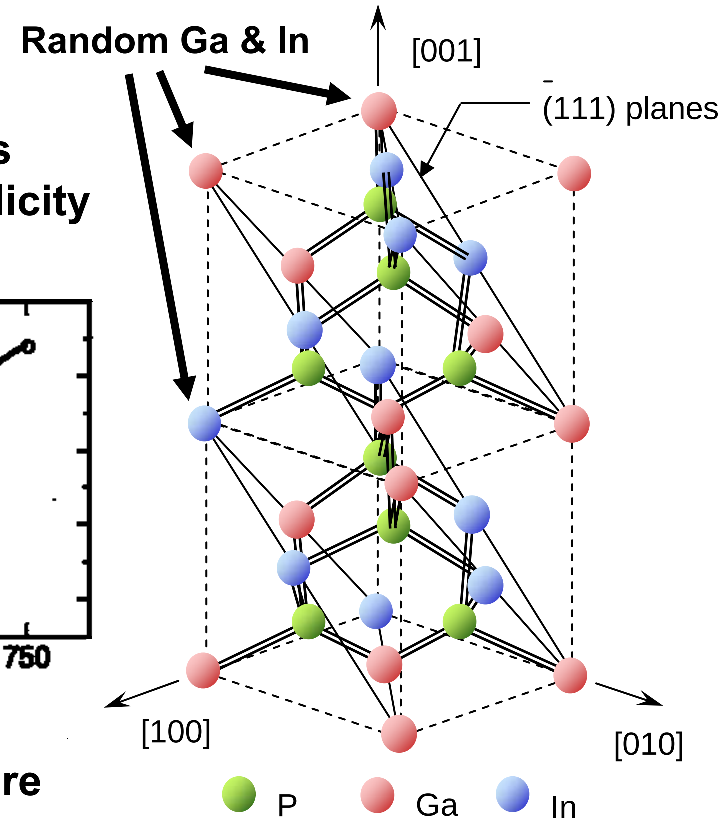


Fully Ordered
(order parameter $\delta = 1$)

Order parameter δ is affected by a multiplicity of process factors



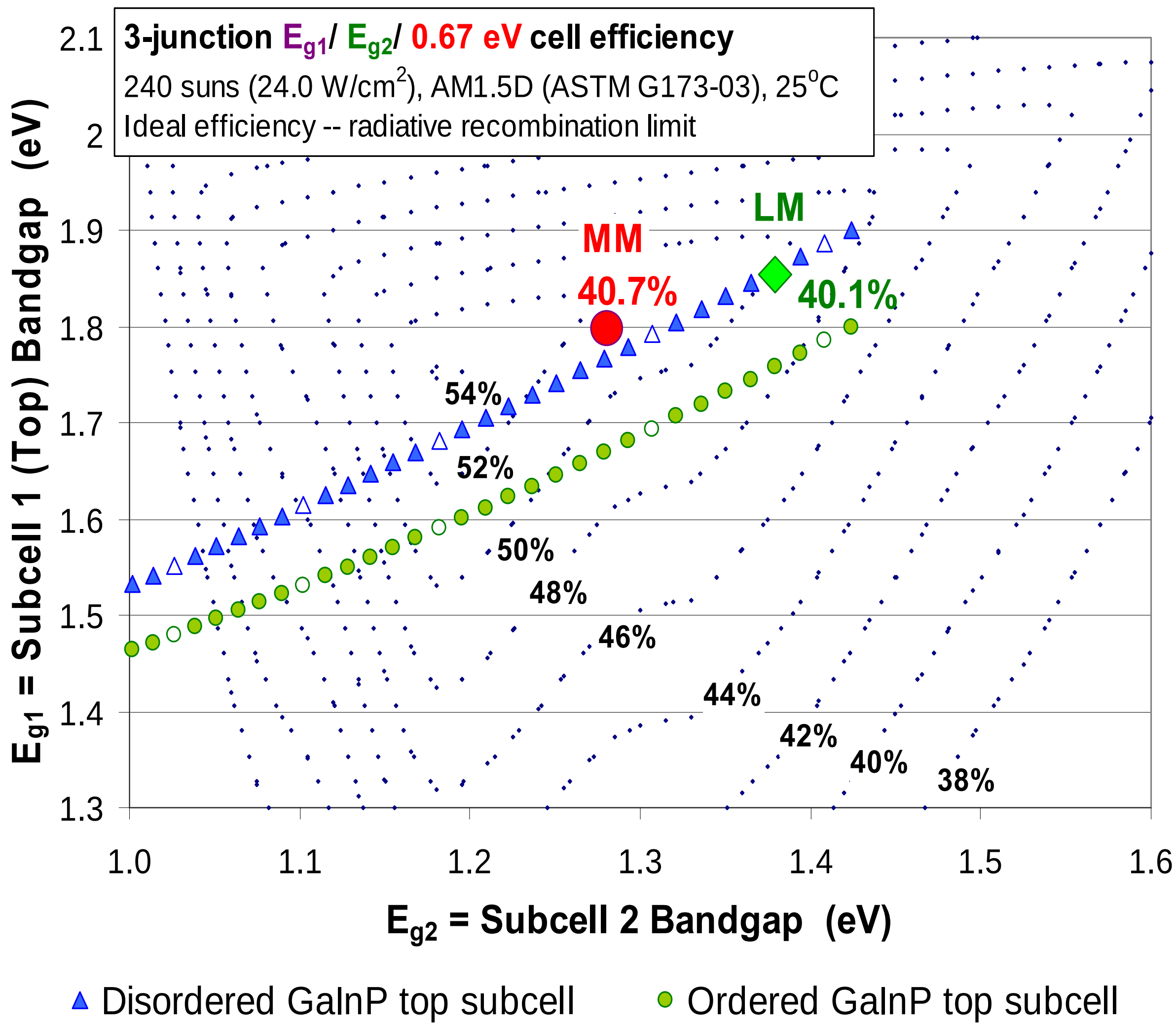
Growth temperature is one process lever to control δ



Fully Disordered
(order parameter $\delta = 0$)

$$E_g(\eta) = E_g(0) - 0.471\,\delta^2 \text{ (eV)}$$

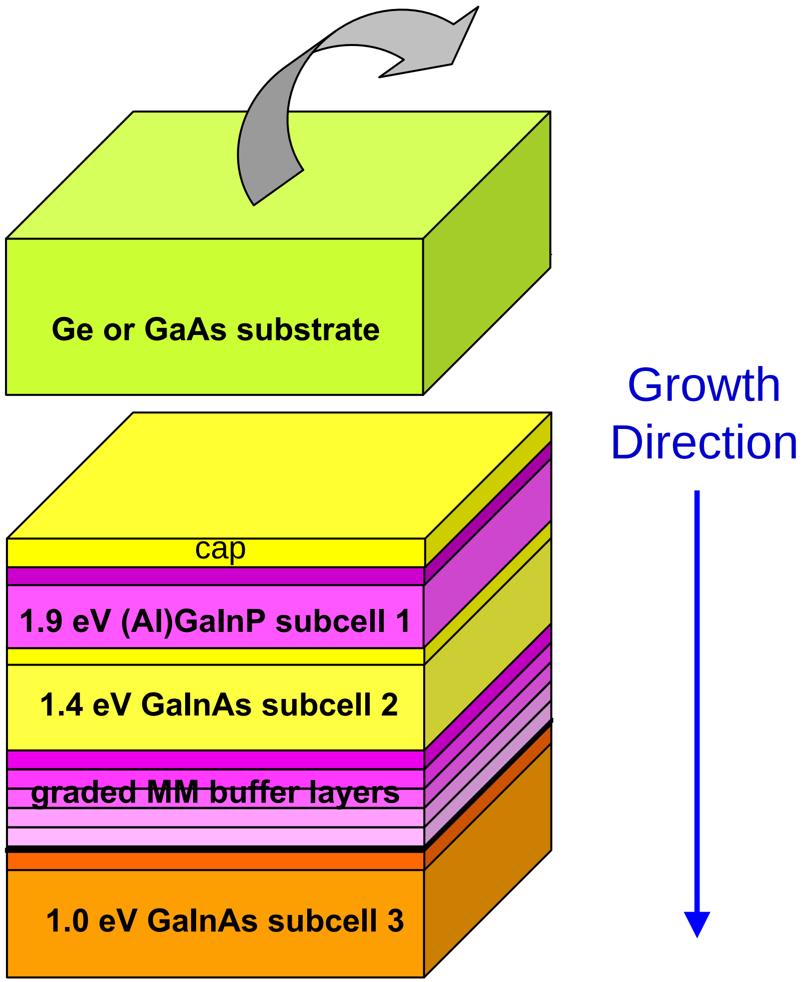
3-Junction Theoretical Efficiency — Vary E_{g1} and E_{g2}



Ref.: R. R. King et al., Appl. Phys. Lett., 90, 183516, 4 May 2007

- Iso-efficiency contour plots for 3-junction cells limited only by radiative recombination
- Dependence of ideal efficiency on band gaps E_{g2} and E_{g3}
- Ideal efficiency contours → show limiting efficiencies possible without the effects of grid shadowing, series resistance, and non-radiative carrier recombination

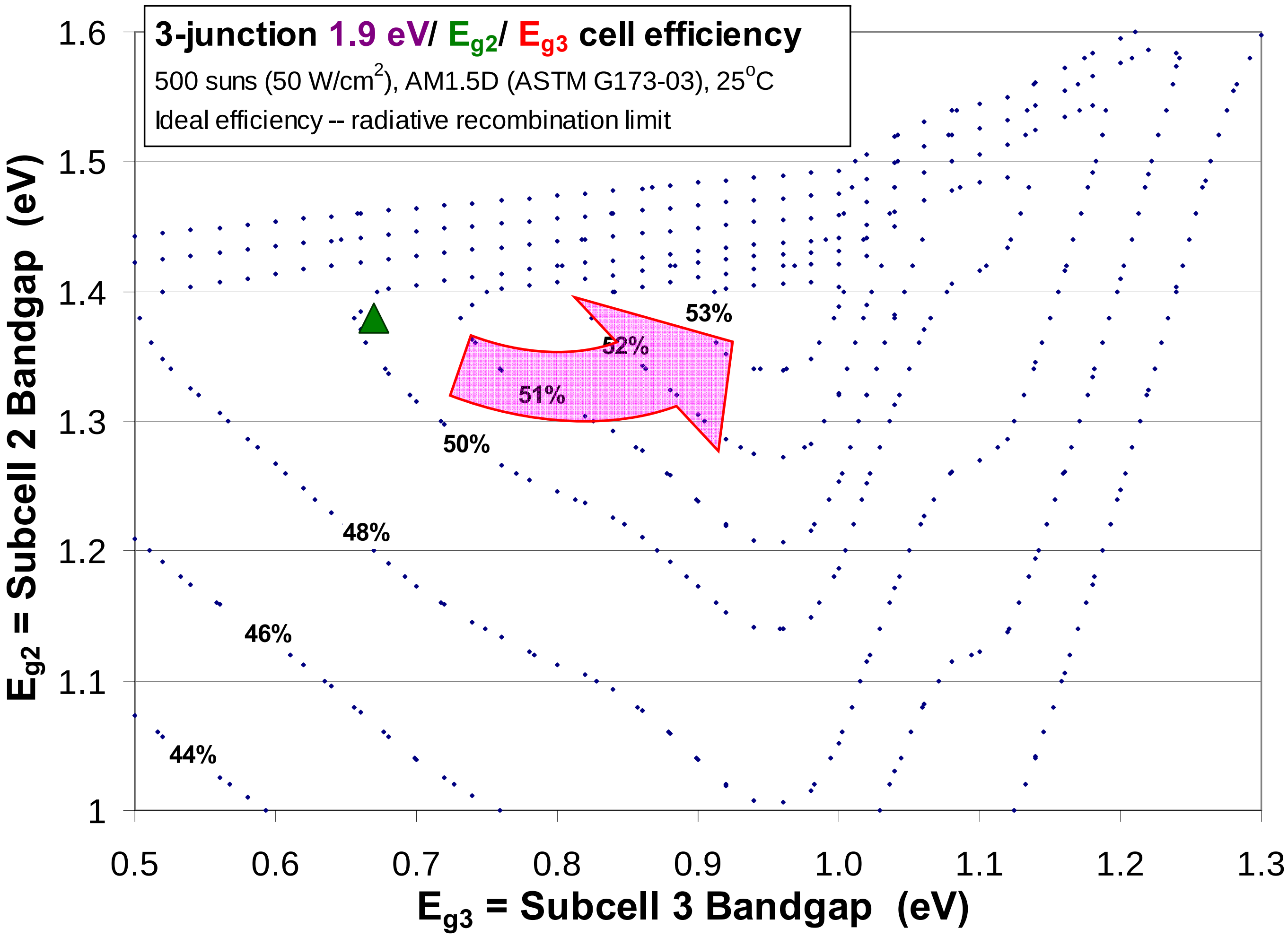
Metamorphic (MM) 3-Junction Cells – Inverted 1.0-eV GaInAs Subcell



- **Growth on Ge or GaAs substrate, followed by substrate removal from sunward surface**
- **Offers new band gap engineering possibilities**
  - Widest band gap cell grown first, 1-eV band gap cell (largest lattice mismatch) grown last
- **Possibility of reuse of the substrate**
- **Final device is a thin film**

R. R. King et al., 20th European Photovoltaic Energy Conf., Barcelona, Spain, June 6-10, 2005

Inverted Metamorphic (IMM) 3-Junction Concentrator Cell Development



- Iso-efficiency contour plots for 3-junction cells limited only by radiative recombination
- Dependence of ideal efficiency on band gaps E_{g2} and E_{g3}
- Move subcell E_g combination toward optimum through band gap engineering, particularly bottom subcell 3

R. R. King et al., 21st European Photovoltaic Energy Conf., Dresden, Germany, Sep. 4-8, 2006

Summary

- Bandgap engineering offers the ability to match multiple bandgaps to the solar spectrum
- Metamorphic semiconductors offer vastly expanded palette of E_g
- Three device designs (lattice-matched, metamorphic, and inverted metamorphic) have all demonstrated $\eta > 40\%$
- These achievements offer diverse vectors for further research and performance improvement

η of 50% or more is achievable and within reach