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Electronic Materials Science Challenges in Renewable Energy

Richard R. King

Spectrolab, Inc.

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51st Electronic Materials Conference

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Acknowledgments

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Thank You !

Electronic Materials in Renewable Energy

- Virtually all of the topics in the EMC Program have a potential impact on renewable energy technologies

- Electronic materials research can make or break many of these emerging technologies

- Challenge that is being picked up increasingly by Academic, Gov't, and Industry research centers:

"How can the basic materials science we have been working on for devices in telecom, computing, imaging, displays... be applied to photovoltaic cells, energy storage, and other renewable energy applications?"

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A Few Key Growth Areas for Renewable Energy

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This talk is 'focused' on the huge area of photovoltaics...

- **Multijunction photovoltaic cells for grid-connected solar electricity**
  - Metamorphic (MM) semiconductors to access new band gaps
  - III-V growth on Ge, SiGe, and silicon
  - Wafer bonding and engineered substrates
  - Narrow band gap semiconductors: antimonides and others
  - Wide band gap semiconductors: nitrides and others
  - Point and extended defects in MM materials
  - Low-dimensional structures: quantum dots, wires, and wells
- **Flat-plate photovoltaics**
  - *Polycrystalline thin-film compound semiconductor solar cells ($CuInSe_2$, CdTe,...)*
  - *Microcrystalline silicon solar cells*
  - Organic-inorganic hybrid photovoltaics

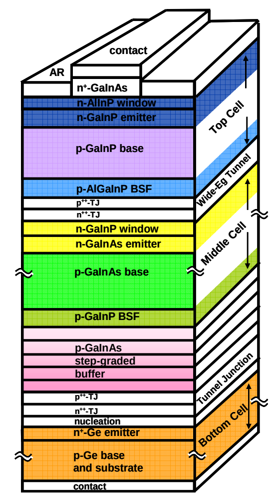
A Few Key Growth Areas for Renewable Energy

...but electronic materials impact many more aspects of renewable energy

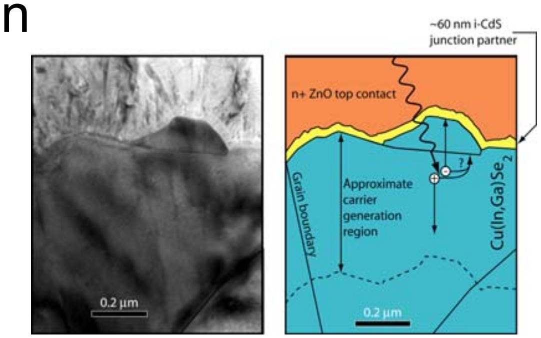
- **General Applications**
  - Carbon nanotubes, graphene
  - Zinc oxide
  - Flexible and printed thin film electronics
- **Batteries, fuel cells for vehicles**
  - Porous, catalytic electrodes
  - Ionic conductors
- **Power conditioning, DC to AC conversion**
  - Silicon carbide
- **Thermoelectrics and thermionics**

Outline

- **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***
  - Metamorphic SiGe buffer and solar cell growth
  - III-V solar cells on Si substrates

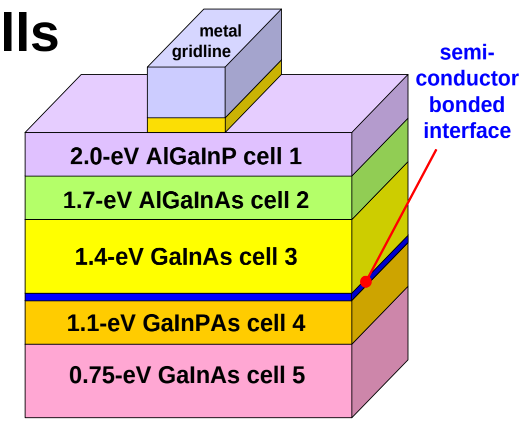


- **Polycrystalline Cu(GaIn)Se2 and CdTe for flat-plate solar cells**
  - Remarkable recombination inactivity for grain boundaries
  - Understanding energetically-favored defect formation
  - Defect energy levels, Fermi stabilization energy



Outline (cont'd)

- **Nanostructures for high-efficiency photovoltaics**
  - Nanorod solar cell arrays grown by VLS (vapor-liquid-solid) method
  - Quantum wells, wires, dots, low-dimensional structures in solar cells
  - Organic semiconductors for PV
- **High-efficiency Multijunction terrestrial concentrator cells**
  - **Metamorphic** and **lattice-matched** 3-junction solar cells with ***>40%*** efficiency
  - ***39%***-efficient cells at ***>1000*** suns
  - ***4-junction*** metamorphic (MM) and lattice-matched (LM) concentrator cells
  - Inverted metamorphic 3- and 4-junction cells for terrestrial concentrators
  - Semiconductor bonded technology (SBT) for MJ terrestrial concentrator cells



- **Concentrator photovoltaic (CPV) systems and economics**

Global Climate Change

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Climate and CO_2 Over the Last 400,000 Years

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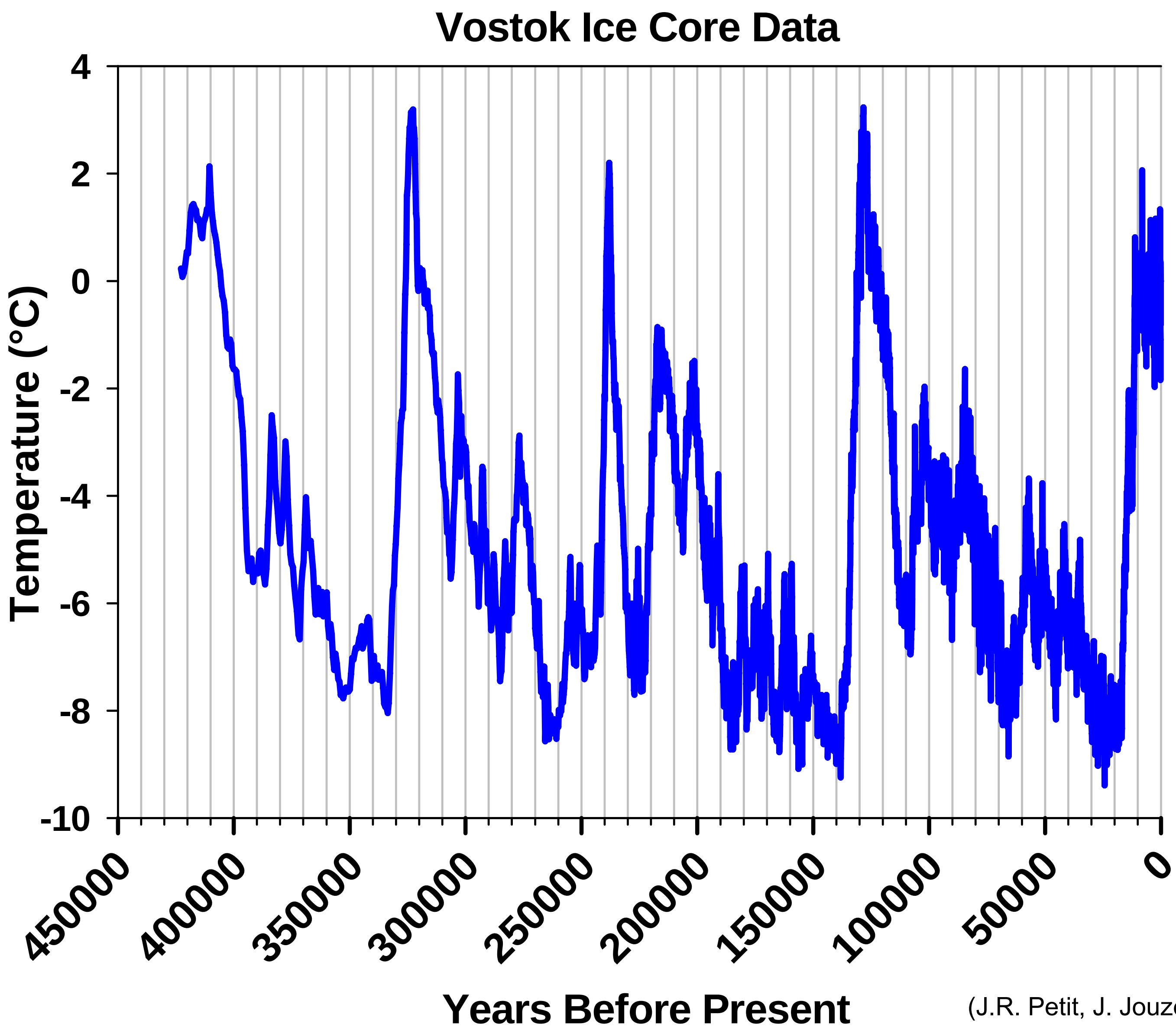
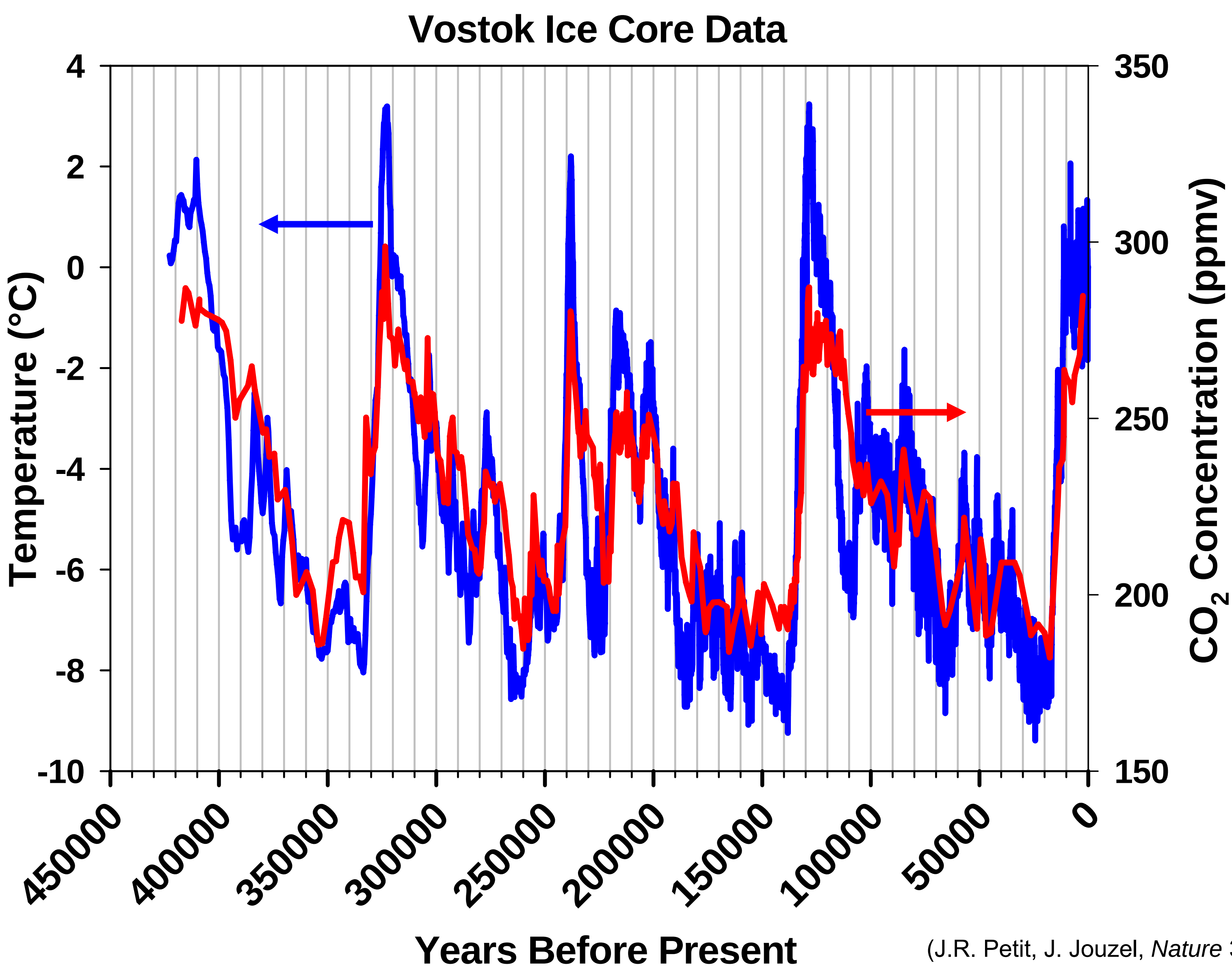


(J.R. Petit, J. Jouzel, *Nature* 399:429-436)

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

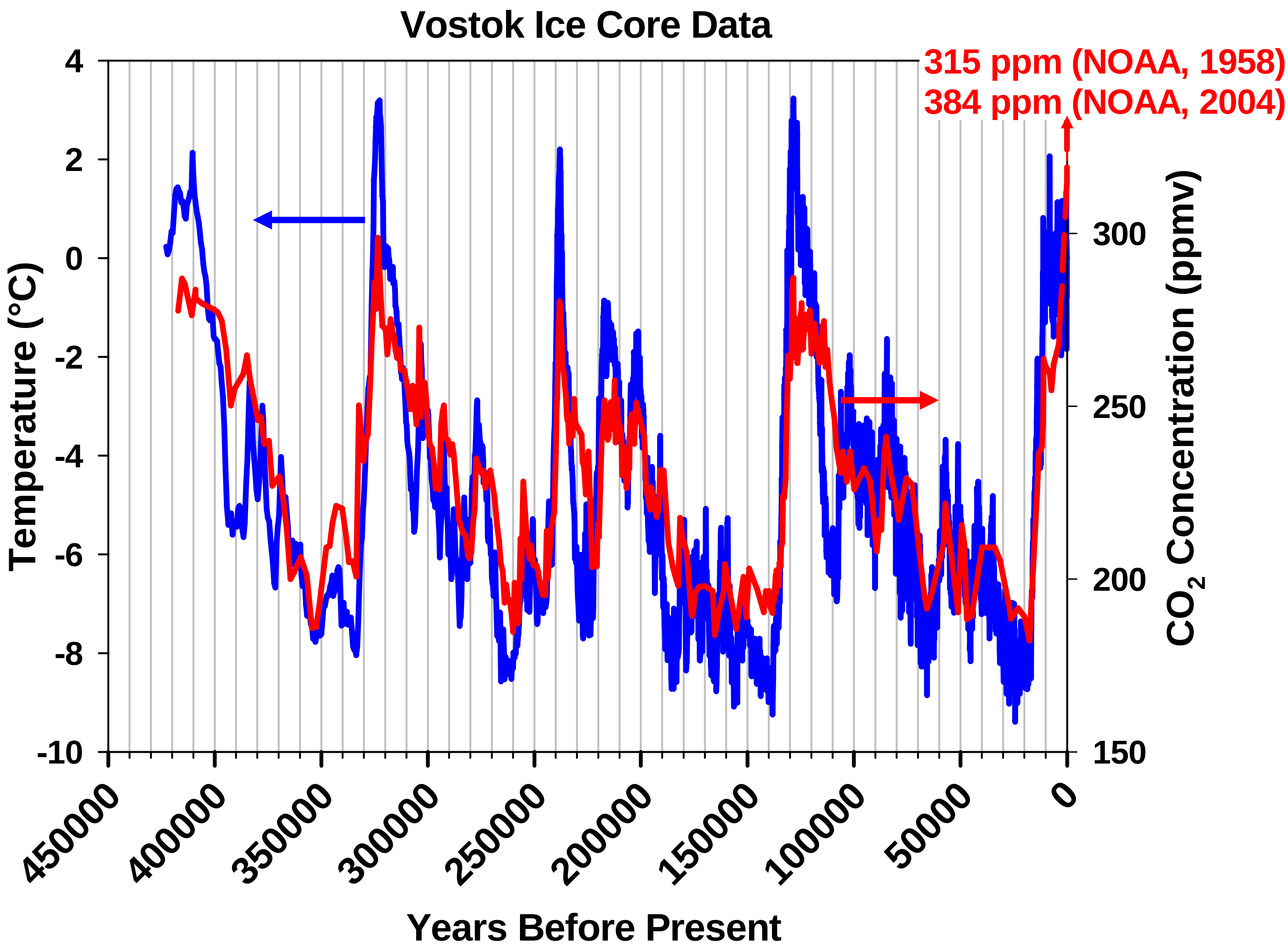
Climate and CO_2 Over the Last 400,000 Years



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

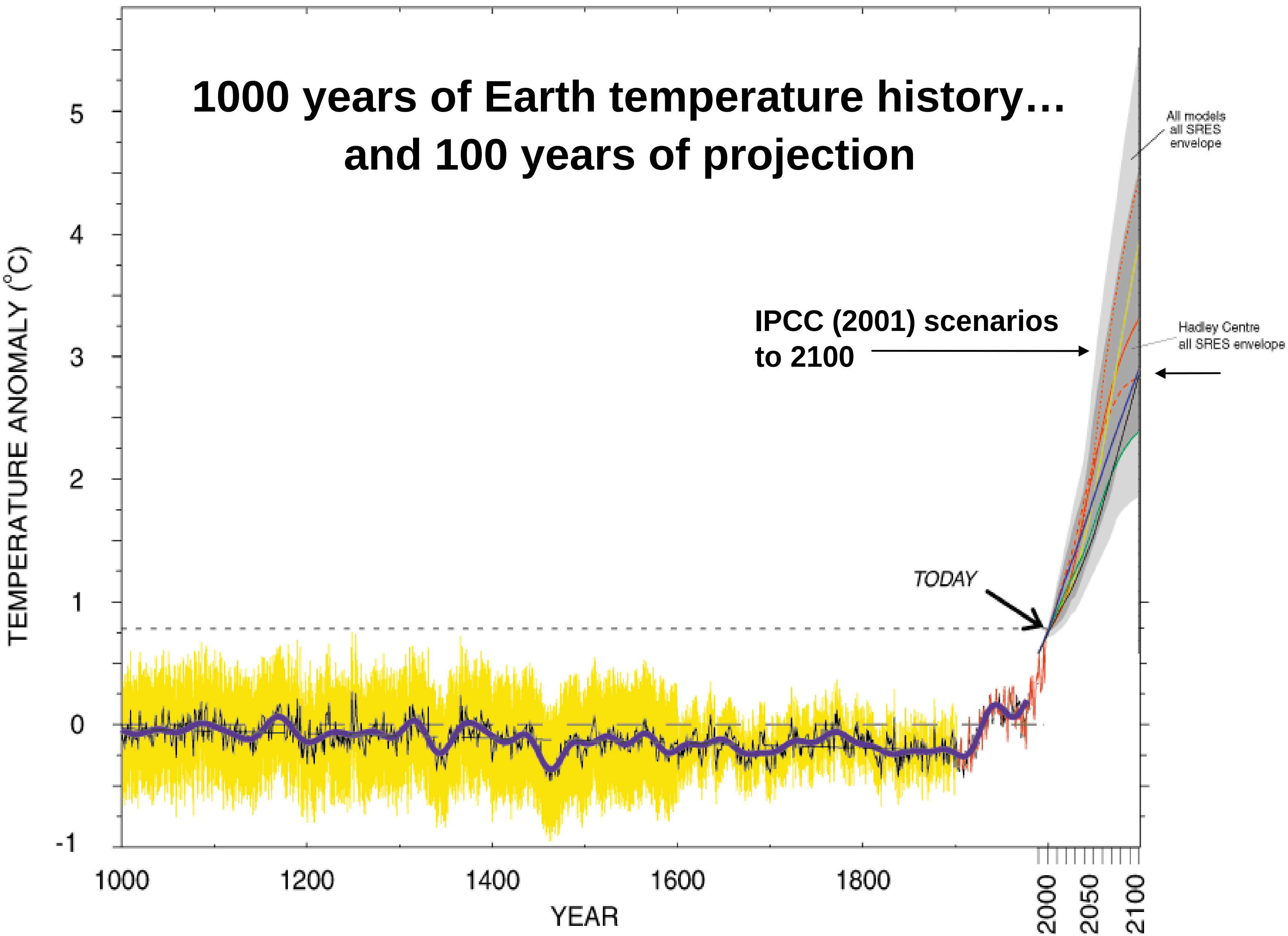
- Clear correlation between temperature and CO_2 levels

Climate and CO_2 – Recent History



- 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

Temperature Anomaly by Year

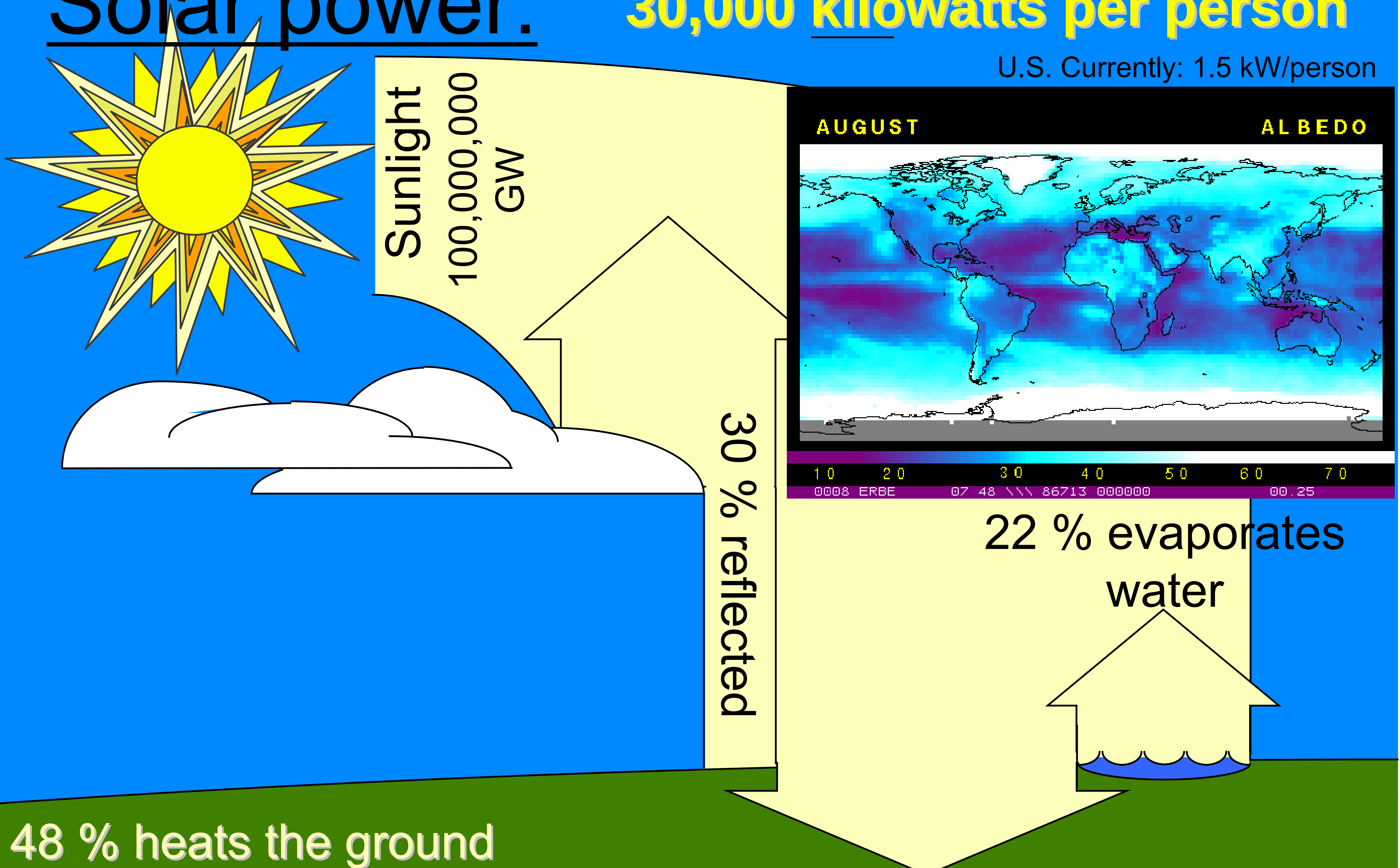


Rosina Bierbaum, Univ. of Michigan, IPCC

The Solar Resource

Solar power: 30,000 kilowatts per person

U.S. Currently: 1.5 kW/person



48 % heats the ground

0.56% used for photosynthesis in plants (840 TW)

0.25% converted to wind (380 TW)

Angus Rockett, Univ. of Illinois

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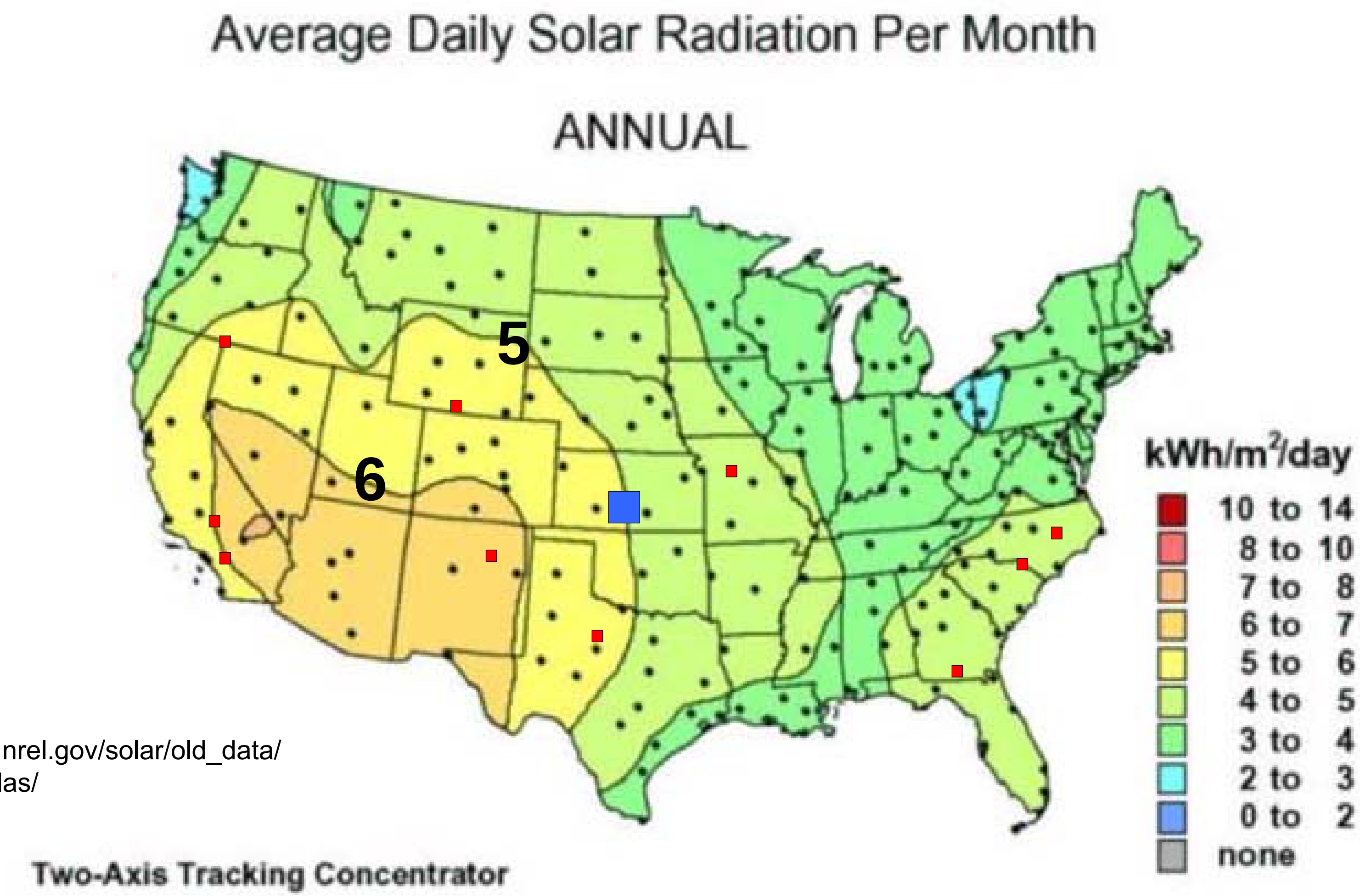
The Solar Resource



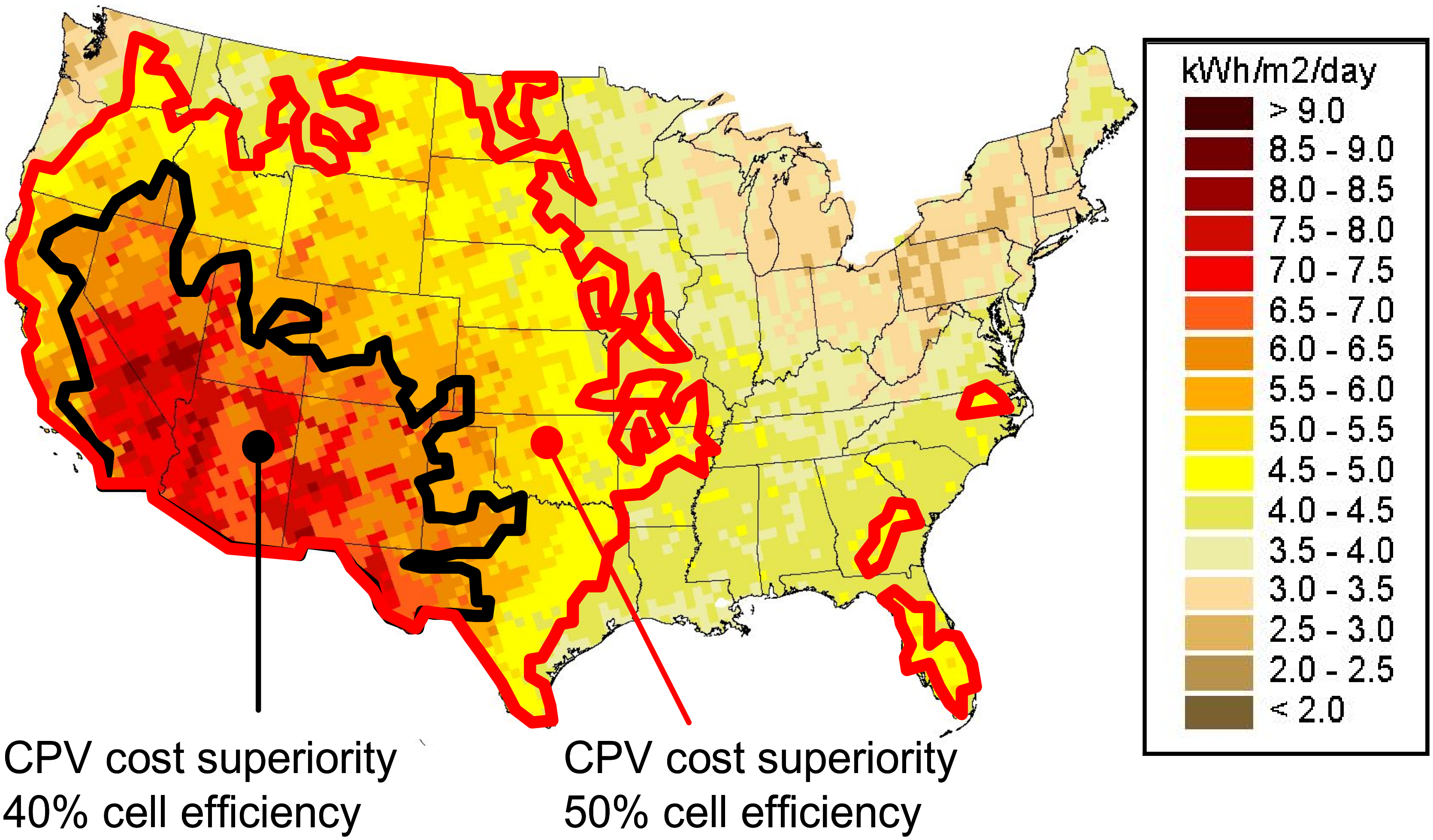
Ref.: http://rredc.nrel.gov/solar/old_data/nsrdb/redbook/atlas/

- **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

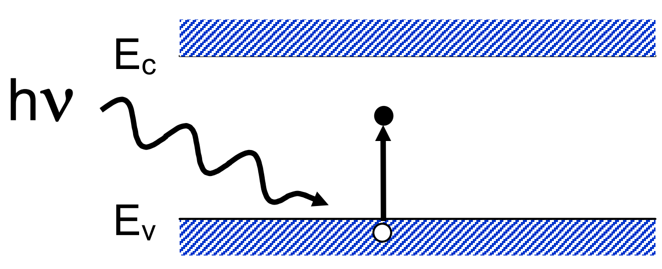


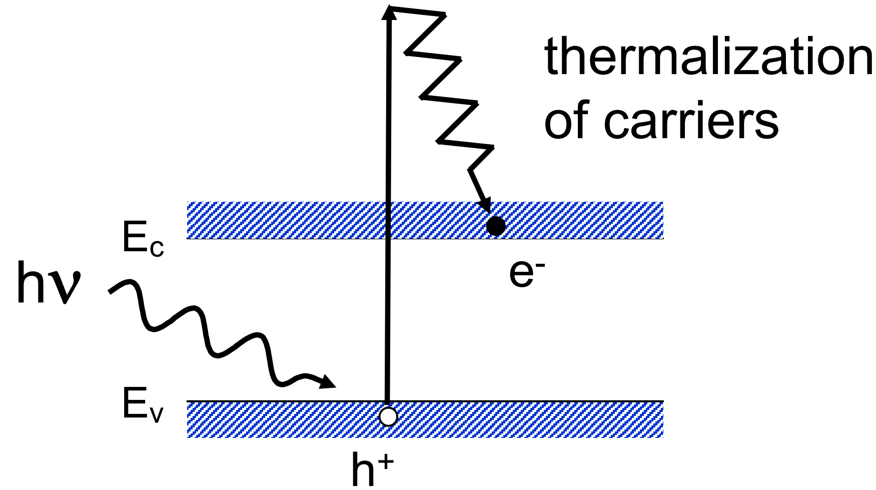
Map source: http://www.nrel.gov/gis/images/map_csp_us_annual_may2004.jpg

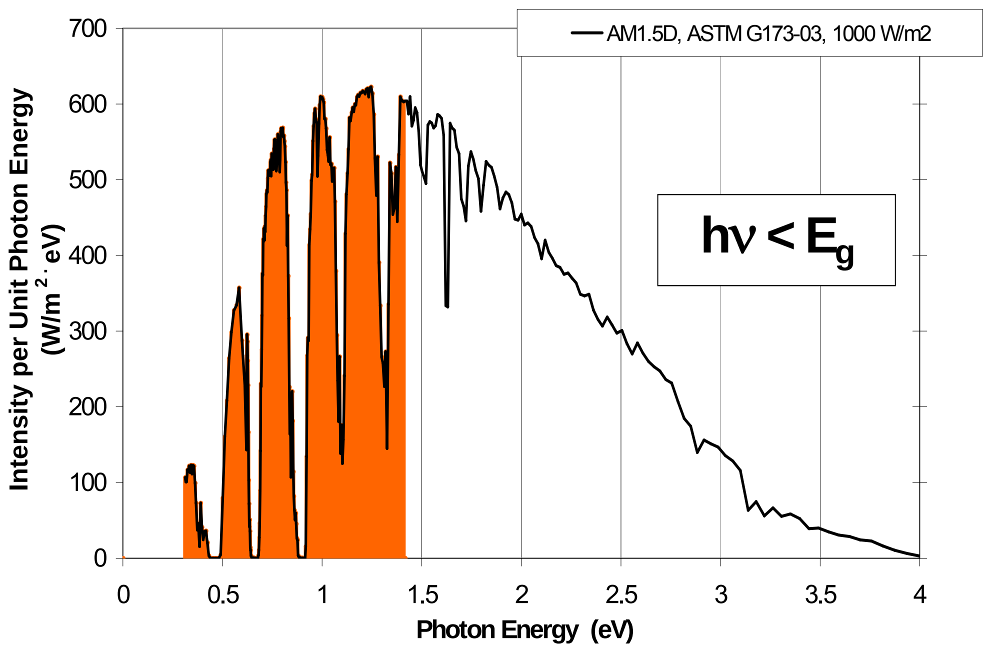
Higher multijunction cell efficiency has a huge impact on the economics of CPV, and on the way we will generate electricity.

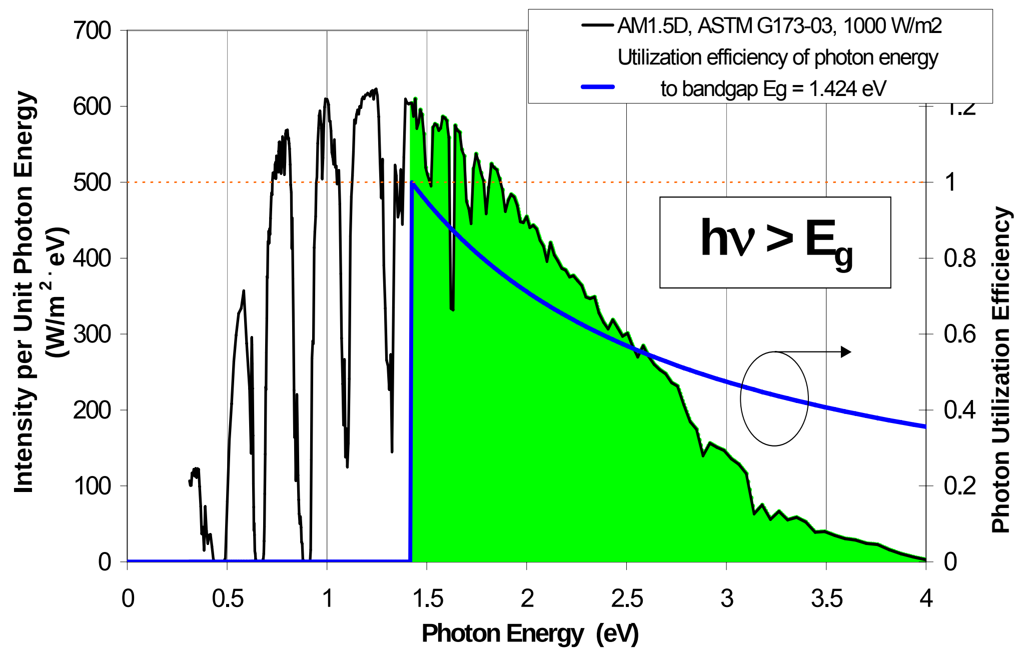
Solar Cell Theoretical Efficiency

Energy Transitions in Semiconductors









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LM and MM 3-Junction Cell Cross-Section

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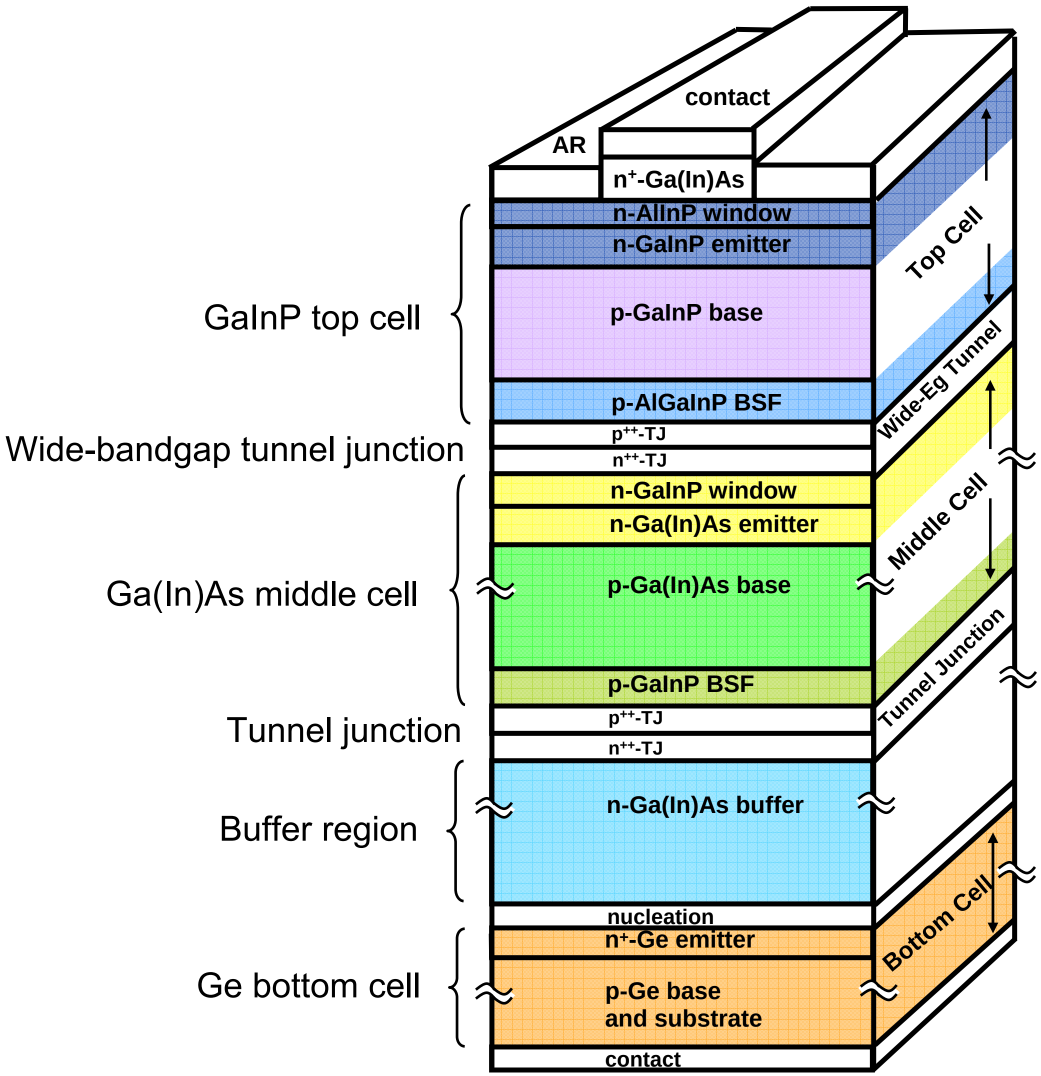
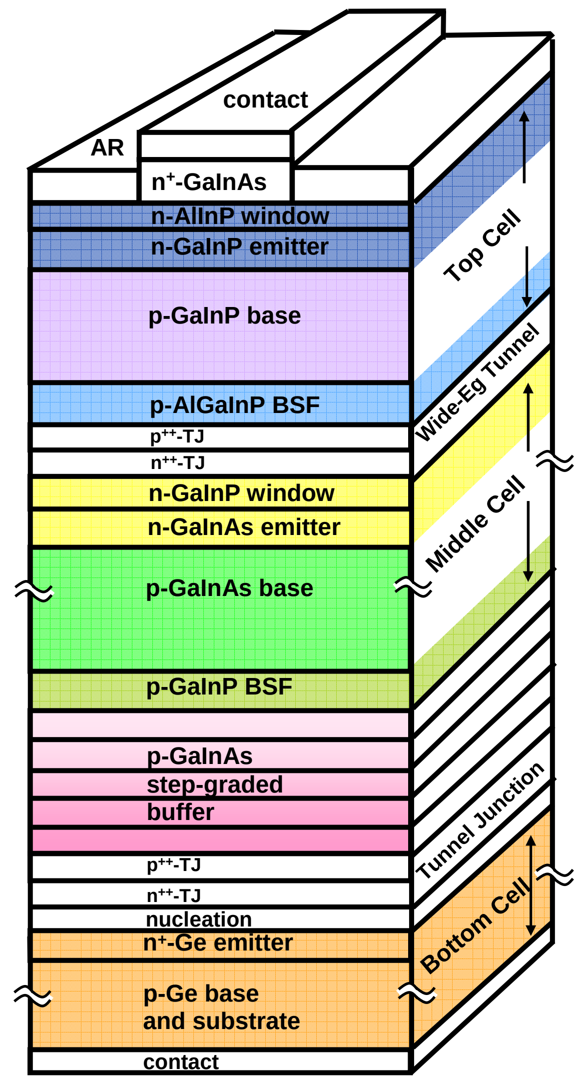


Lattice-Matched (LM)



Lattice-Mismatched or Metamorphic (MM)

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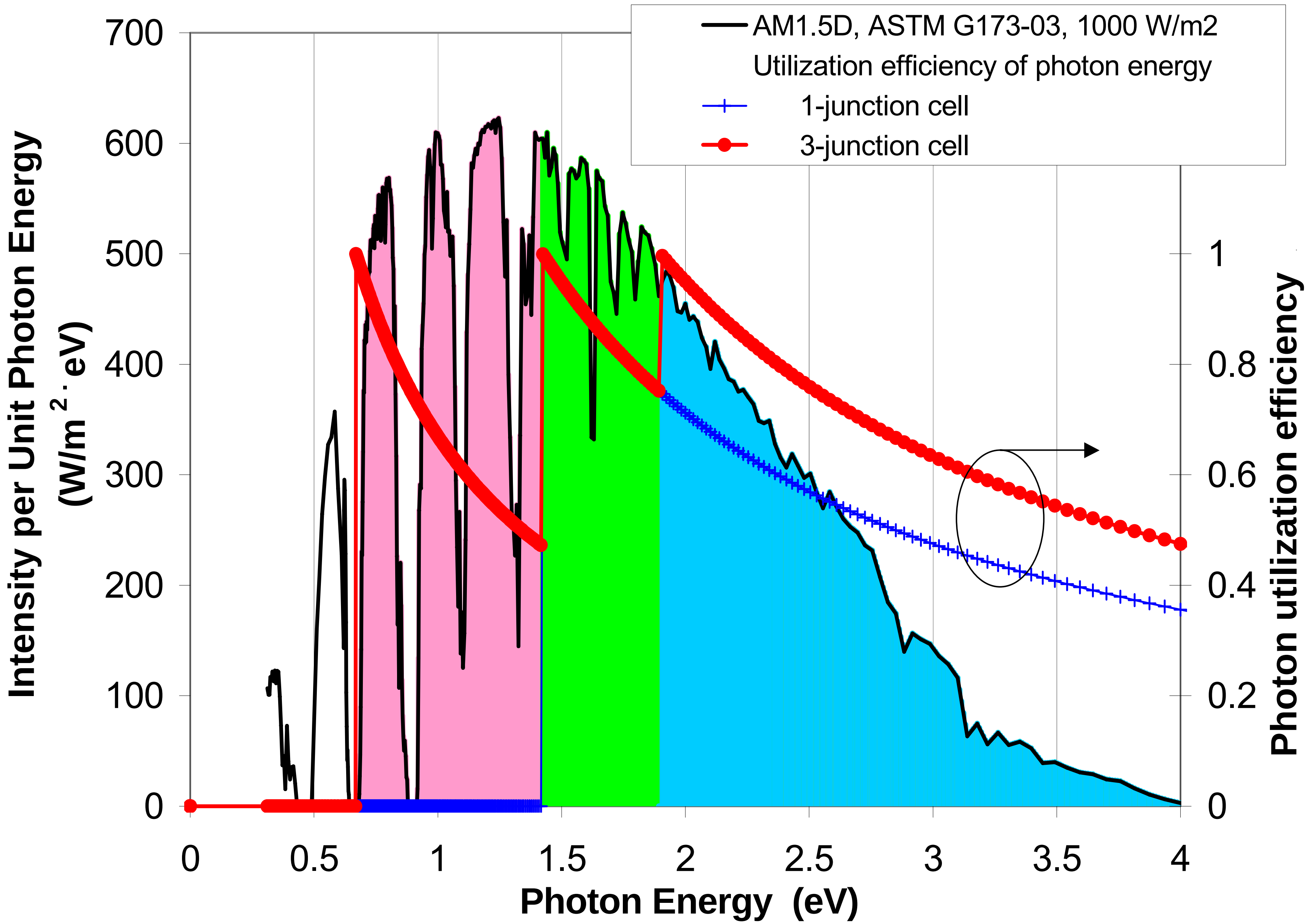
Photon Utilization Efficiency 3-Junction Solar Cells



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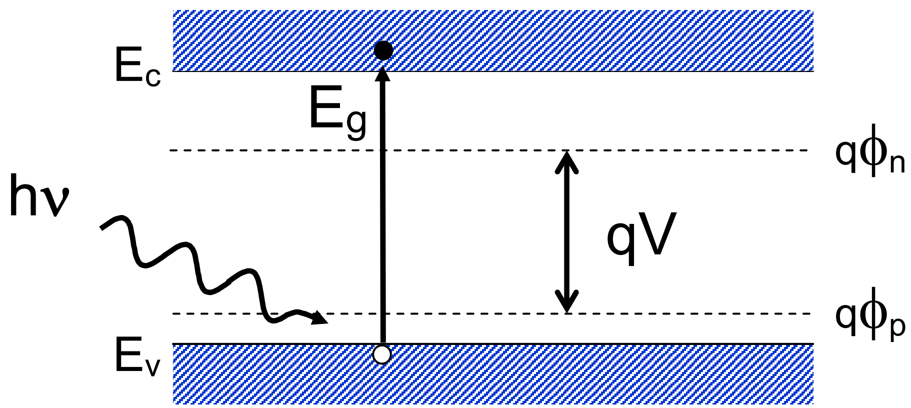
Energy Transitions in Semiconductors



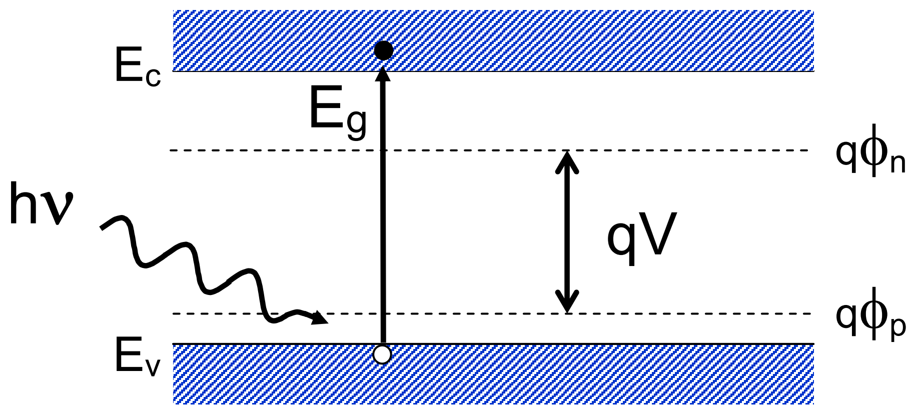
V = voltage of solar cell

= 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



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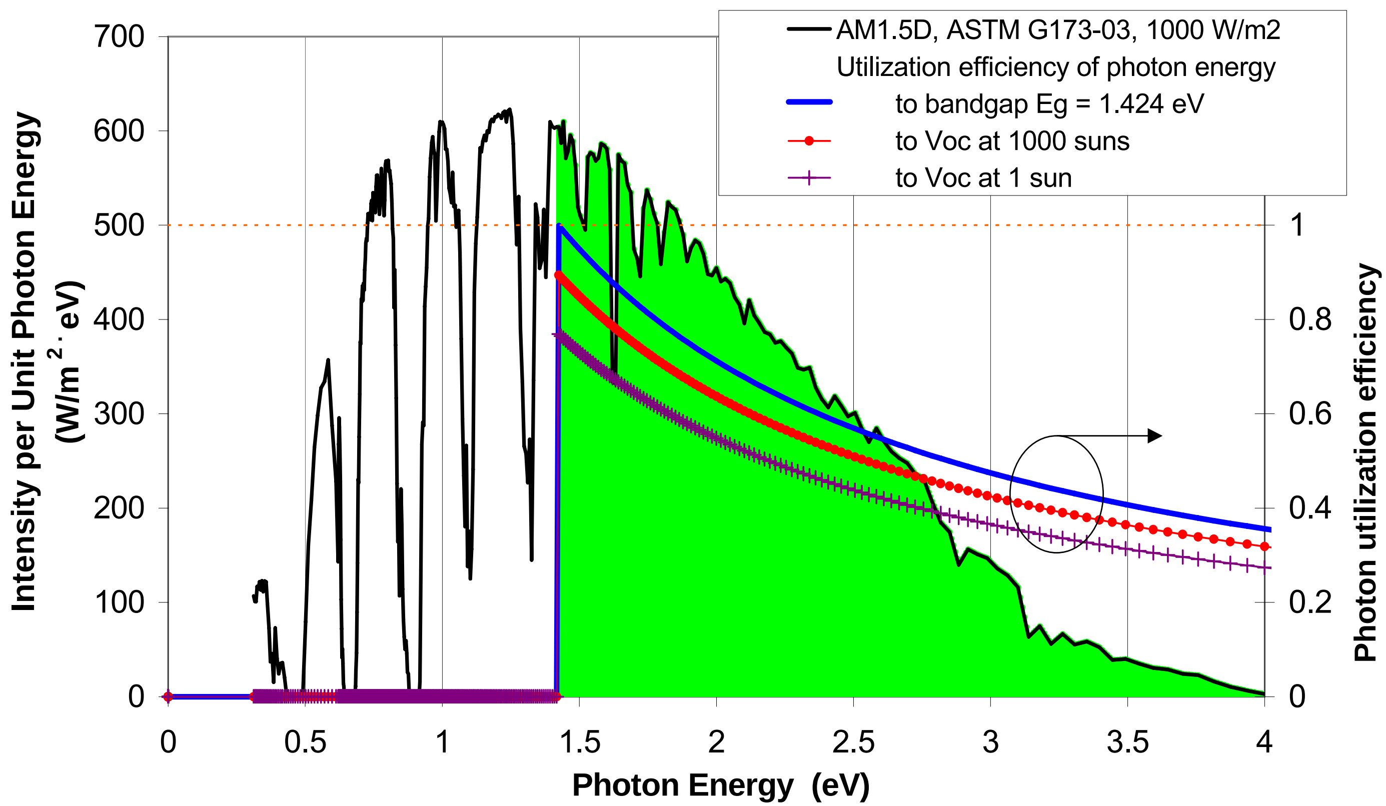

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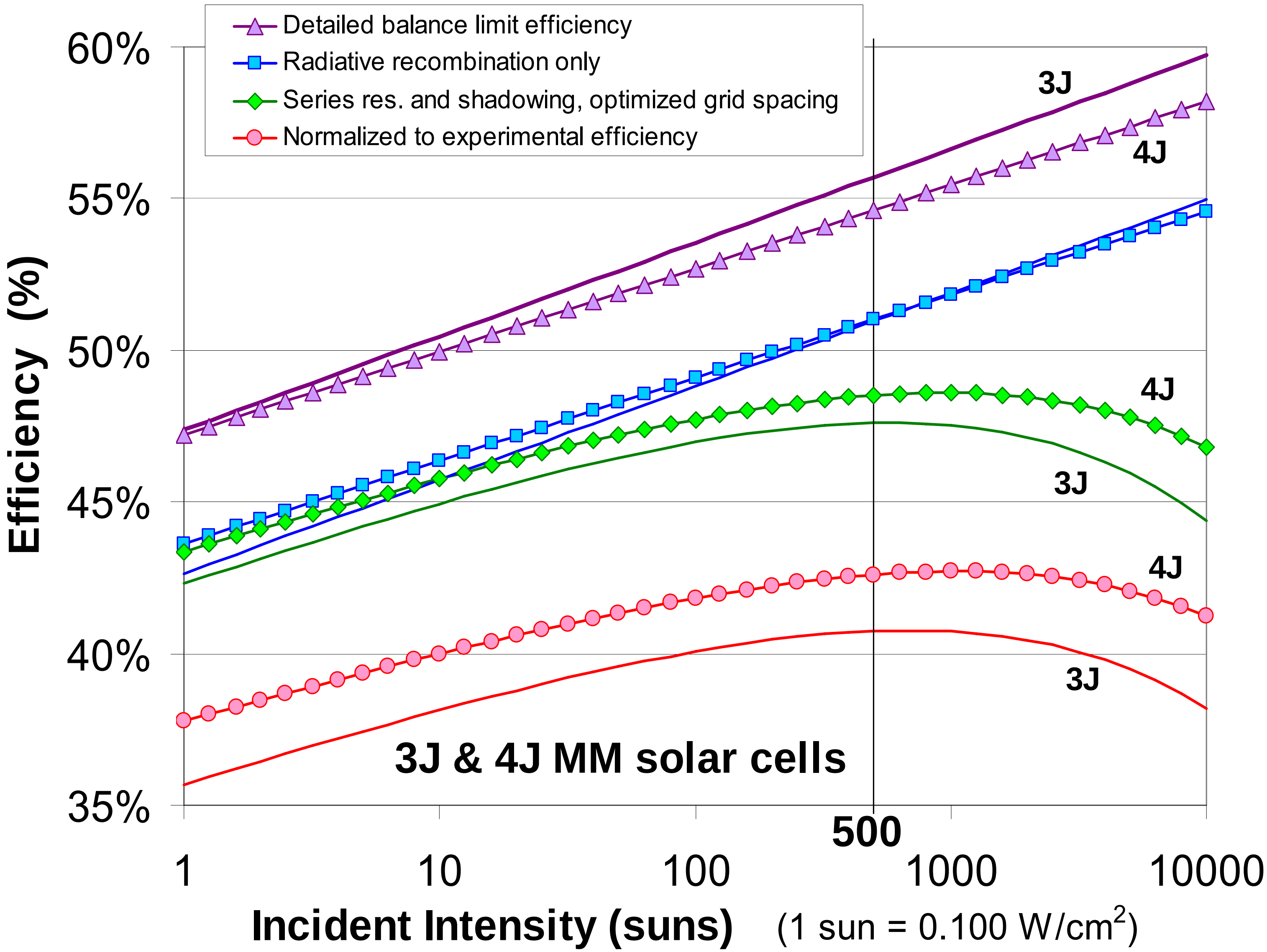
Electronic Materials for Renewable Energy



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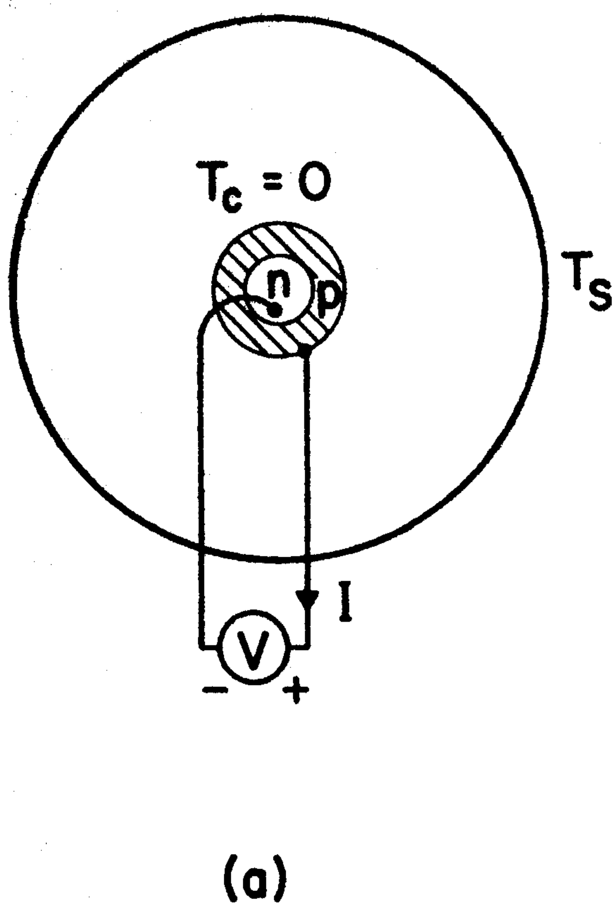
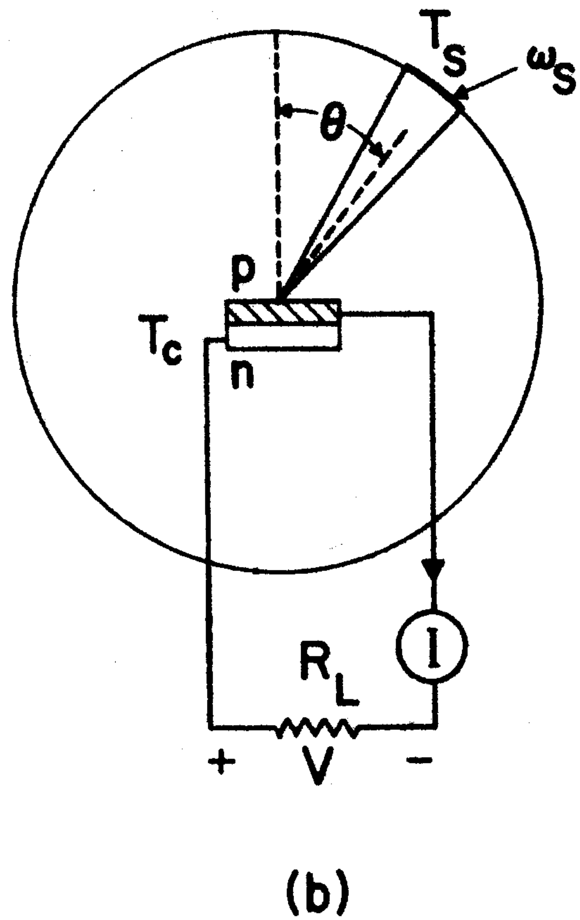
Shockley and Queisser (1961)

Detailed Balance Limit of Solar Cell Efficiency





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

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Assumptions → Opportunities

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- 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

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Maximum Solar Cell Efficiencies

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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/GaInAs cell at 326 suns (NREL) **40.8%**
3-gap GaInP/GaInAs/Ge cell at 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)

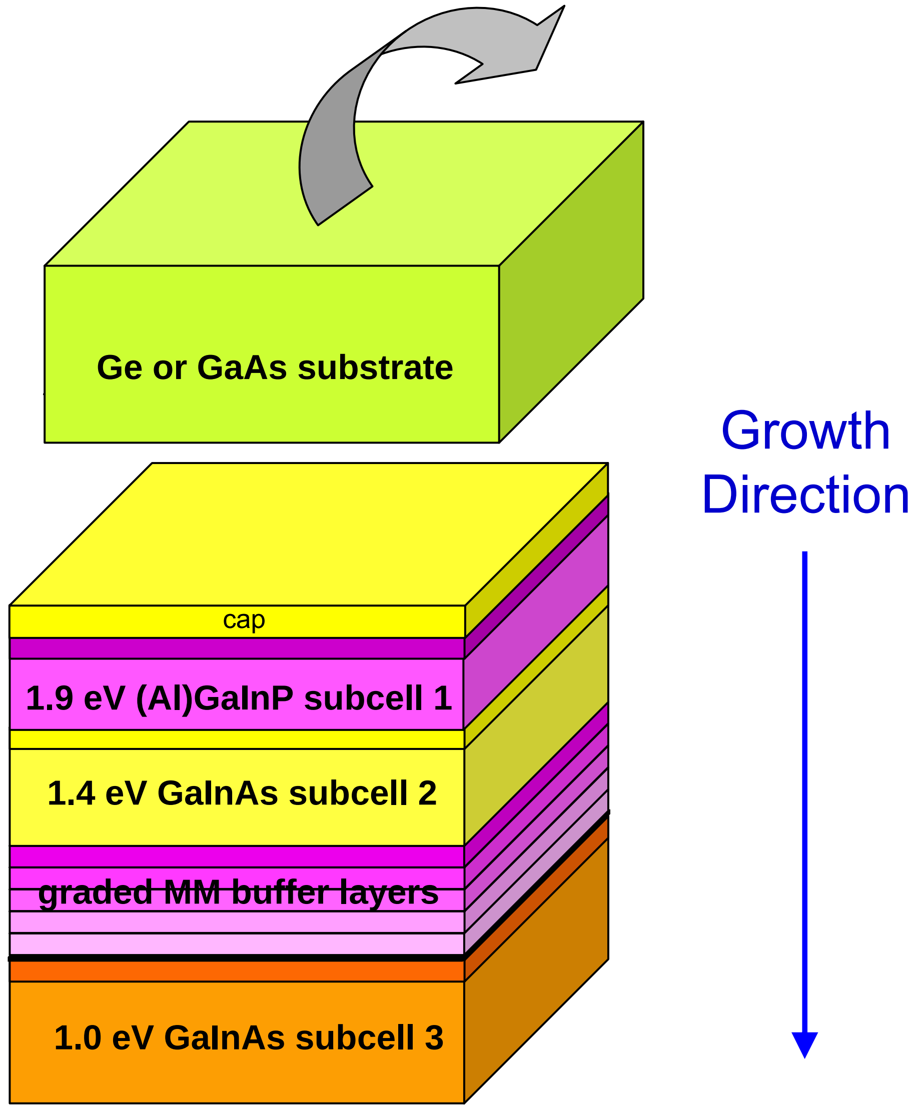
56% Ideal 3-gap solar cell at 1000 suns (Henry)
50% Ideal 2-gap solar cell at 1000 suns (Henry)

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)

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



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

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Solar Spectrum Partition for 3-Junction Cell

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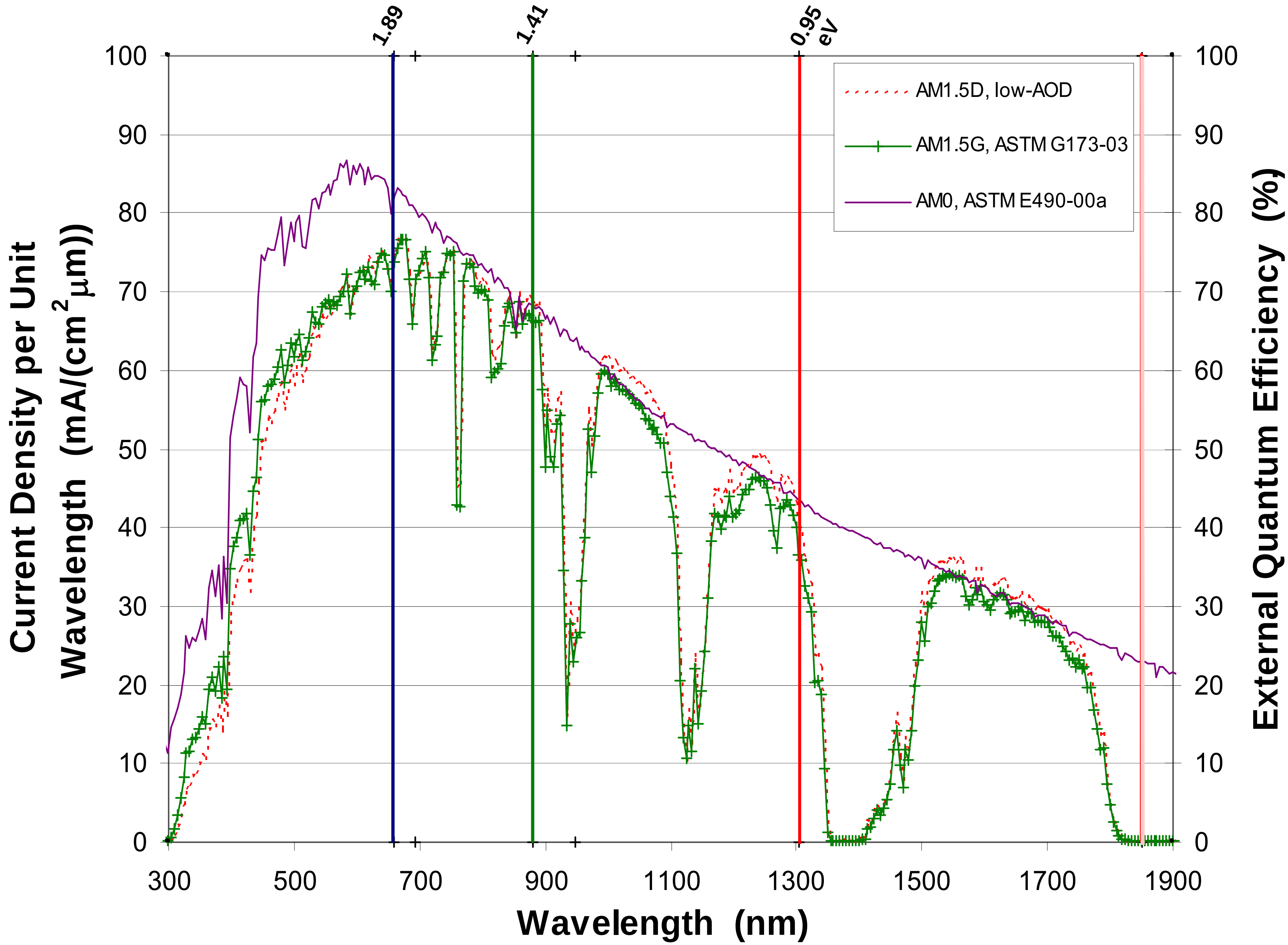

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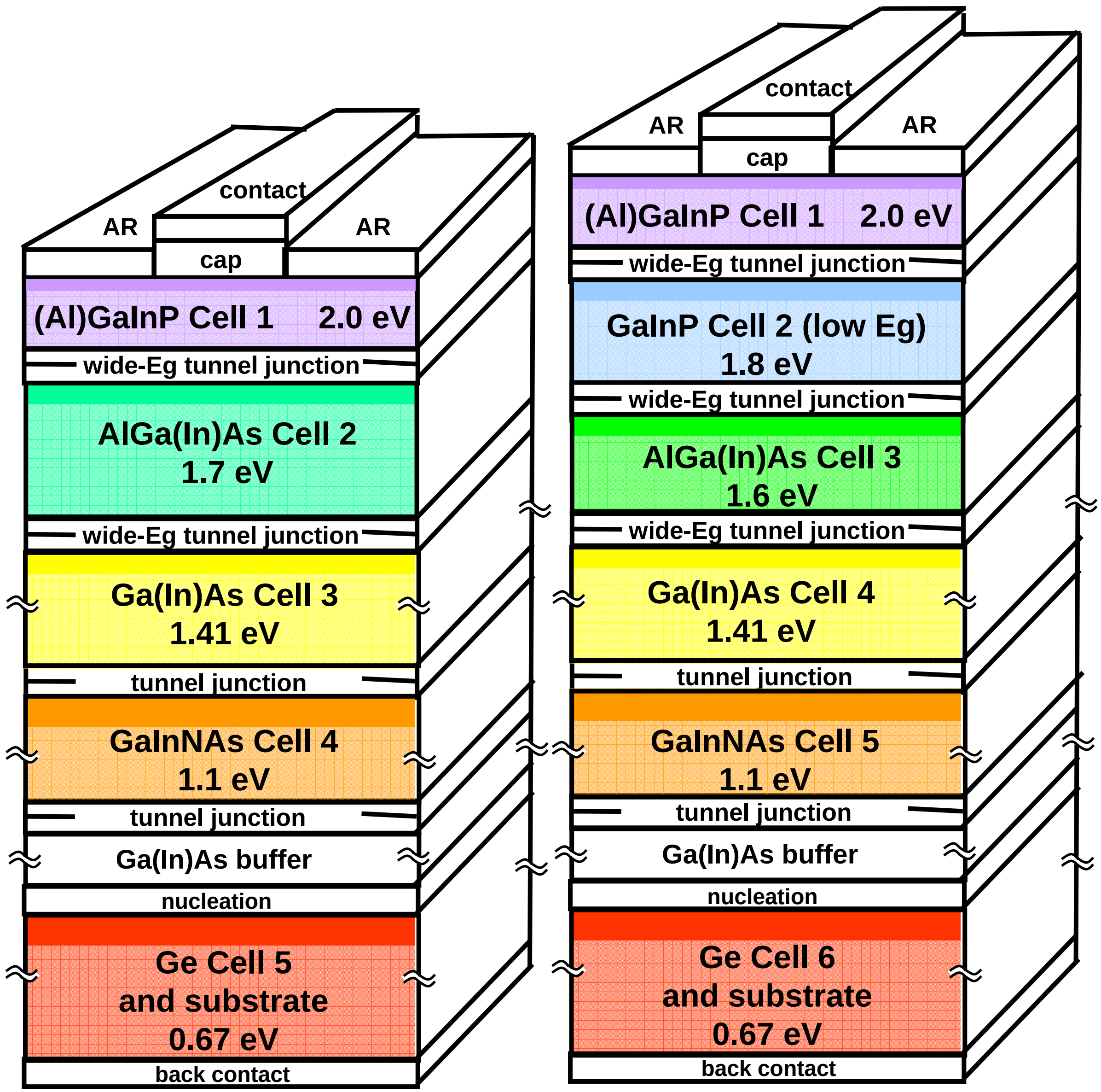
5- and 6-Junction Cells



- **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.

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Photon Utilization Efficiency 3-Junction Solar Cells

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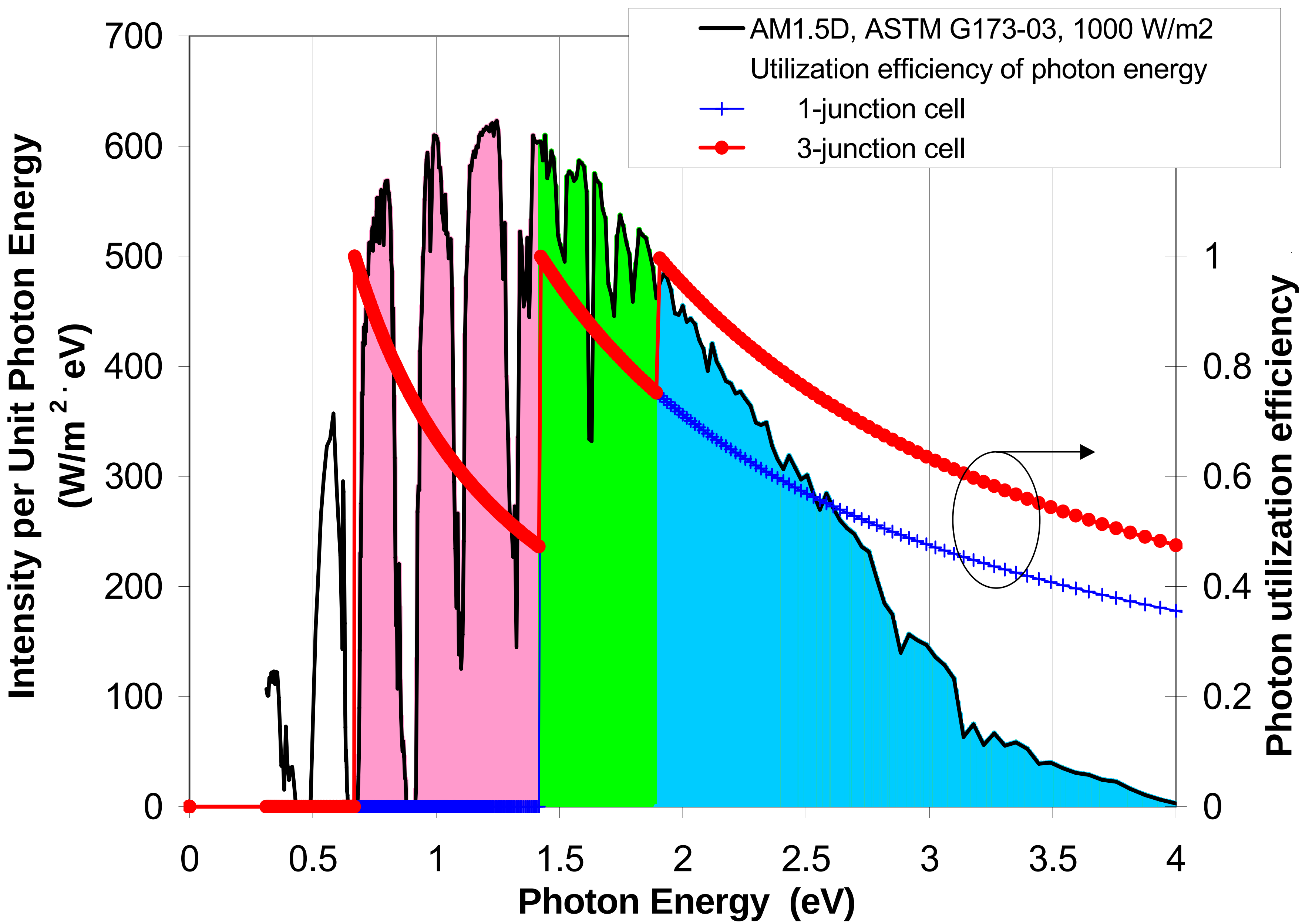

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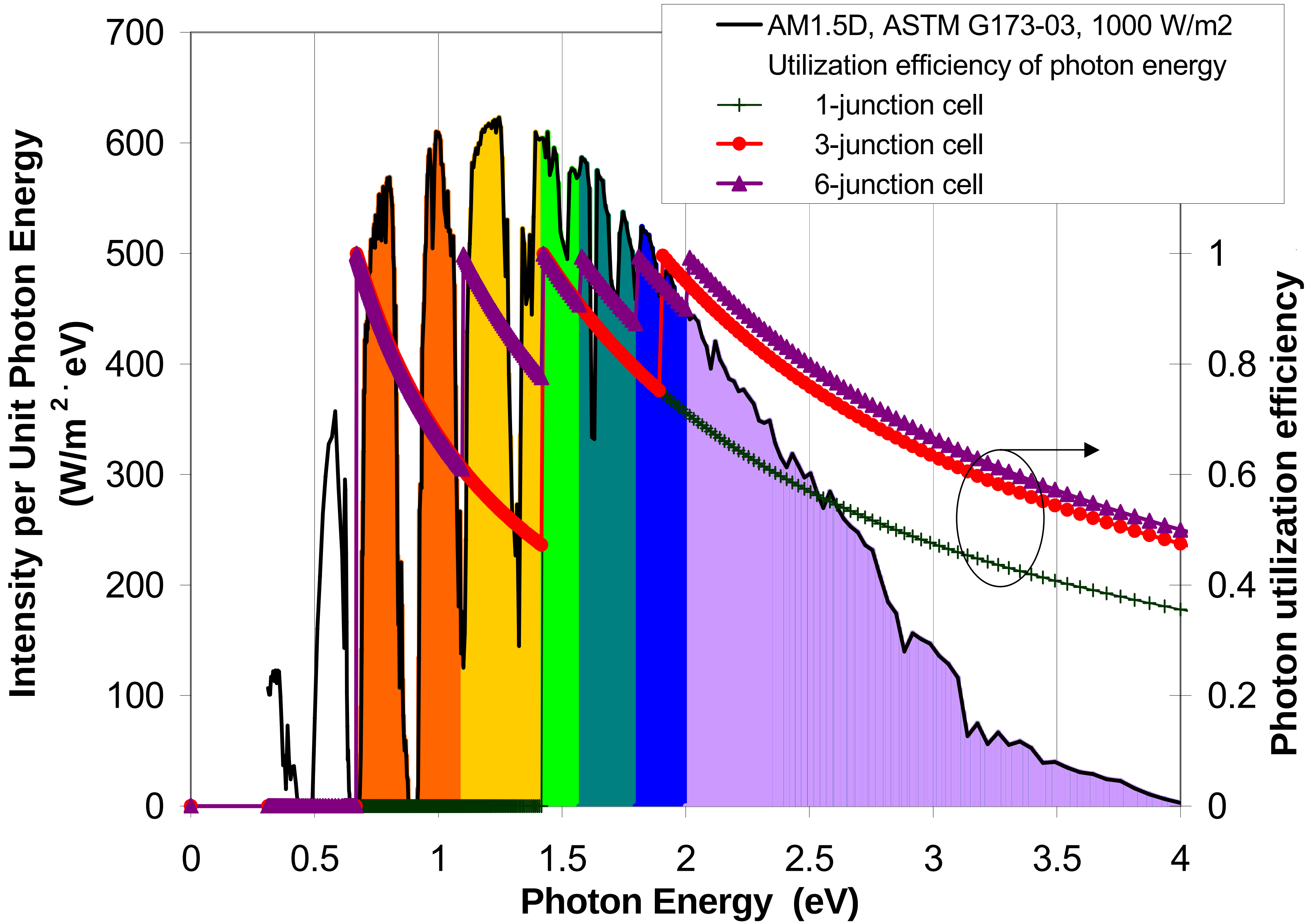
Photon Utilization Efficiency 6-Junction Solar Cells



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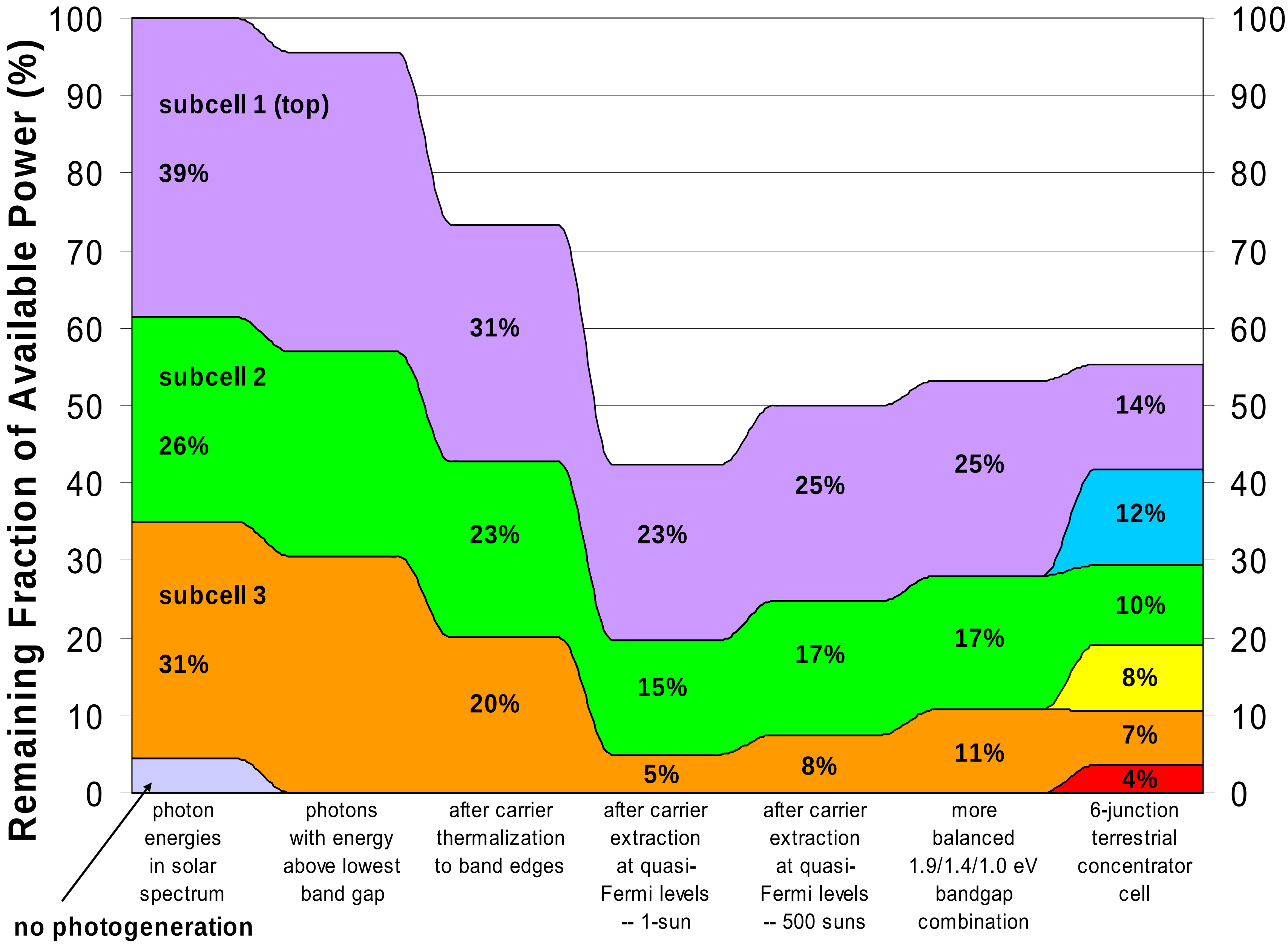
3-Junction Cell Efficiency Losses from 100%



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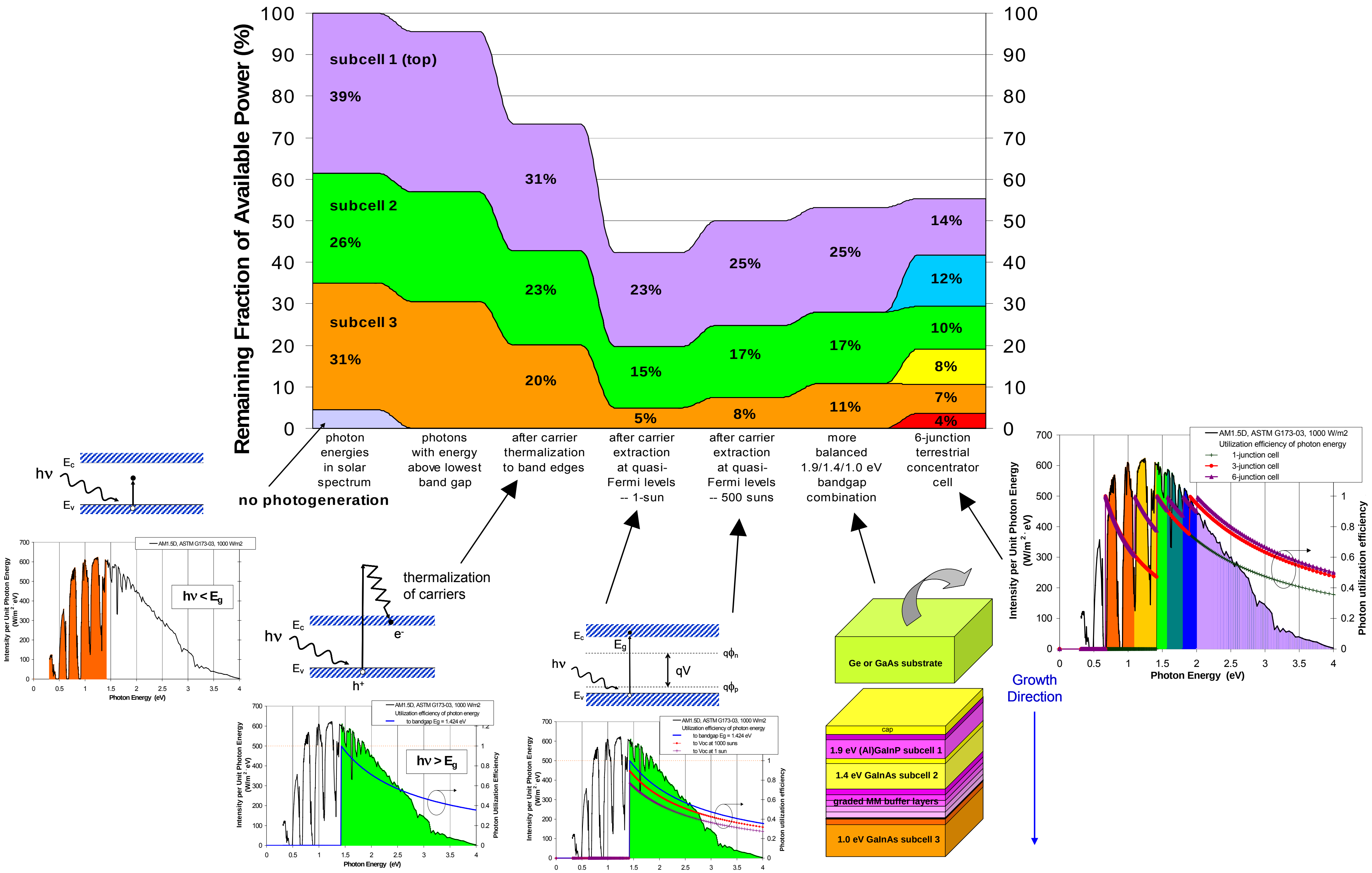
3-Junction Cell Efficiency Losses from 100%



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Metamorphic Semiconductor Materials

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Metamorphic (MM) Semiconductor Materials

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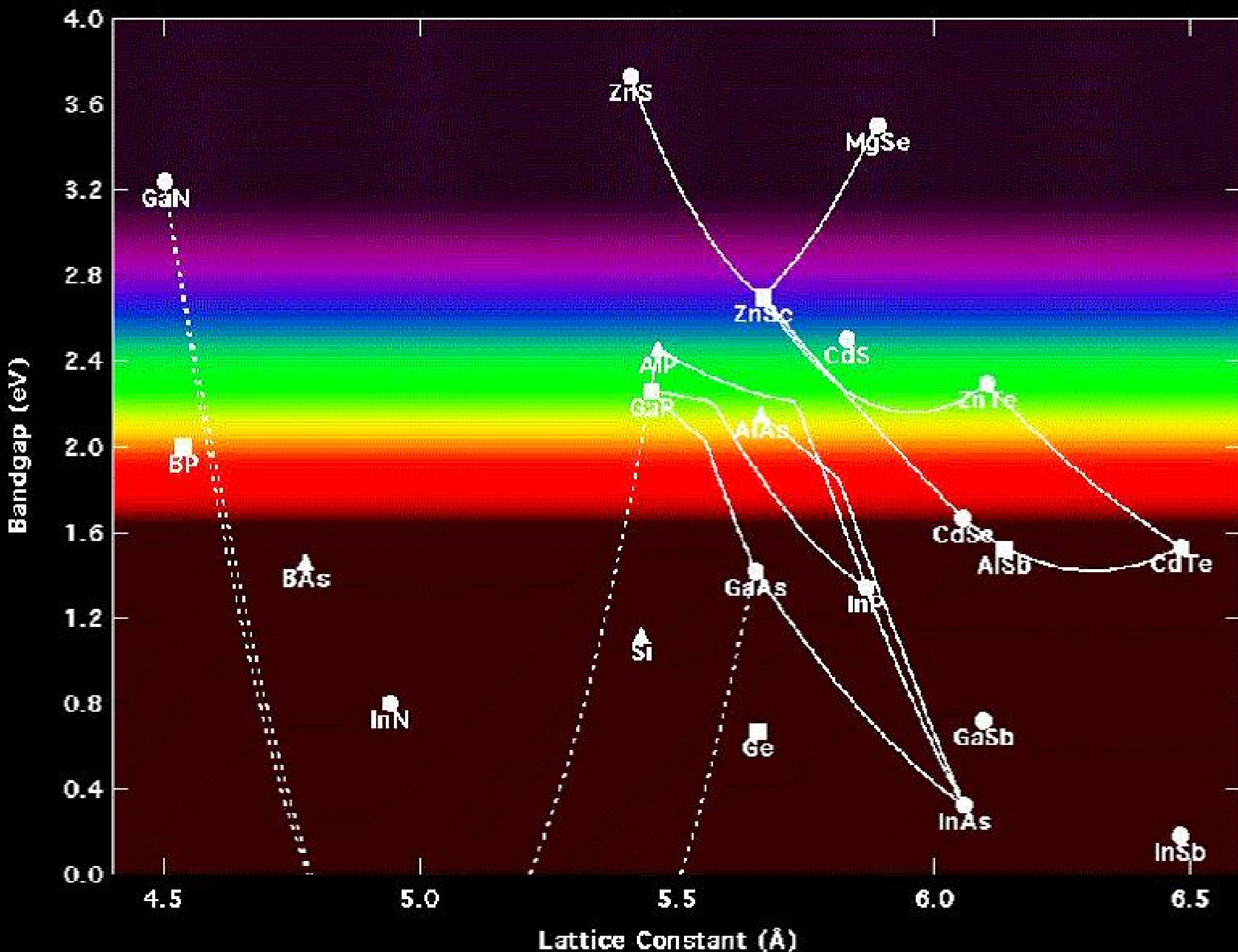
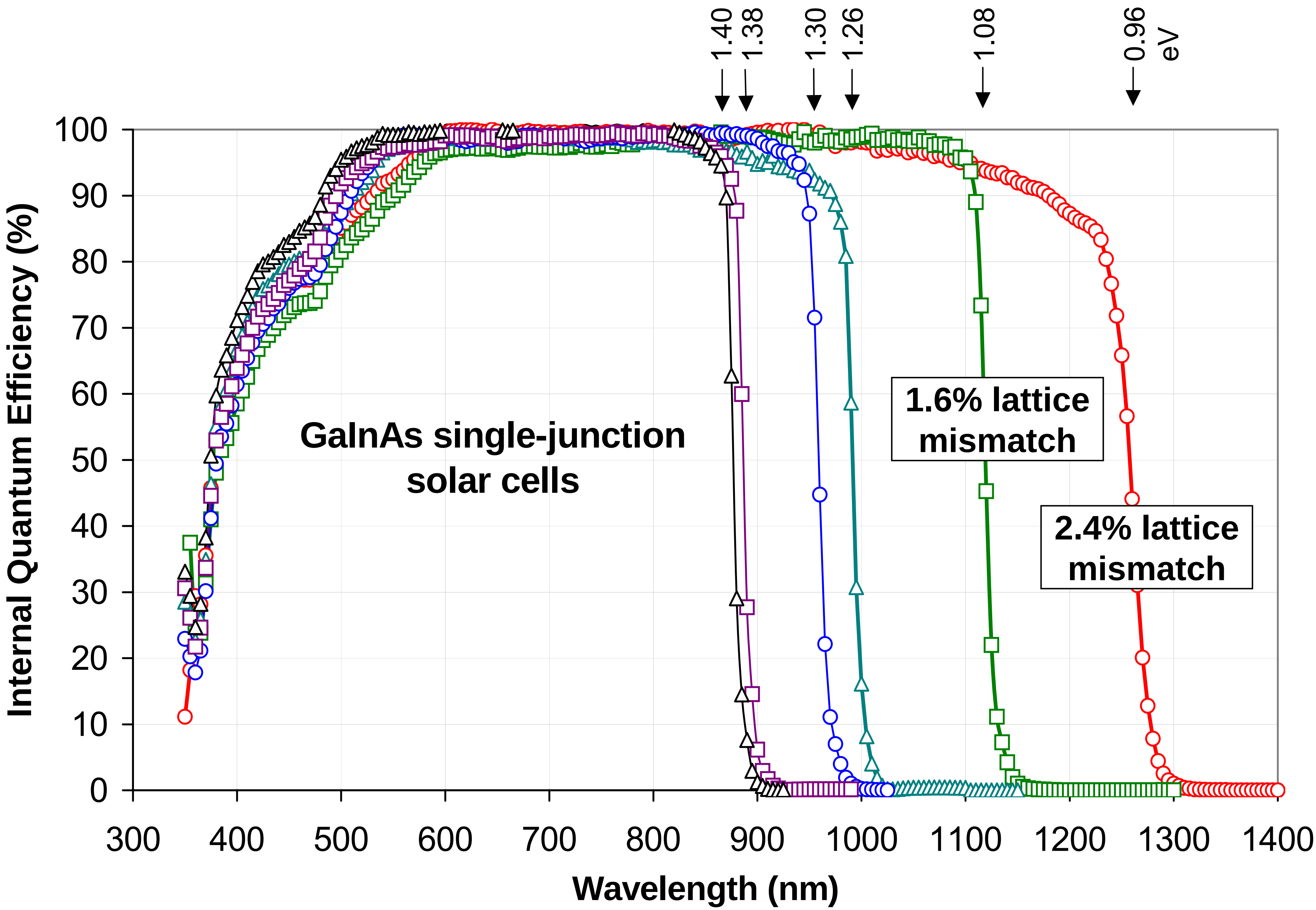
- Metamorphic = "changed form"
- Thick, relaxed epitaxial layers grown with different lattice constant than growth substrate
- Allows access to subcell band gaps desired for more efficient division of the solar spectrum in multijunction solar cells
- Also called lattice-mismatched
- Misfit dislocations 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

Internal QE of Metamorphic GaInAs Cells on Ge



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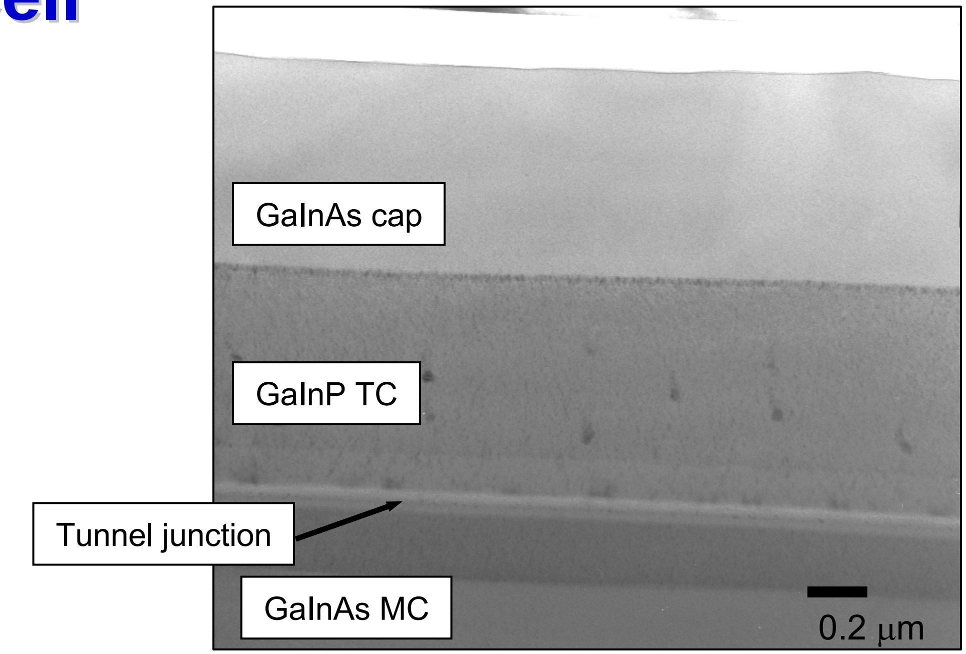
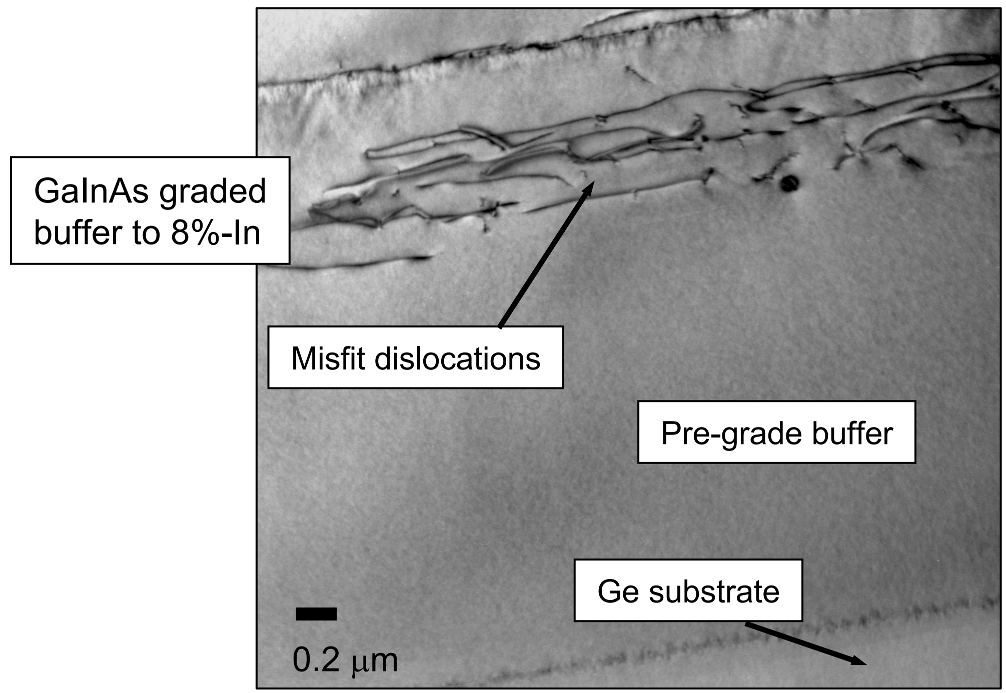
Cross sectional TEM $Ga_{0.44}In_{0.56}P$/ $Ga_{0.92}In_{0.08}As$/ Ge Cell

- 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





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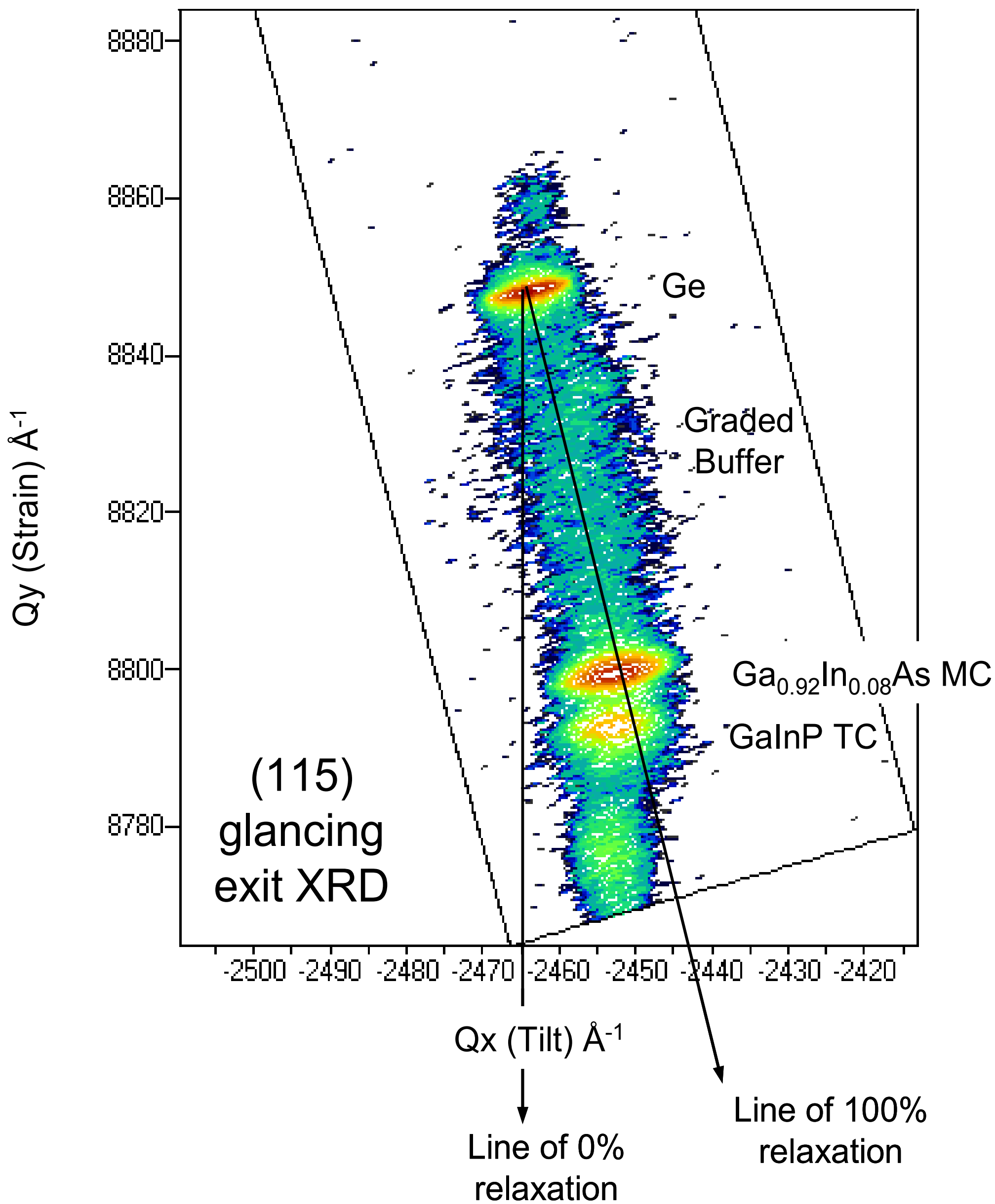
High-Resolution XRD Reciprocal Space Map (RSM)



- 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

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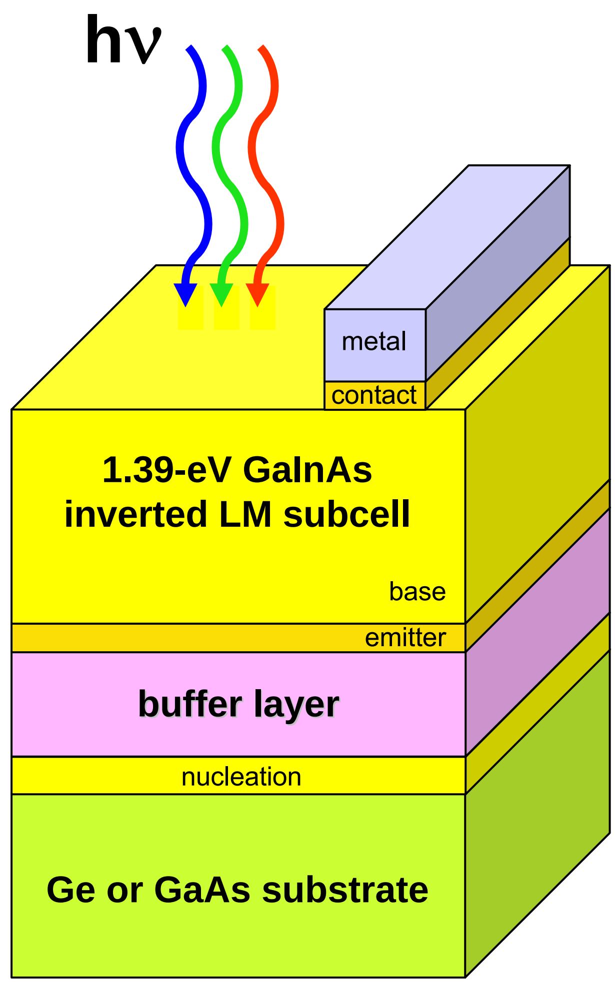
Inverted Lattice-Matched (LM) 1.39-eV GaInAs Subcell



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

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

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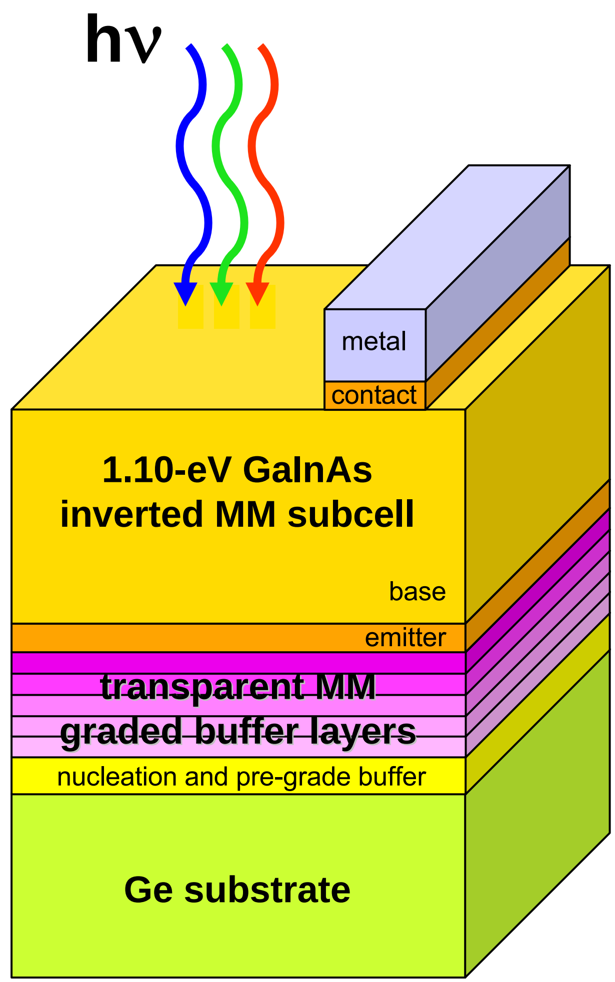

Growth on Ge or GaAs substrate, followed by substrate removal from sunward surface

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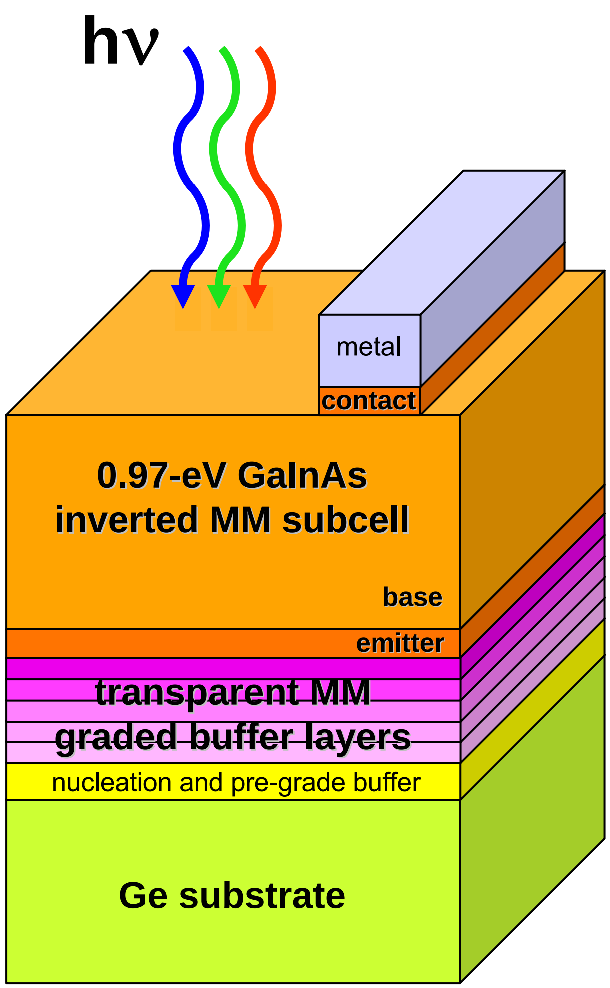
Metamorphic (MM) 3-Junction Cells –– Inverted 0.97-eV GaInAs Subcell



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

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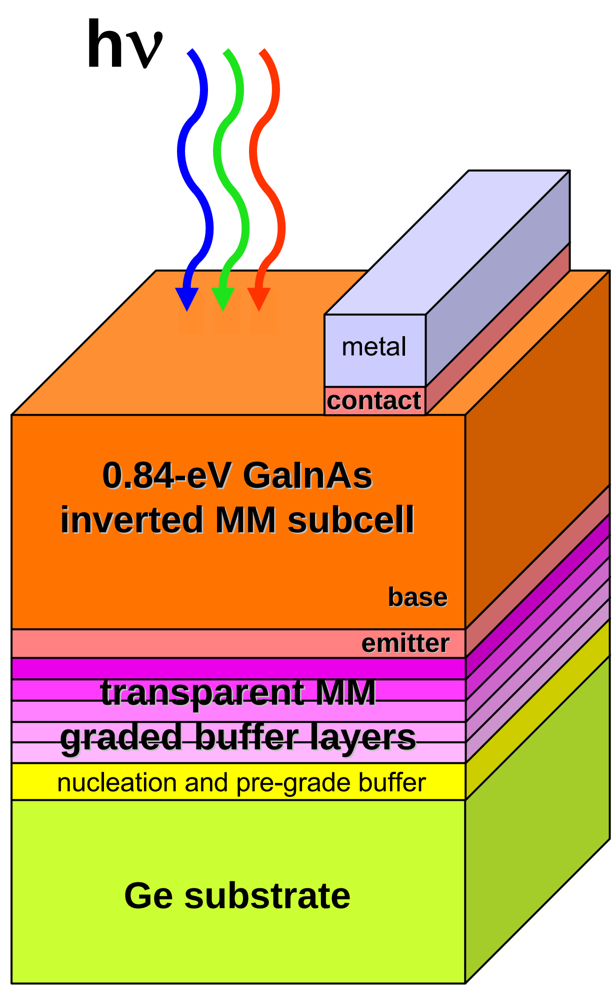
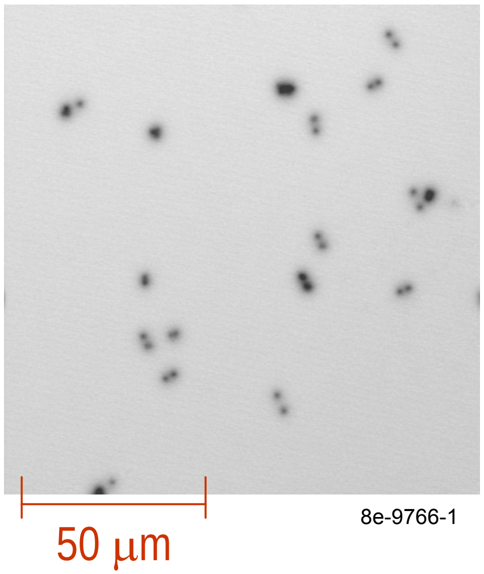
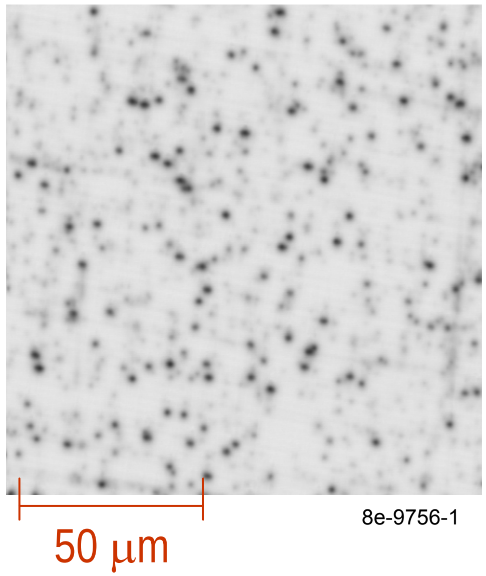
Metamorphic (MM) 3-Junction Cells –– Inverted 0.84-eV GaInAs Subcell

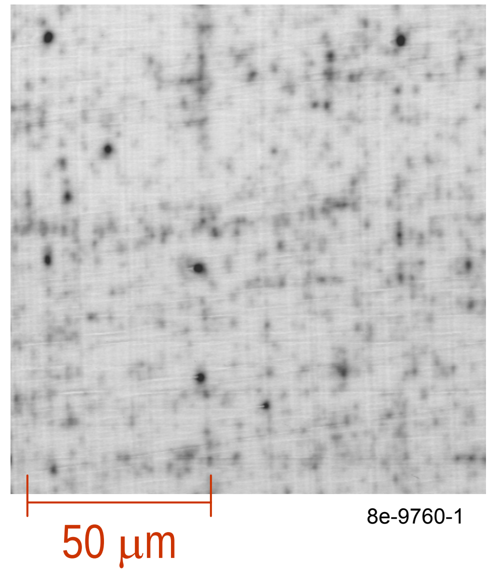


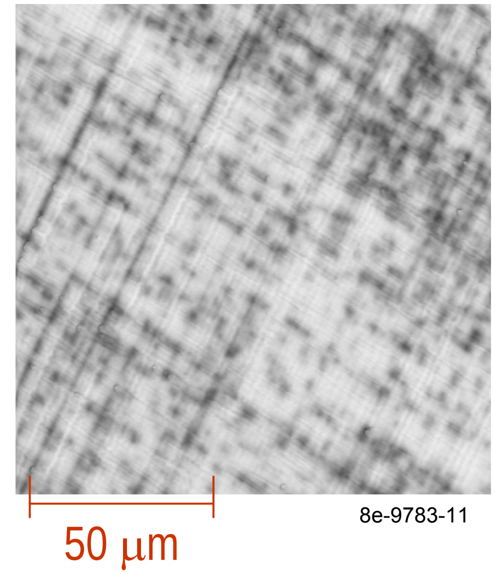
Growth on Ge or GaAs substrate, followed by substrate removal from sunward surface

Dislocations in Inverted Metamorphic Cells – EBIC

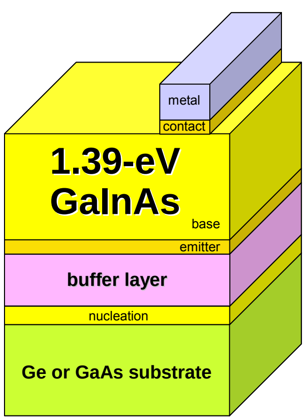


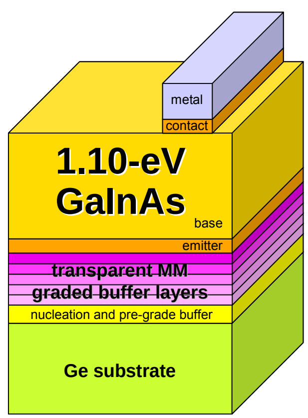


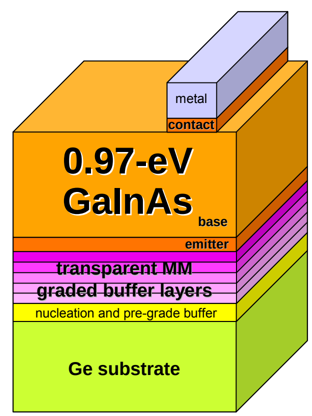


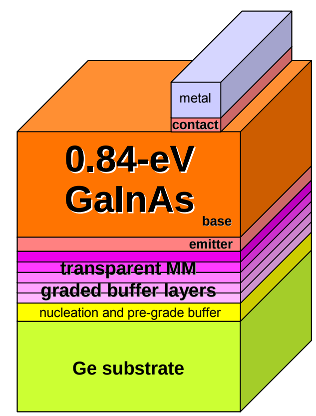


	1.39-eV ILM subcell	1.10-eV IMM subcell	0.97-eV IMM subcell	0.84-eV IMM subcell
GaInAs comp.	2% In	23% In	33% In	44% In
Latt. mismatch	0.1%	1.6%	2.3%	3.1%
Disloc. density	2.5 x 10^5 cm^{-2}	3.9 x 10^6 cm^{-2}	5.0 x 10^6 cm^{-2}	6.3 x 10^6 cm^{-2}



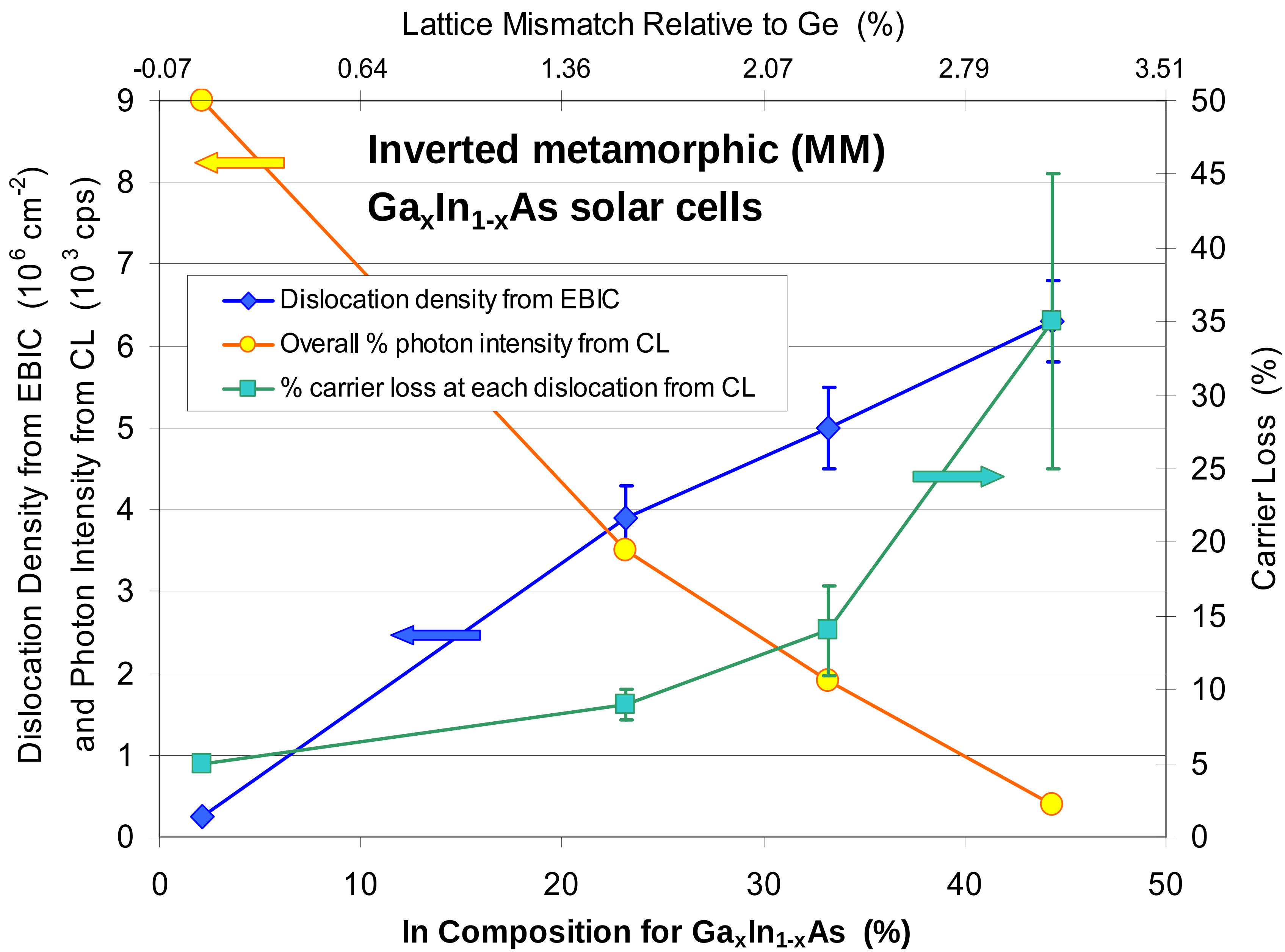






EBIC images and dislocation density of inverted metamorphic cell test structures

Dislocations in Inverted Metamorphic Cells



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Solar Cell Voltage

Voltage depends on non-equilibrium concentrations of electrons and holes

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

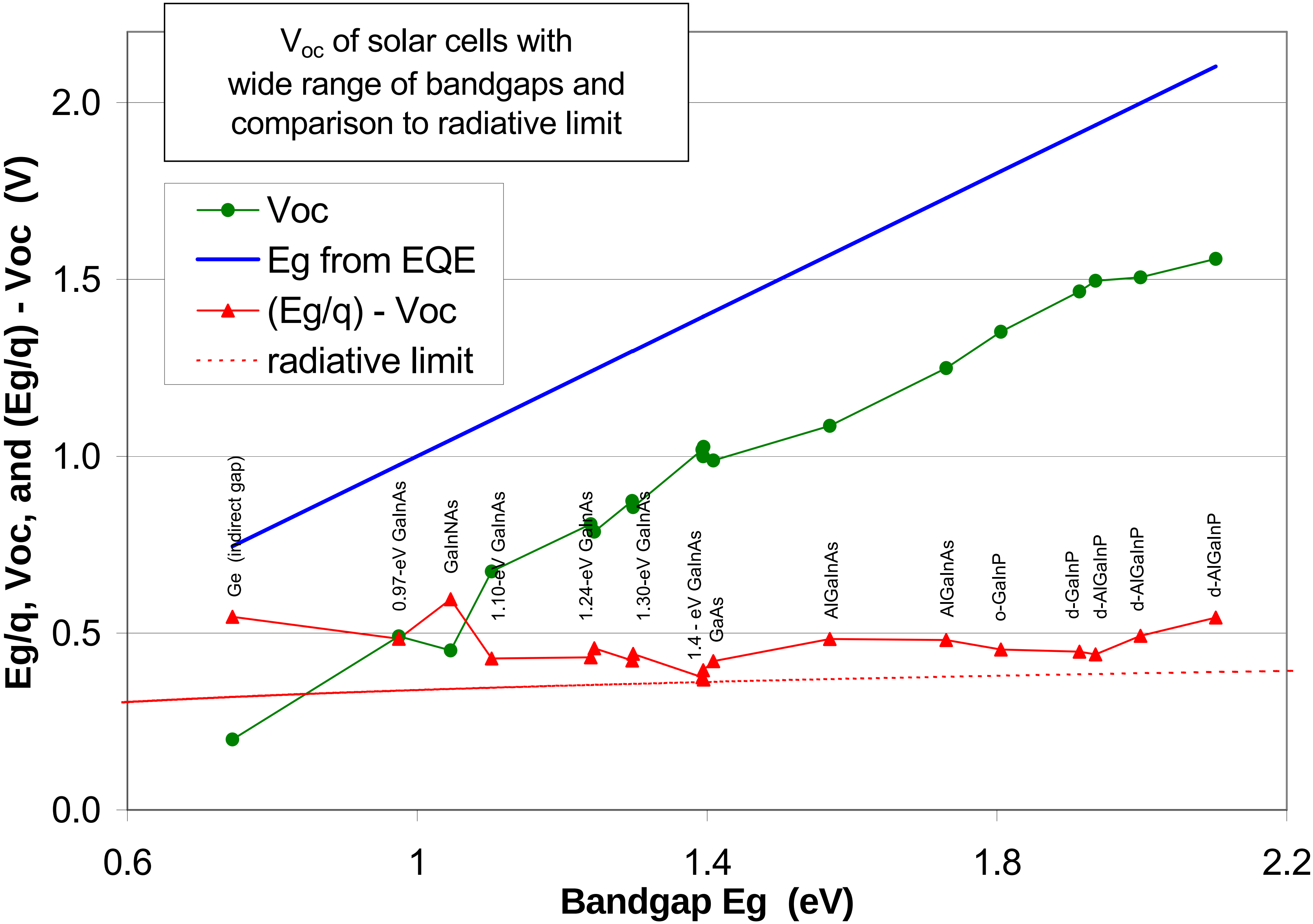
$$n_i^2 = N_C N_V e^{-E_g/kT} \qquad pn = N_C N_V e^{-(E_g - qV)/kT} = N_C N_V e^{-qW/kT}$$

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

- 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



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

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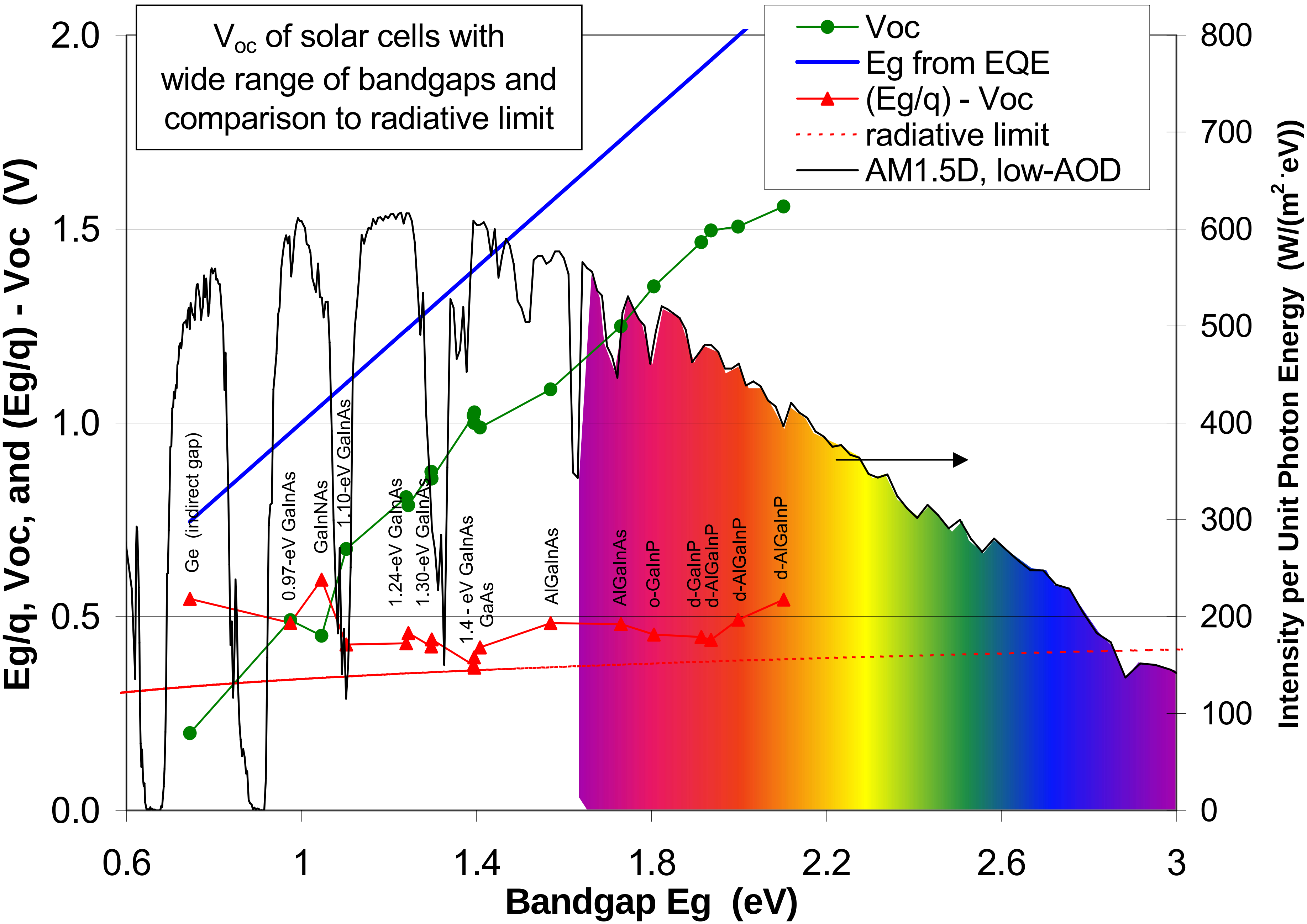

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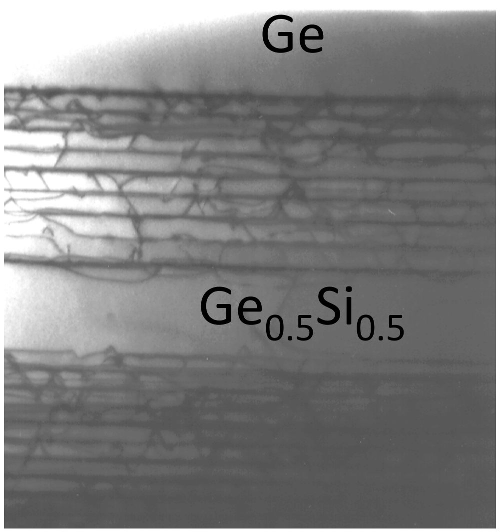
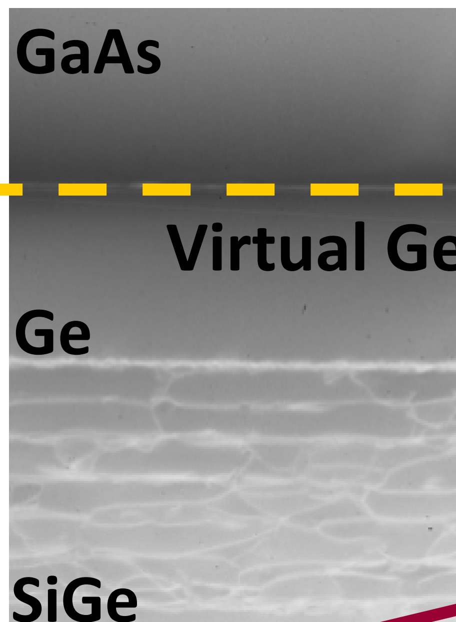
Metamorphic III-V Growth on Si Substrates Using SiGe Buffers

SiGe metamorphic substrate engineering for III-V/Si PV

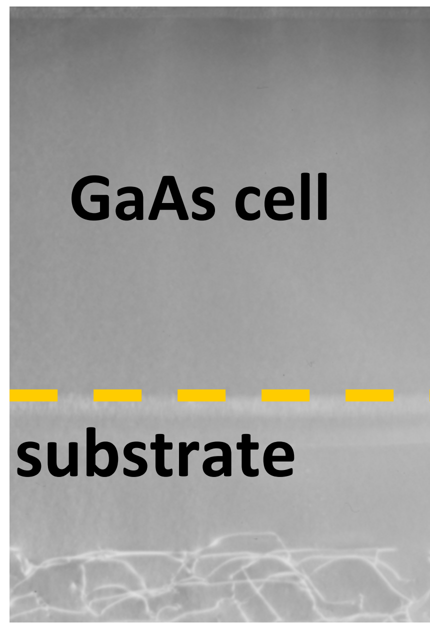
engineered Si substrate: Virtual Ge



GaAs matl on Si: virtual GaAs



Single junction PV cell on Si



Dual junction PV cell on Si

Virtual Ge substrate

Being commercialized by 4Power

Steve Ringel, Ohio State, and Gene Fitzgerald, MIT

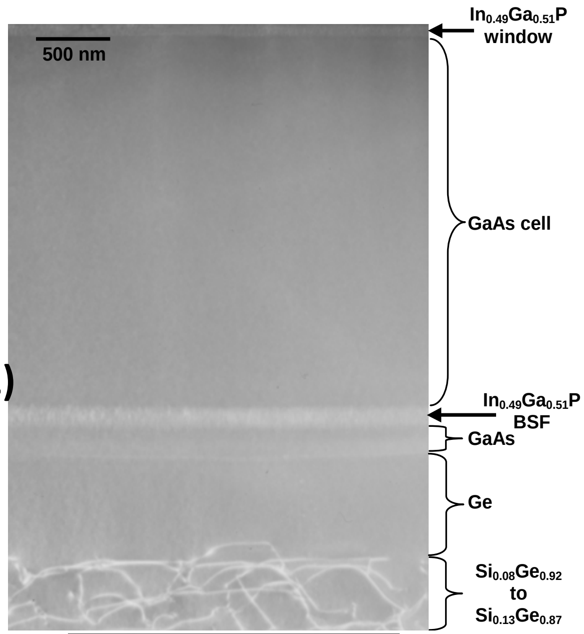
III-V/Si PV Results via SiGe Substrate Engineering

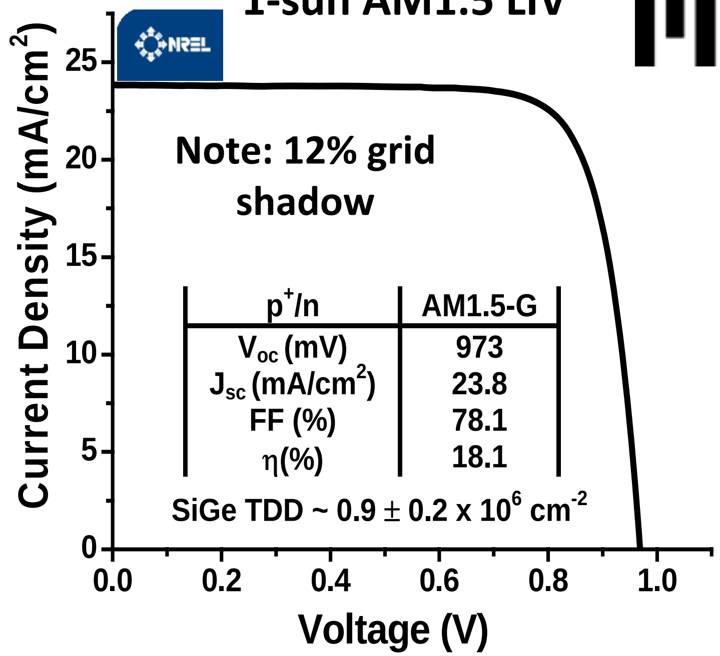
GaAs SJ cell on SiGe

(Andre, et al., IEEE TED 2005)

(Ringel et al., Prog. In PV, 2002)

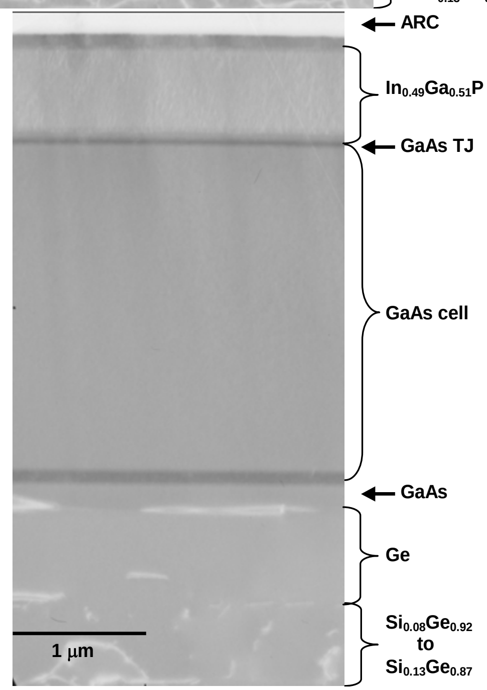
X-TEM

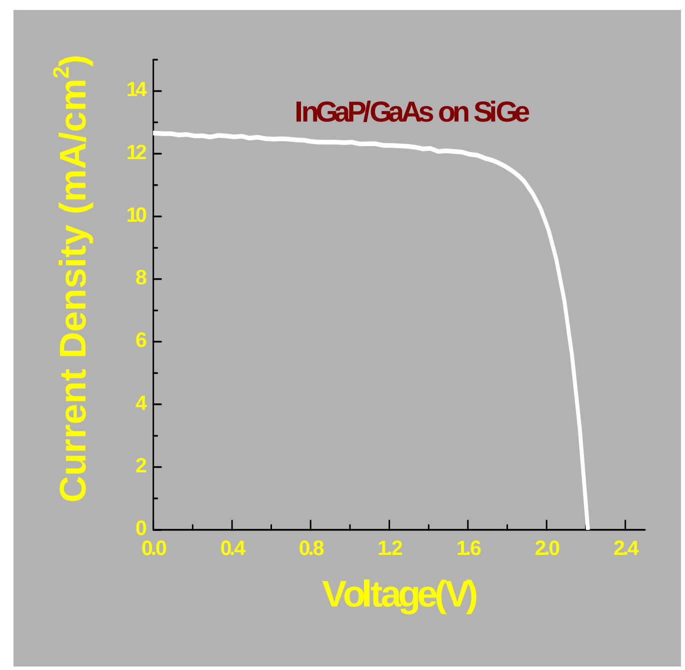




GaInP/GaAs DJ cell on SiGe

(Lueck et al, IEEE EDL 2006)
(Ringel, et al, 2004 Fall MRS; IEEE PVSC 2005)





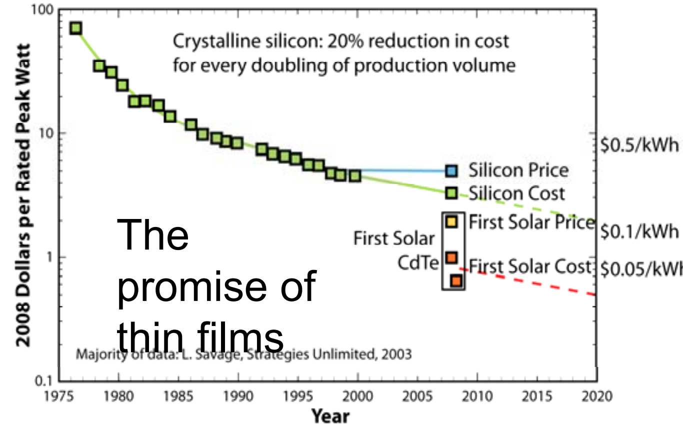
Steve Ringel, Ohio State, and Gene Fitzgerald, MIT

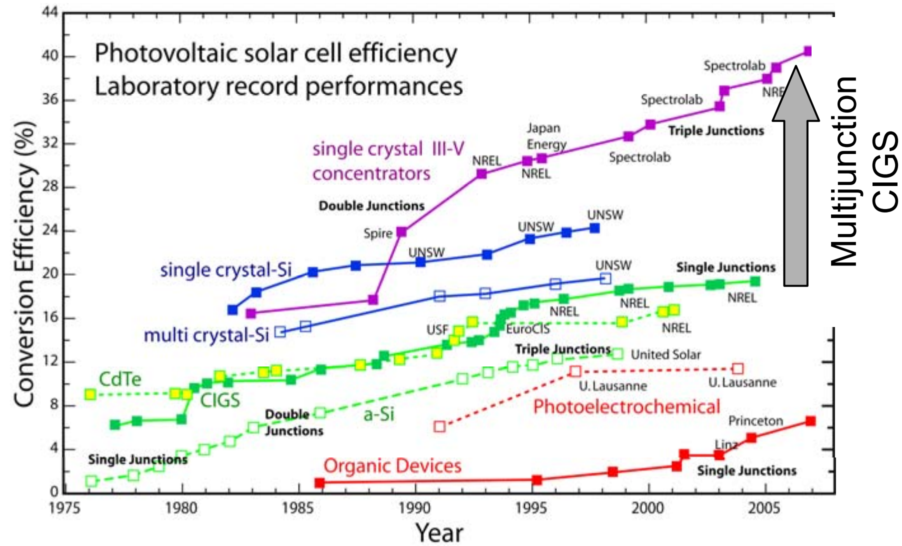
Polycrystalline Thin-Film Solar Cells:

$Cu(In,Ga)Se_2$

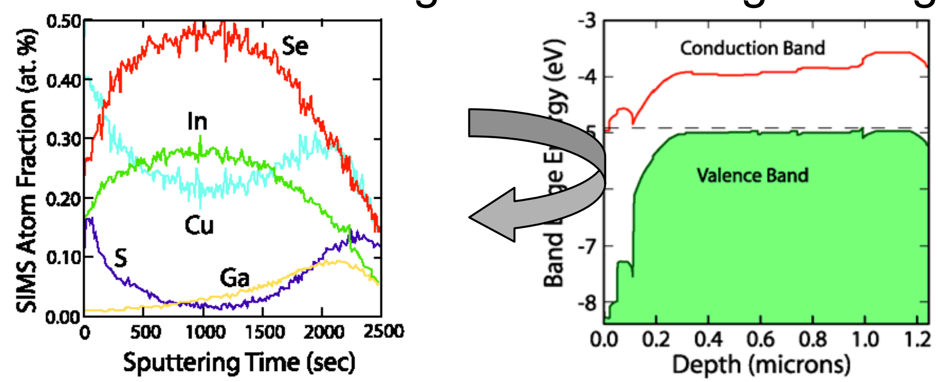
$Cu(In,Ga)Se_2$

- Promise:
  - Cost / watt equivalent to First Solar CdTe
  - Performance matching the best multijunctions
- Issues:
  - Major defect contributing to carrier loss
  - Wide-gap devices to enable multijunctions?
  - Fundamental understanding of the device incomplete





Understanding for Device Engineering



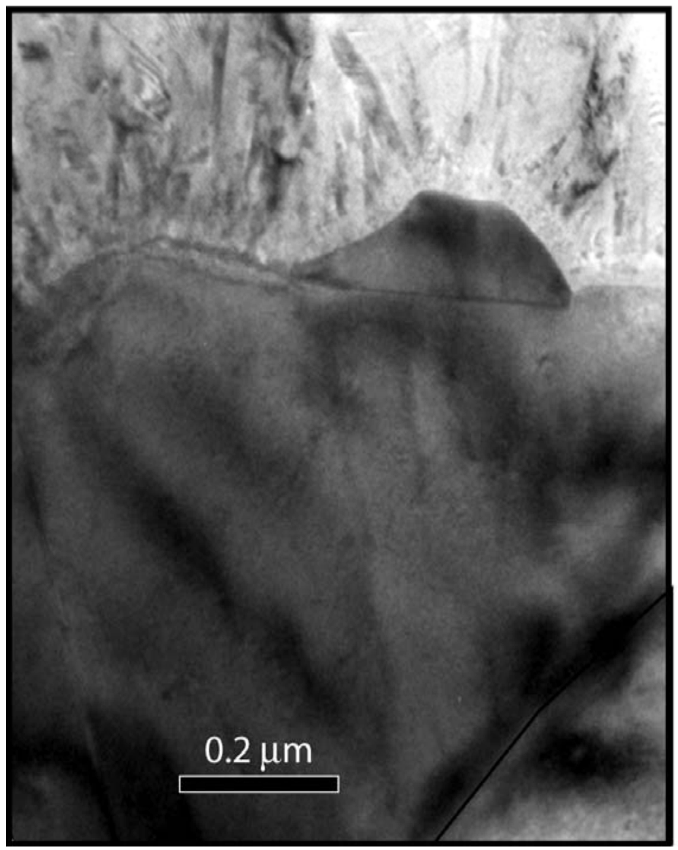
Angus Rockett, Univ. of Illinois

The Real Device

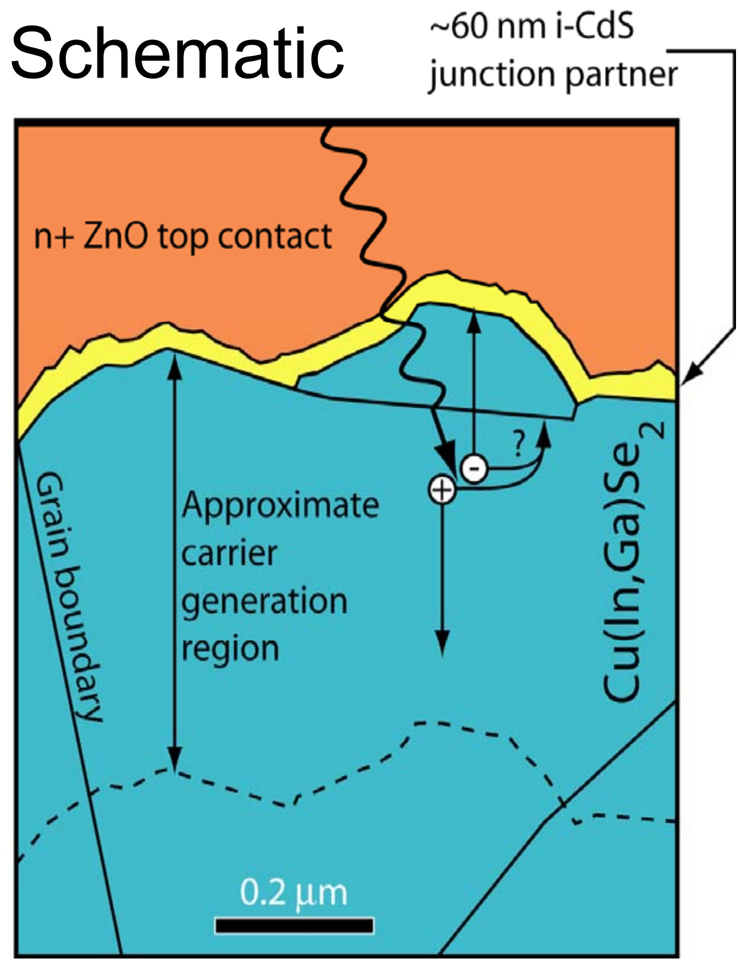
Devices are thought to be limited by recombination in the depletion region, not by heterojunction recombination.

- **What is the major recombination center?**
- **What do grain boundaries do?**
- **Why does $CuGaSe_2$ not work well?**
- **Why do some growth processes work better than others?**

TEM image

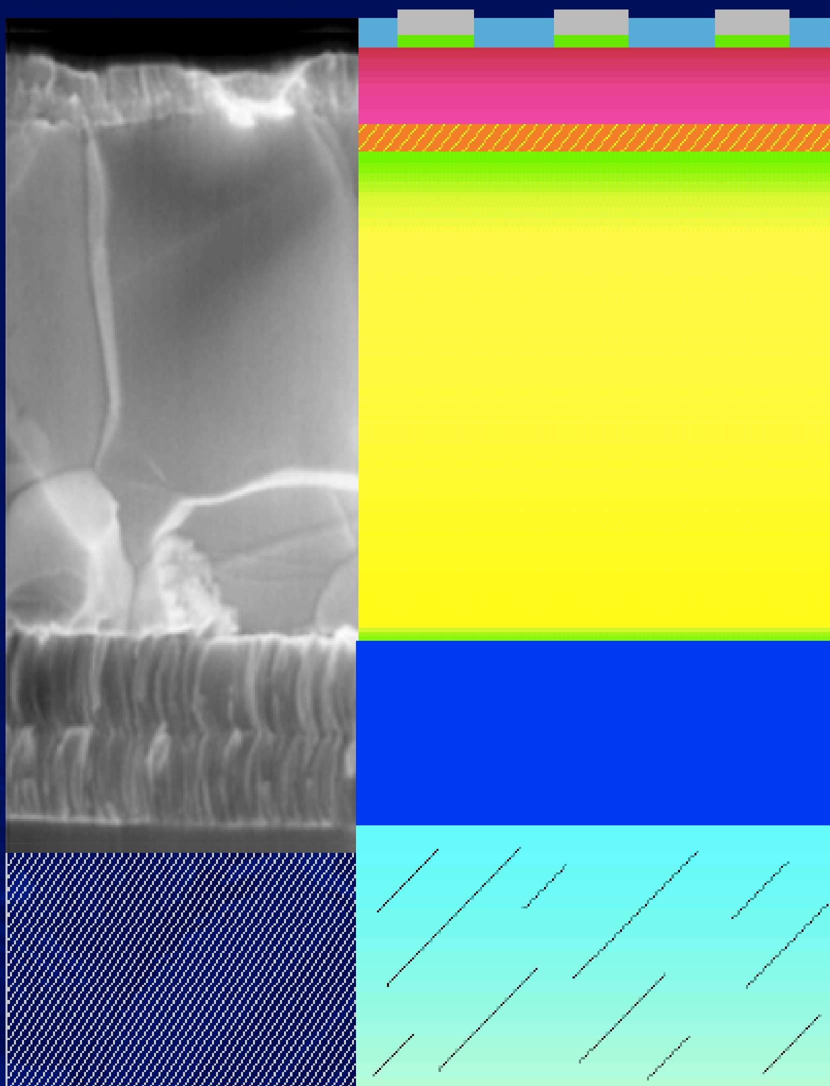


Schematic



Angus Rockett, Univ. of Illinois

Thin-Film $Cu(In,Ga)(S,Se)_2$ - CIGSSe

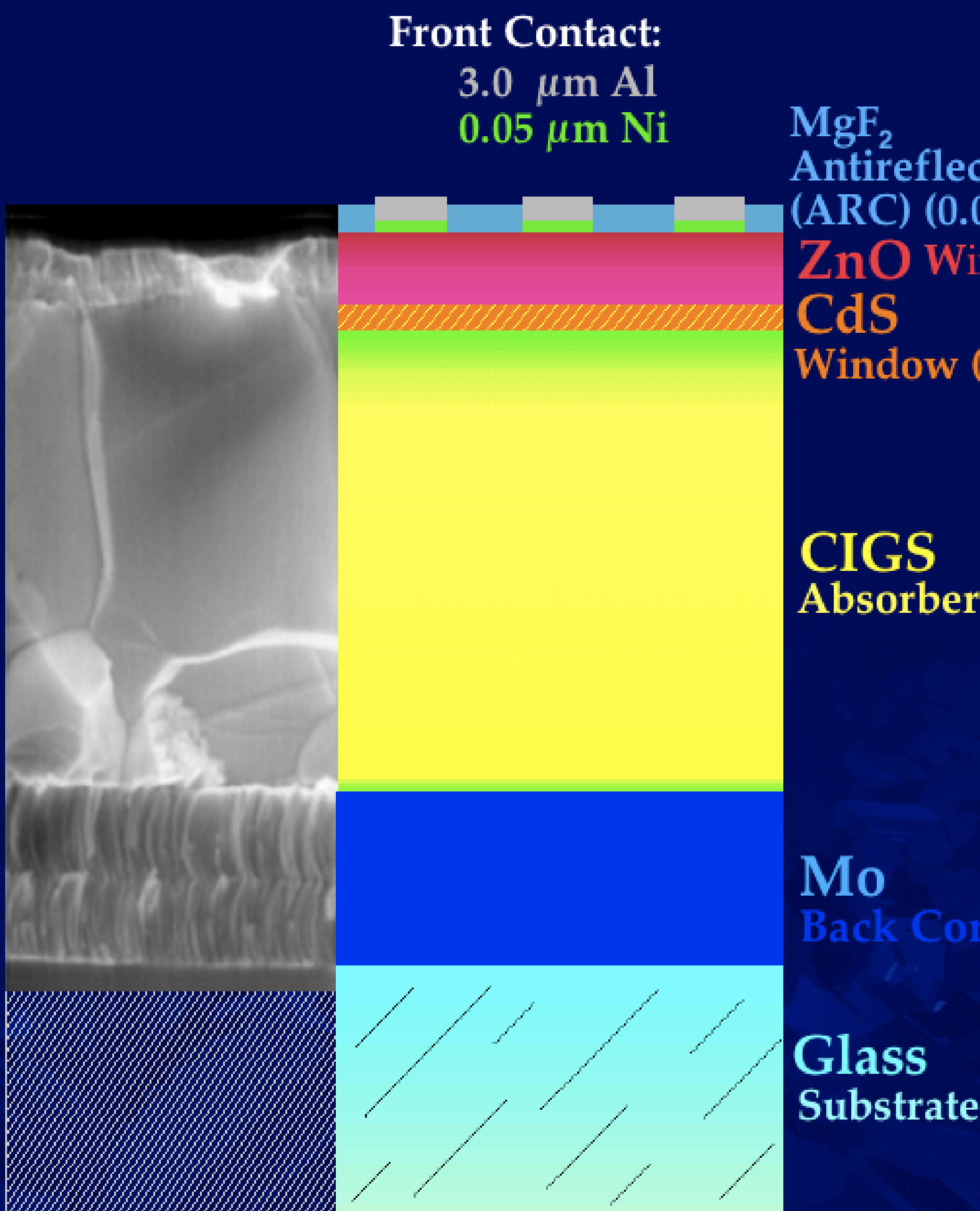


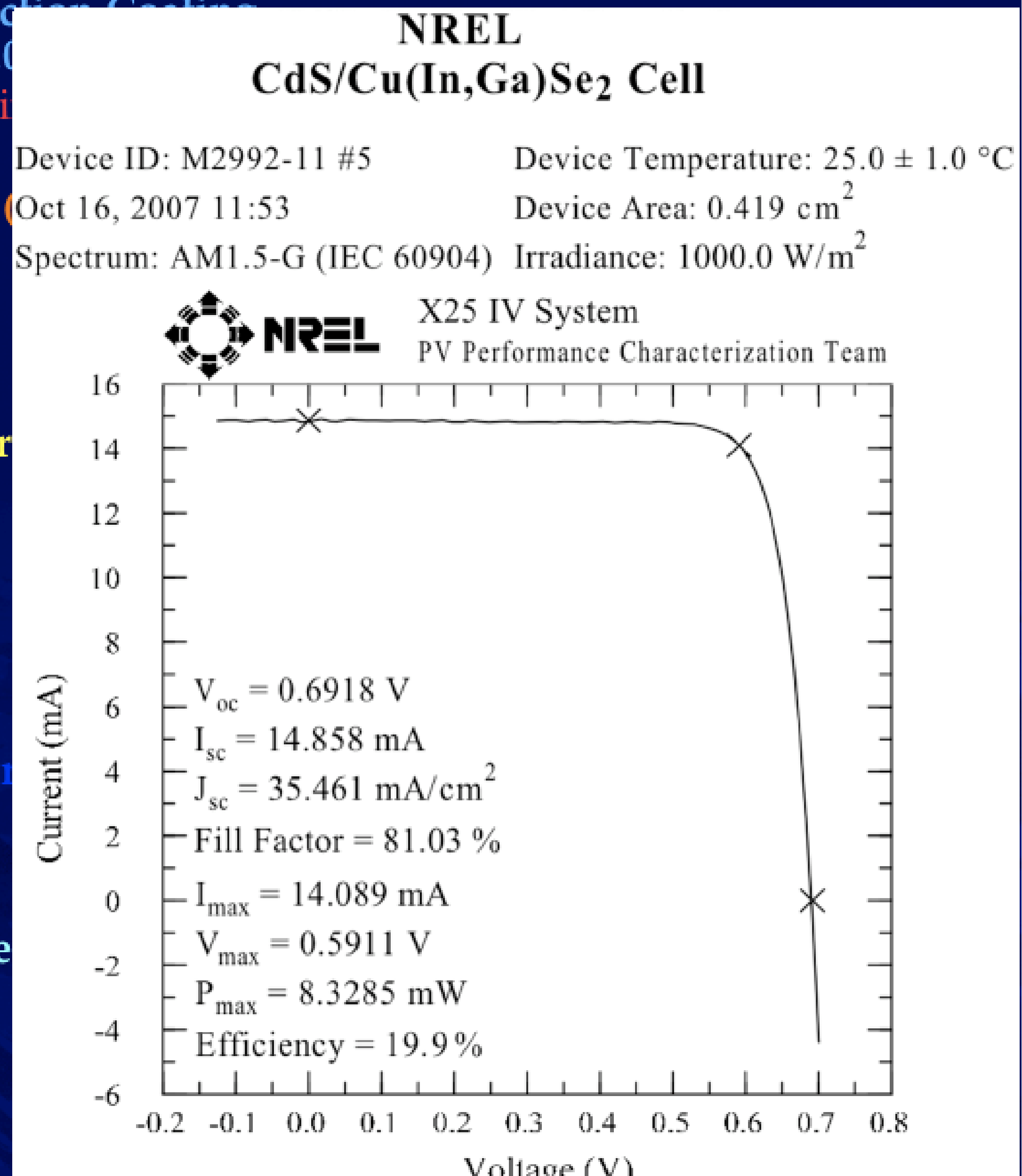
Challenges

- Higher module efficiency
- Thinner aborber layers (< 1.0 μm)
- Alternative absorber production (processes)
- Gaps in efficiency between various absorbers
- Faster absorber processing
- Stability (water ingress)
- Materials availability/cost
- Uniformity and stoichiometry
- Standardization of equipment
- Environmental concerns
- Recycling, "Insurance"
- Substrates (glass, plastics)

Larry Kazmerski, NREL

Thin-Film $Cu(In,Ga)(S,Se)_2$ - CIGSSe

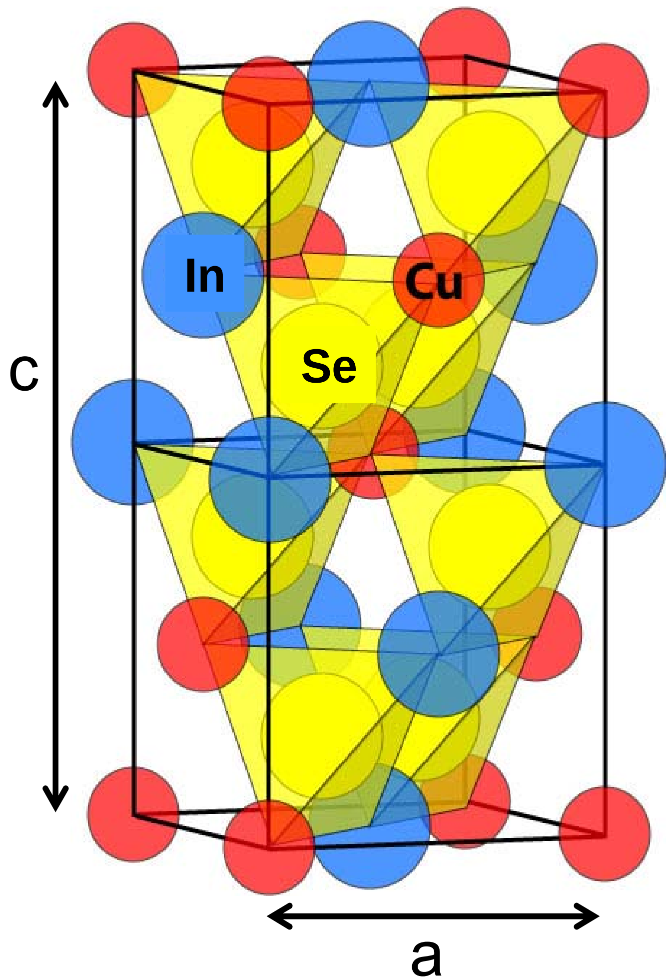


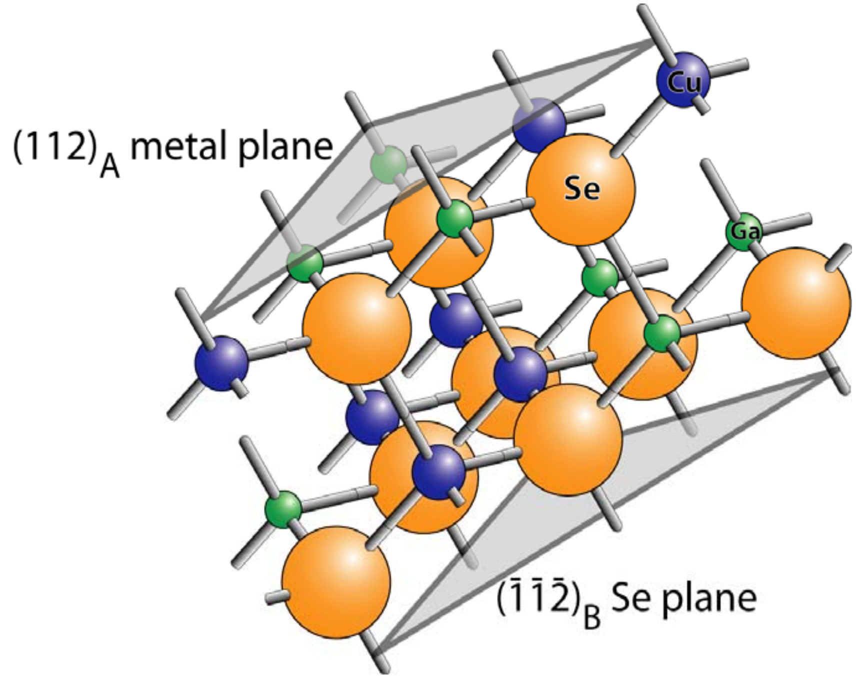


Larry Kazmerski, NREL

Chalcopyrite CIGS

- Disordering energy is low so there are many point defects
- CIGS is a polar compound so charged surfaces could be a problem





Yet:

- Extended defects inactive
- Polar surfaces most stable
- Hole mobility phonon limited for p to $>10^{19}$ cm^{-3}
- Polycrystalline devices work better than single crystals

Angus Rockett, Univ. of Illinois

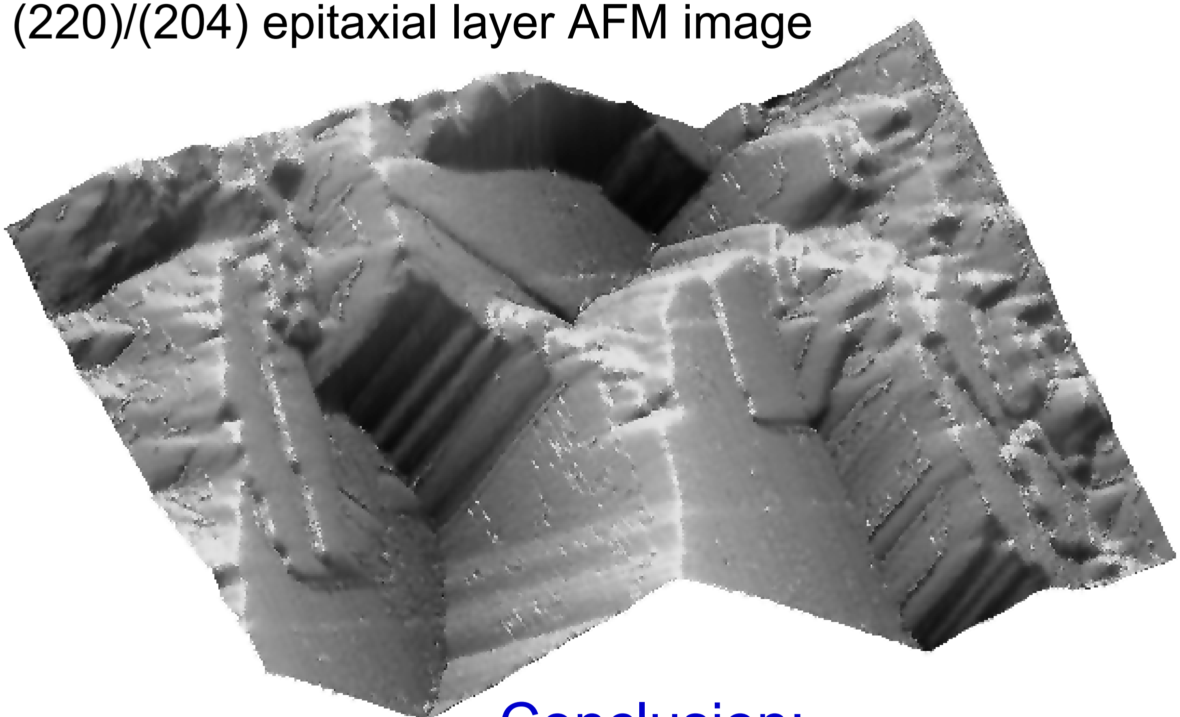
Self-Passivating Defects in $Cu(GaIn)Se_2$

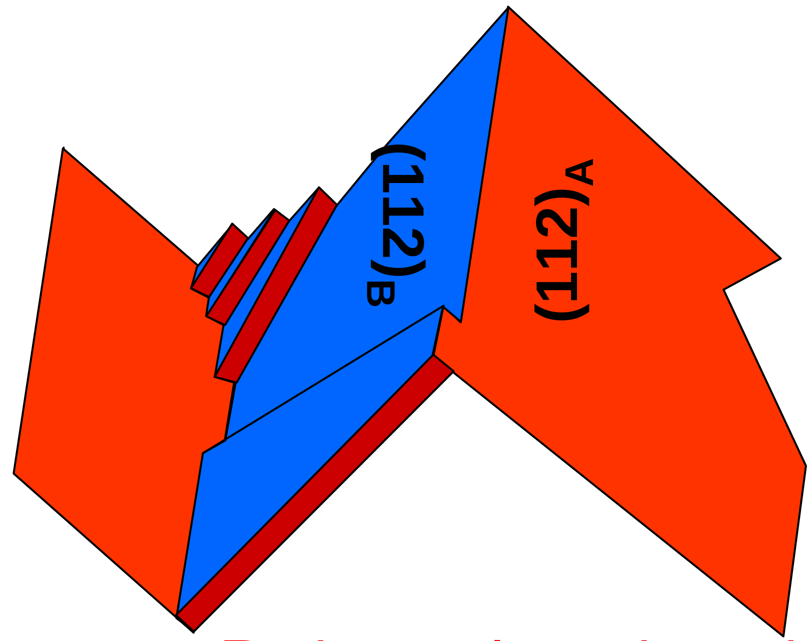
- Certain materials systems exhibit low minority-carrier recombination in spite of very high defect densities
  - *e.g.*, GaN and InGaN devices, polycrystalline $Cu(GaIn)Se_2$ (CIGS) solar cells
- Need atomic level understanding of the mechanisms that render dislocations inactive in these remarkable materials
- CIGS solar cells
  - Cu vacancies (V_{Cu}) and cation antisite defects such as In_{Cu} have a low enthalpy of formation
  - spontaneously forms Cu-poor phases of CIGS
  - defects form complexes in which they can neutralize each other electrically
- Microchemical analyses show little composition change between grain boundaries and bulk in CIGS
  - suggests recombination activity self-passivating, due to nature of surface defects
- Can self-passivating behavior of polycrystalline CIGS can be extended to other semiconductors, additional device structures?
  - If so, opens possibility of high-efficiency MJ solar cells in low-cost thin-film configuration
- Understanding of self-passivating phenomena at defects and interfaces is essential for nanostructured photovoltaic cells, *e.g.*, quantum dot and nanowire solar cells
  - Very large interfacial area is natural consequence of nanoscale structures

(220)/(204) Oriented CIGS

- Layers facet spontaneously into **polar** (112) type planes
- Smooth facets alternate with rough facets
- Indexing surface planes shows smooth planes are metal terminated

(220)/(204) epitaxial layer AFM image





Red: metal terminated
Blue: Se terminated

Conclusion:
Somehow the polar surfaces are stabilized, giving a very strong preference for these.

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Conclusions of all of this…

CIGS solar cells

- Are heterojunction devices with a very strongly inverted junction (Cd doping overwhelms Fermi level pinning).
- Do not mind grain boundaries because they are highly faceted to extremely passive (112) surfaces.
- Heterojunction is made to these surfaces regardless of grain orientation.
- Point defects control doping in the bulk and are very consistent.
- Edge dislocations do not matter because they turn into (112) surfaces.

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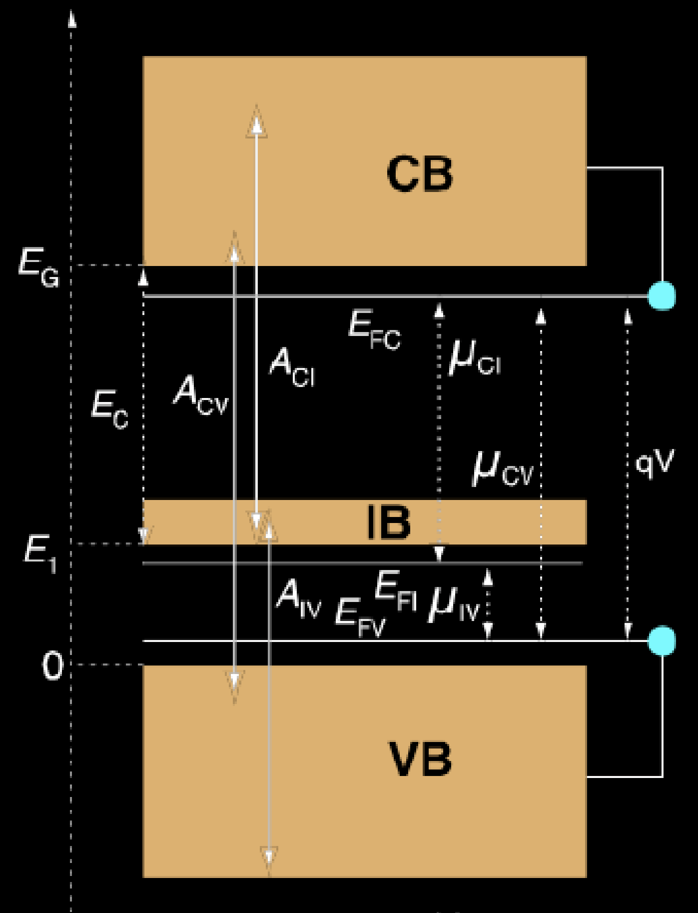
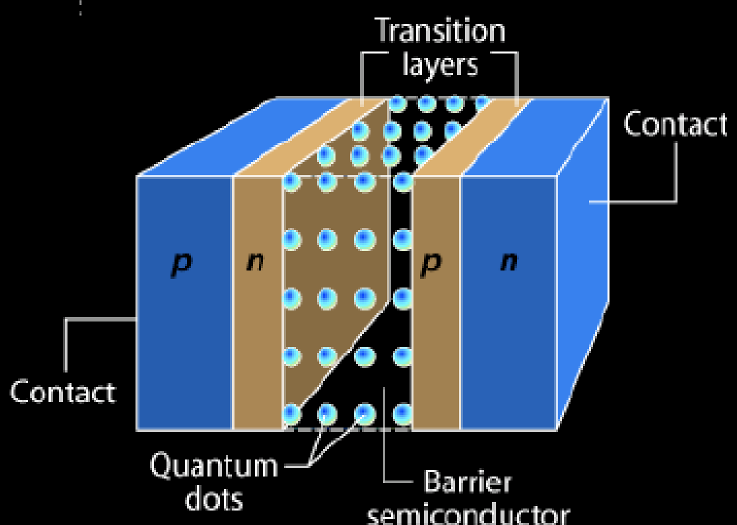
Nanostructured, Organic, and Other Novel Solar Cells

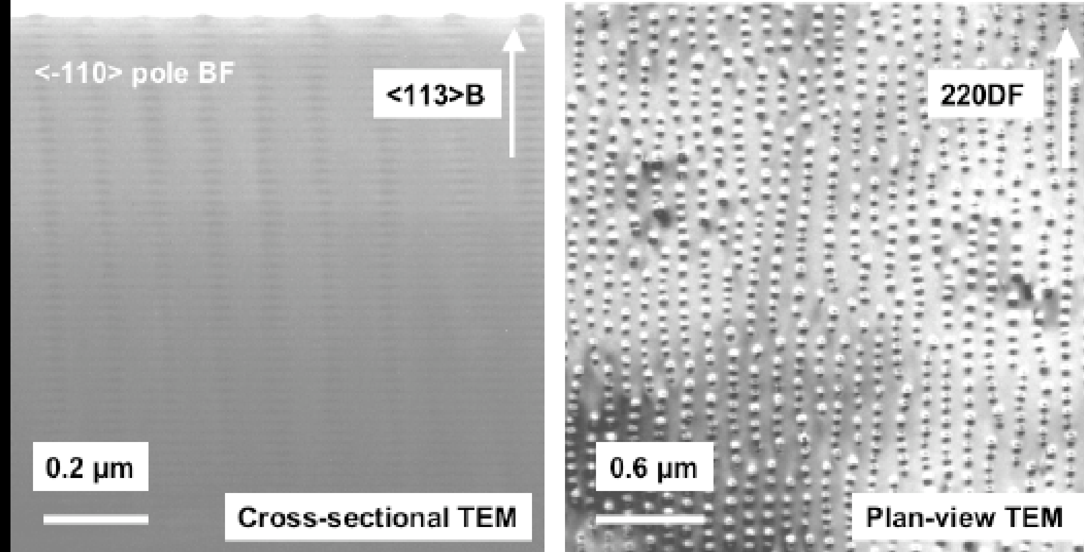
Intermediate Band Solar Cells





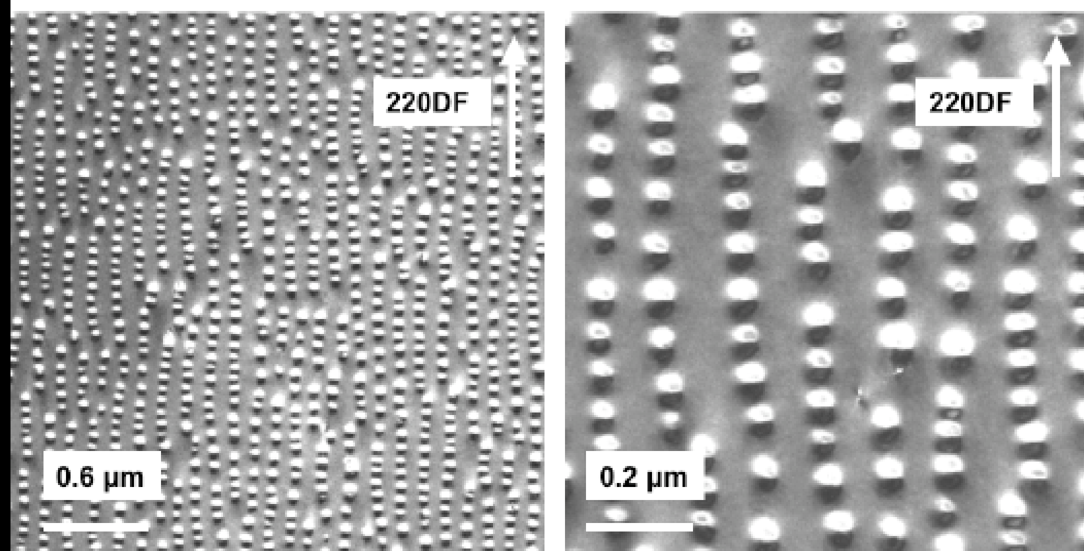
A. Norman, M Romero, and M. Al-Jassim, (NREL), A. Luque, A. Marti, Spain

MOCVD Growth of InGaAs/GaAs QD arrays on (113)B GaAs substrates for intermediate band solar cells



- QD arrays are being grown to test concept of intermediate band solar cell proposed by A. Martí and A. Luque

(311)B 50 period InGaAs/GaAs QD superlattice plan-view TEM



- Chains of quantum dots along <110>

Larry Kazmerski, NREL

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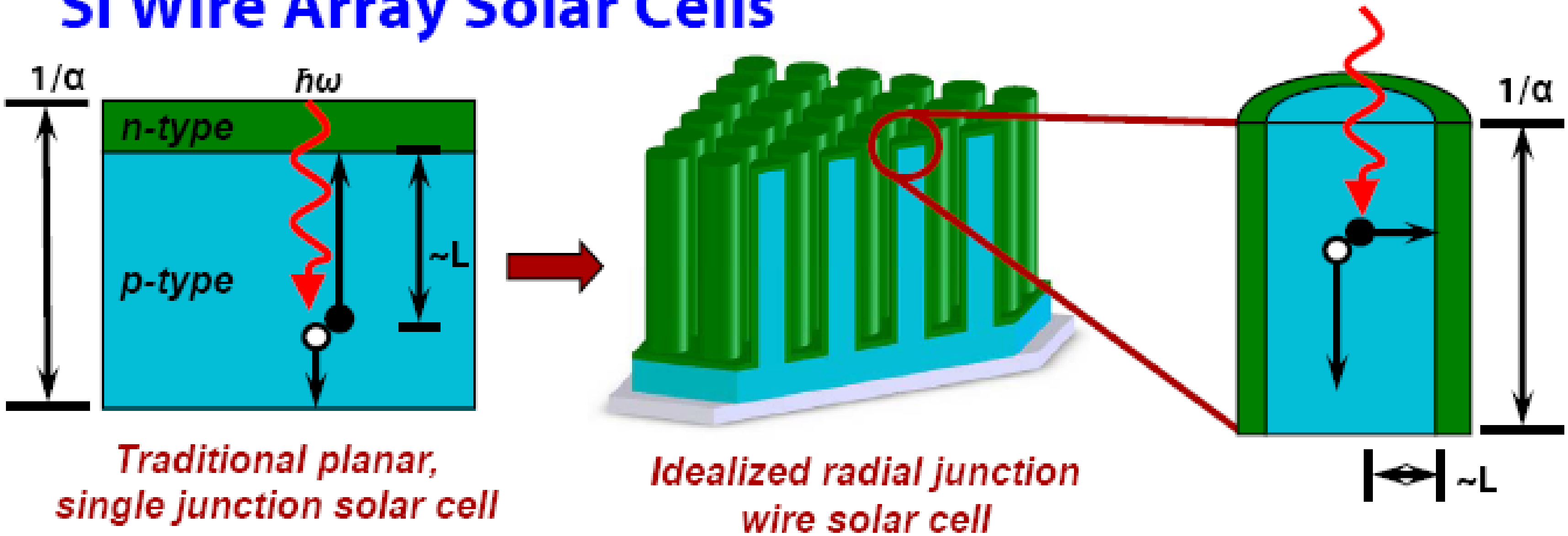
Nanostructures for Solar Cells

BOEING

Si Wire Array Solar Cells



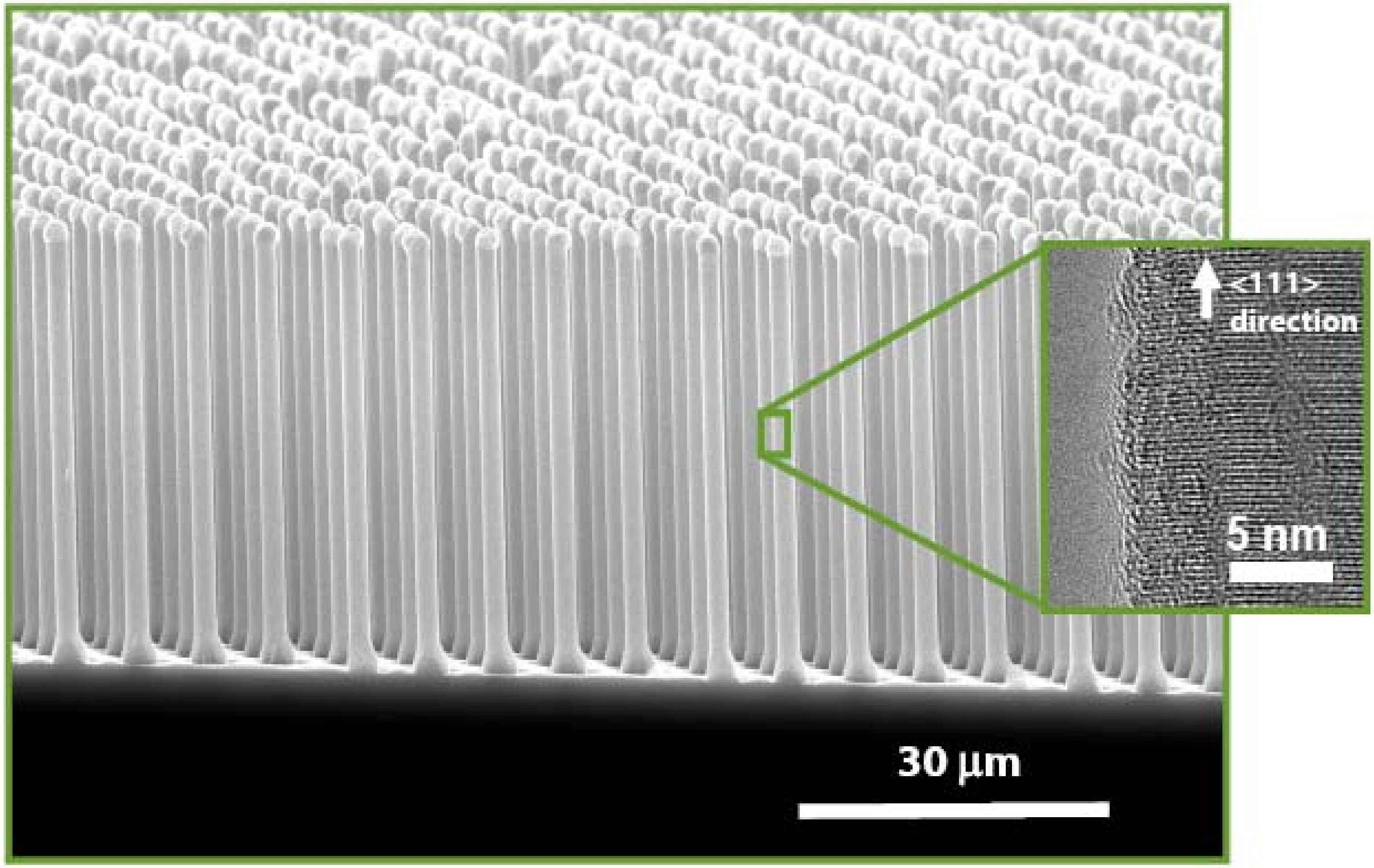
solar cell based on arrays of Si wires features:

- Orthogonalize light absorption and photocarrier collection
- Retain efficiencies competitive with planar, crystalline Si solar cells
- Compatible with low minority carrier diffusion length
- Si wire arrays formed by $SiCl_4$ chemical vapor deposition
- Can be formed into flexible arrays that are peeled off of template Si

Harry Atwater, Caltech

Nanorod Solar Cells

Large Area (>1 cm^2) Si Wire Arrays

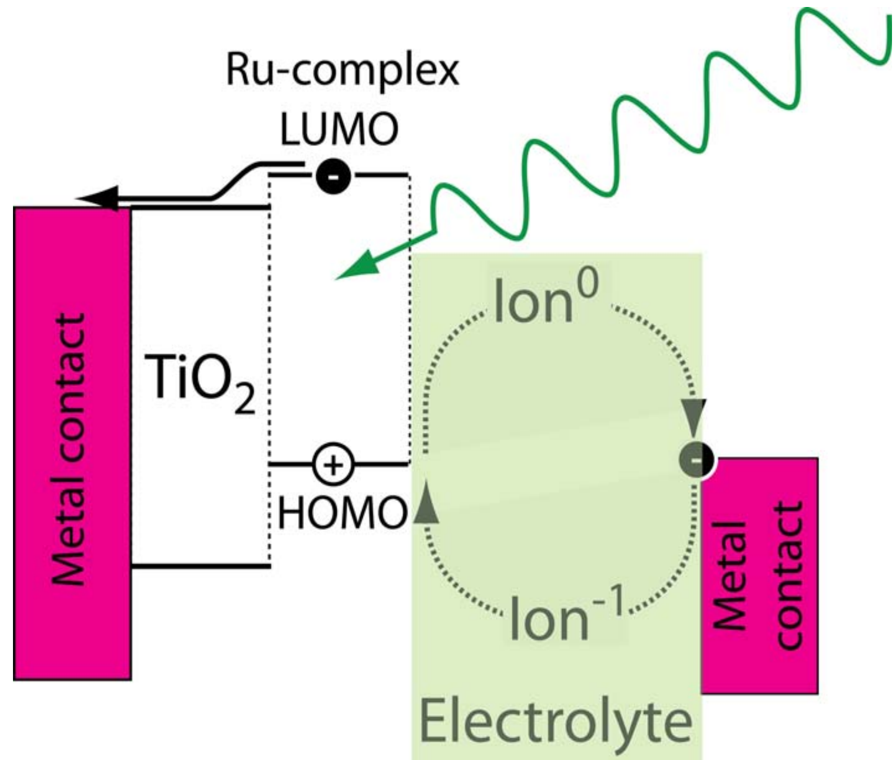


B.M. Kayes, M.A. Filler, et al., *App. Phys. Lett.* **91**, 103110 (2007)

Harry Atwater, Caltech

Photoelectrochemical Cells

- The "Gratzel" cell uses an electrolyte to conduct holes away from the chromophore.
- Issues
  - Energy loss at electrolyte/TiO_2 redox reaction
  - Energy loss at TiO_2 Ru complex interface
  - Hermetic seal to preserve electrolyte
  - Instability of Ru complex



Efficiency ~12% (record)

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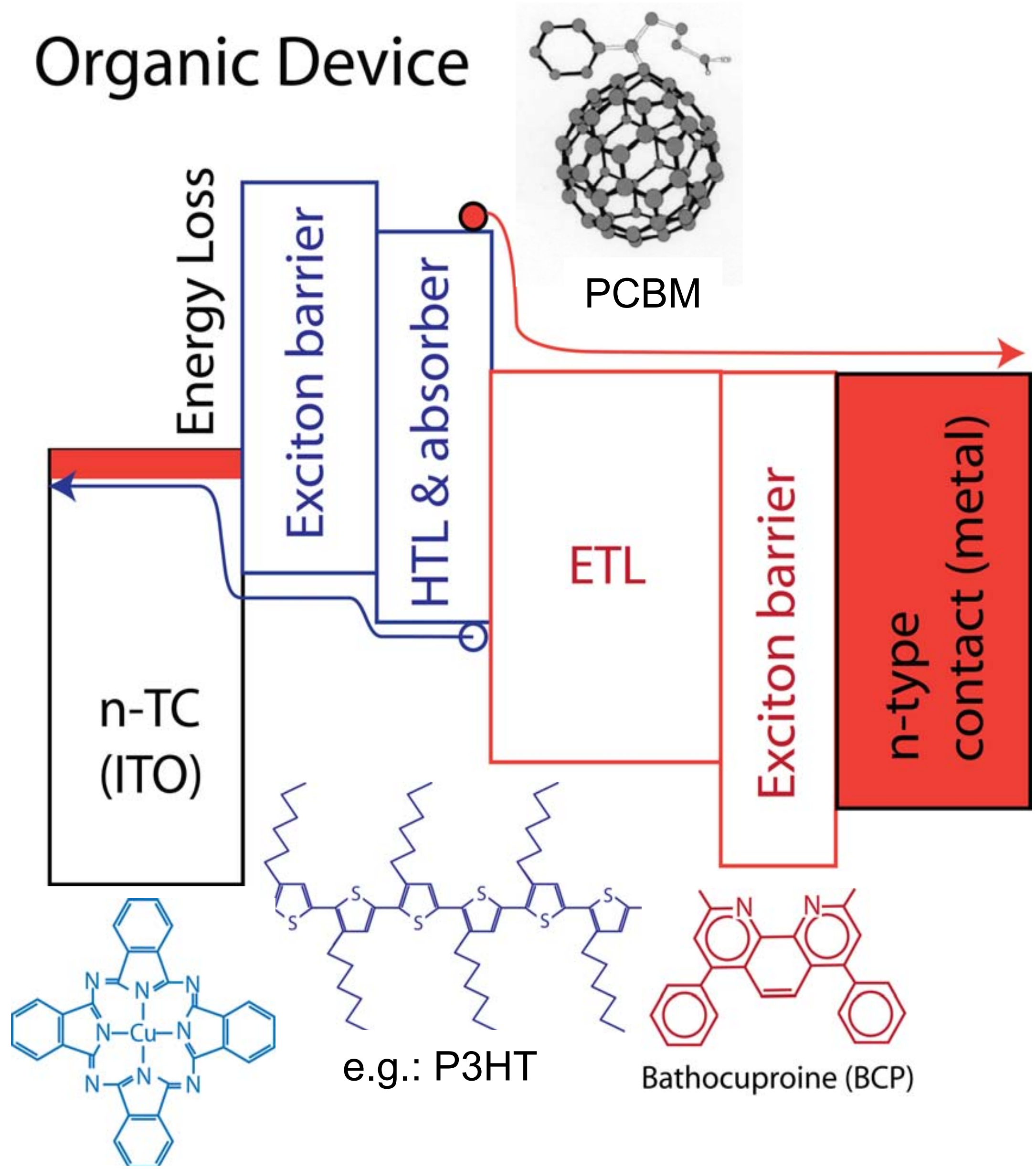
Organic Photovoltaics

- Reasons for:
  - Flexible cells
  - Non vacuum/cheap substrate
  - Enables organic chemistry control

- Reasons against
  - Exciton binding energy
  - Mobility of carriers
  - Stability



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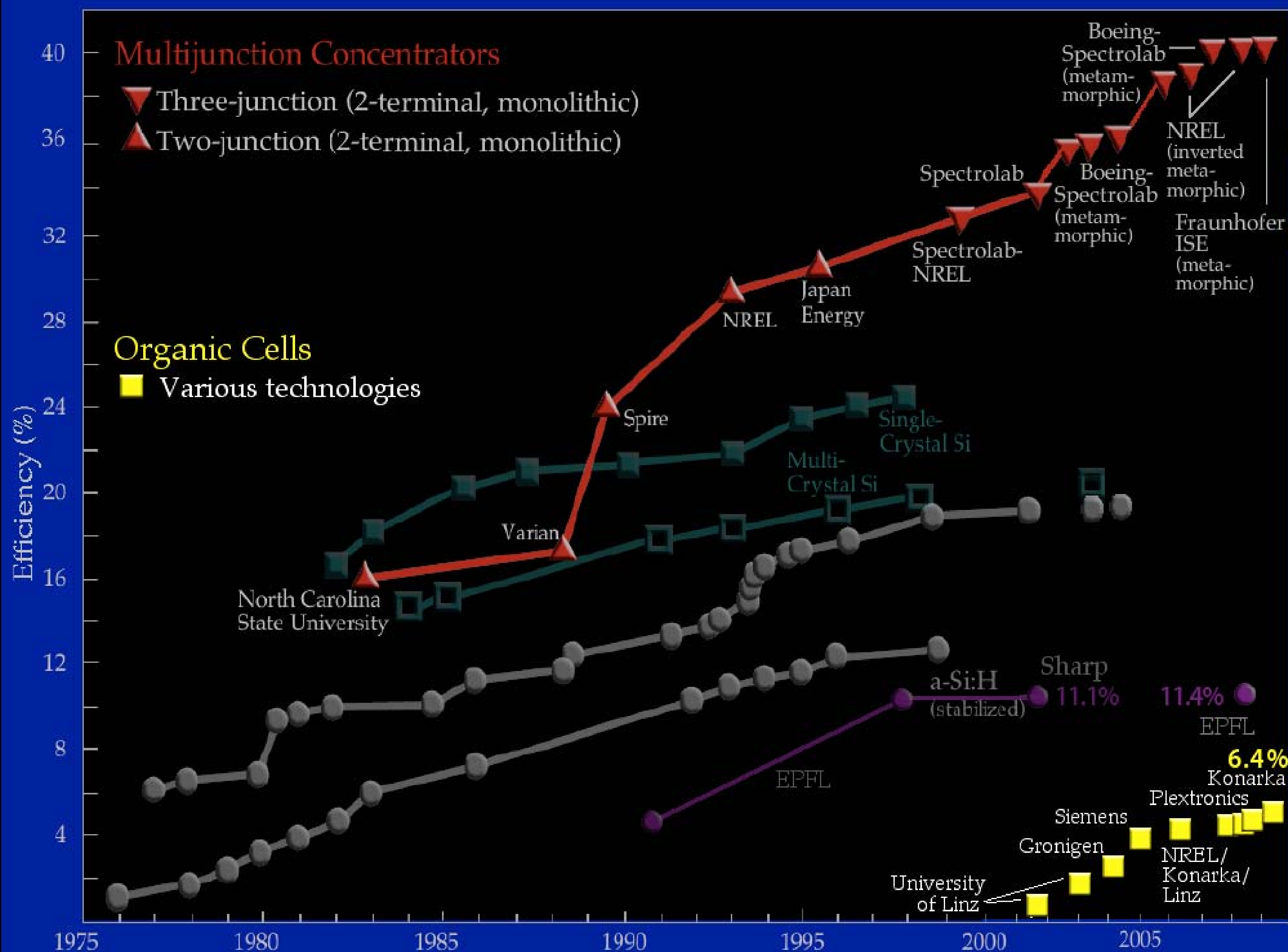

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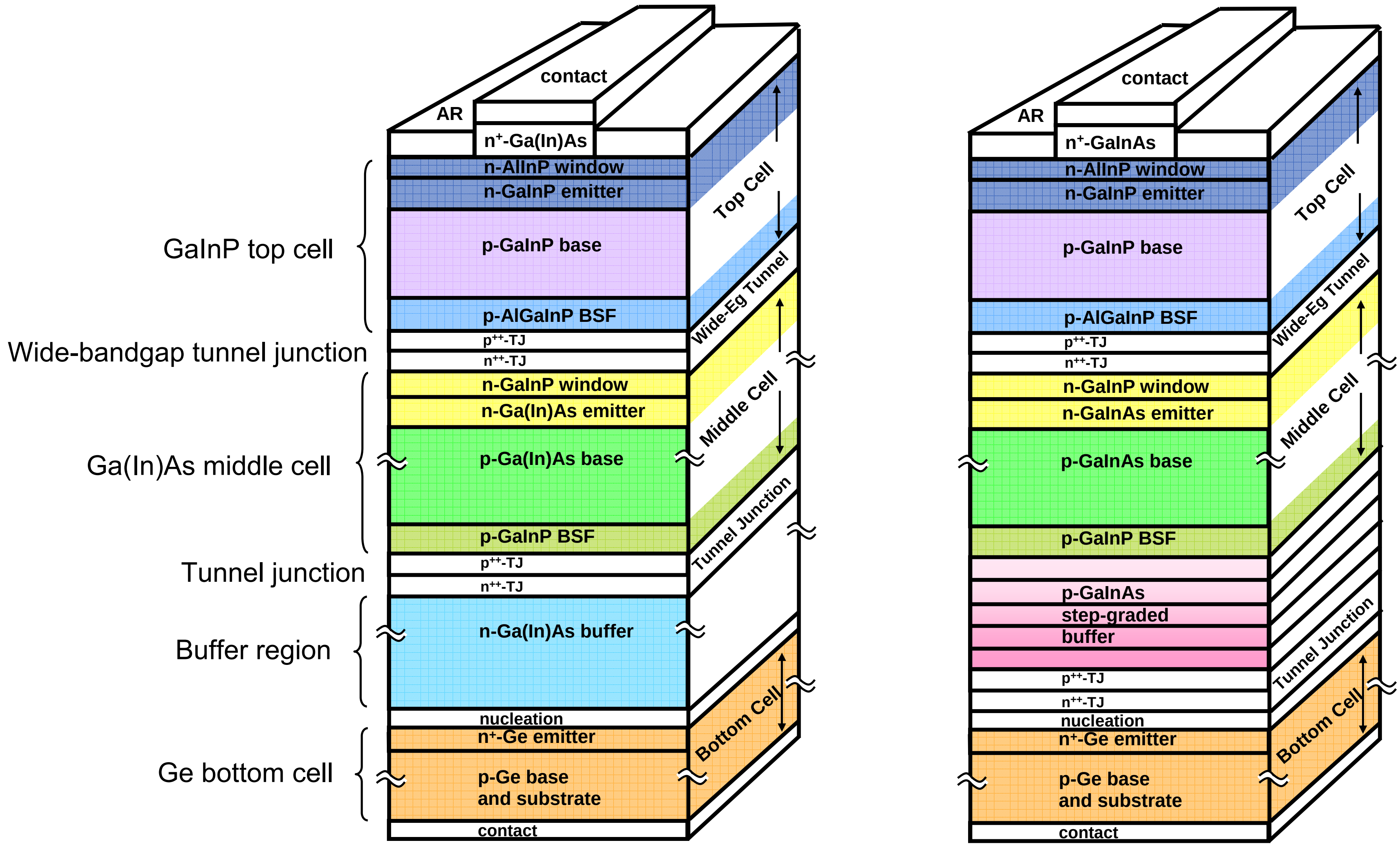
High-Efficiency

Multijunction Cells

LM and MM 3-Junction Cell Cross-Section



Lattice-Matched (LM)

Lattice-Mismatched or Metamorphic (MM)

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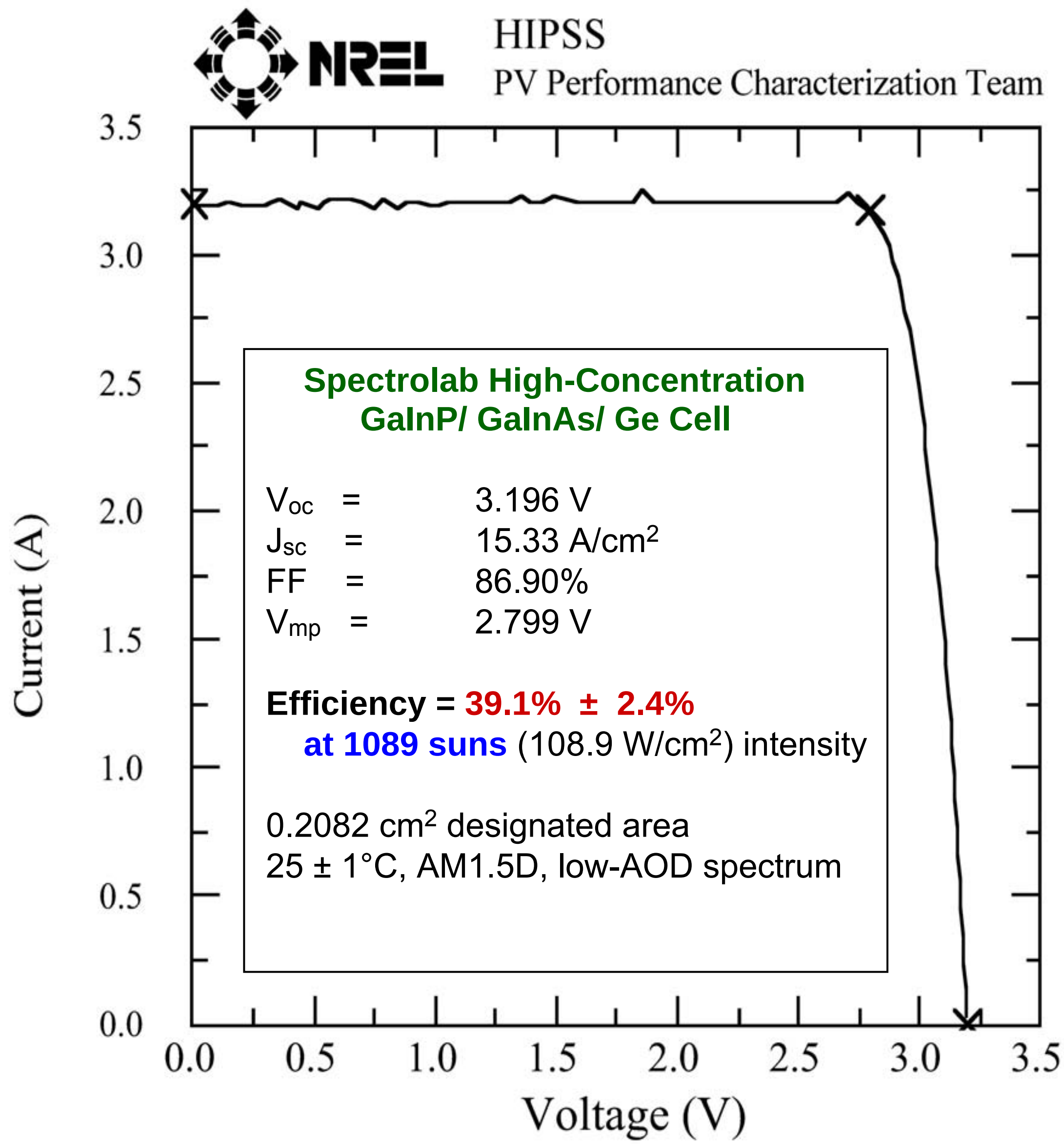
High-Concentration 3-Junction Cell



- **Greater than 39% efficiency at *>1000 suns***

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

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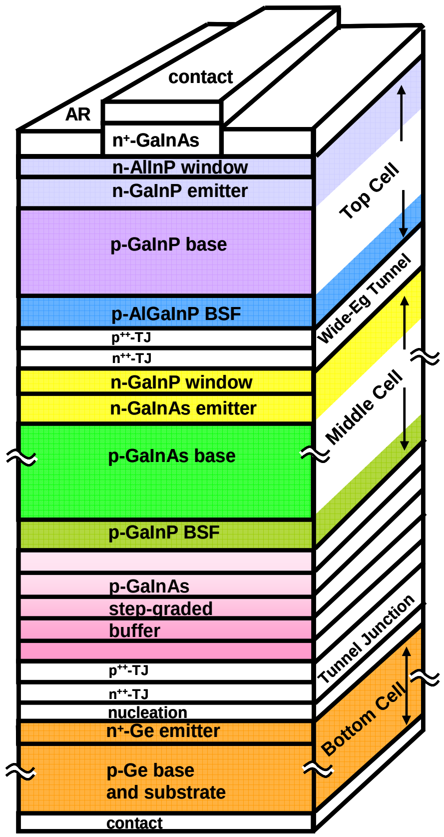
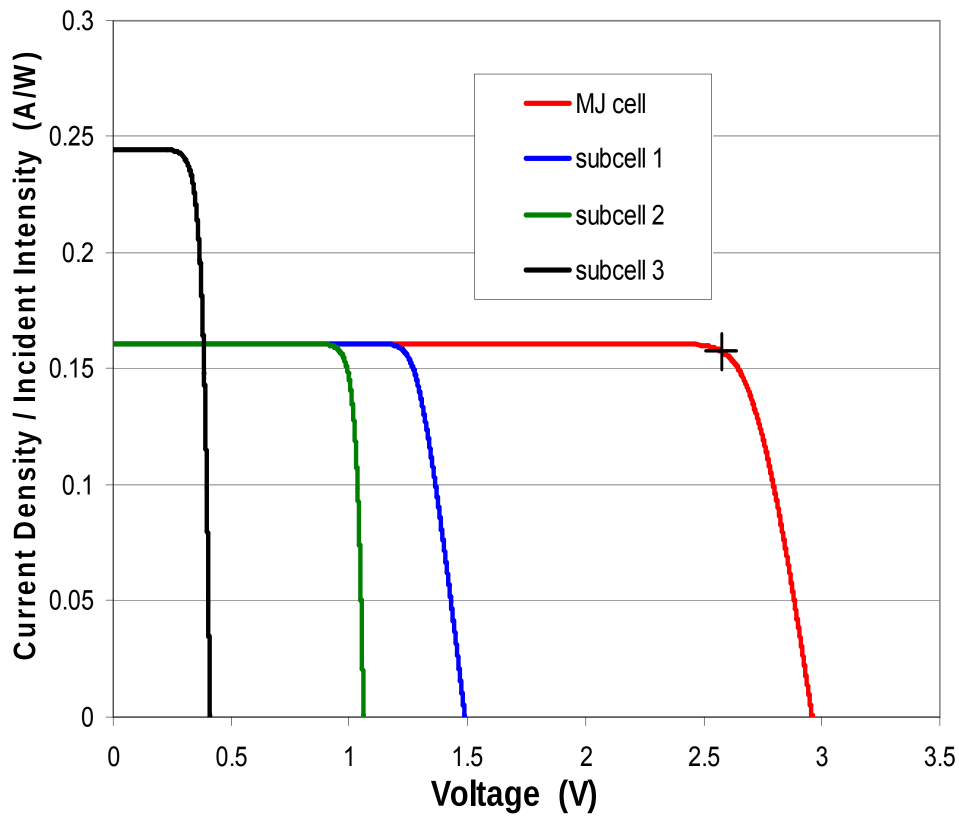
Metamorphic (MM) 3-Junction Solar Cell



Lattice-Mismatched or Metamorphic (MM)



- Metamorphic growth of upper two subcells, GaInAs and GaInP

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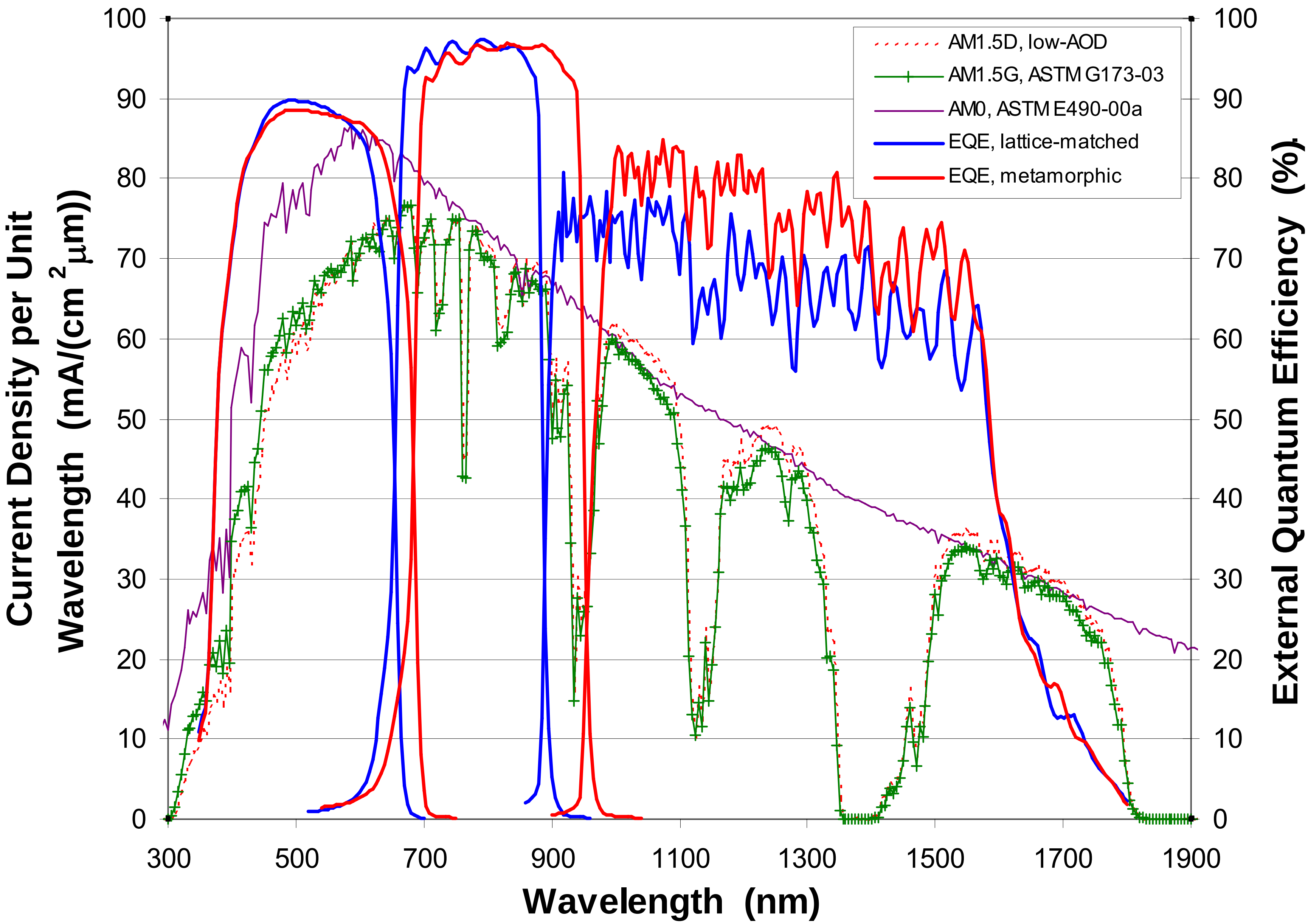
External QE of LM and MM 3-Junction Cells

BOEING



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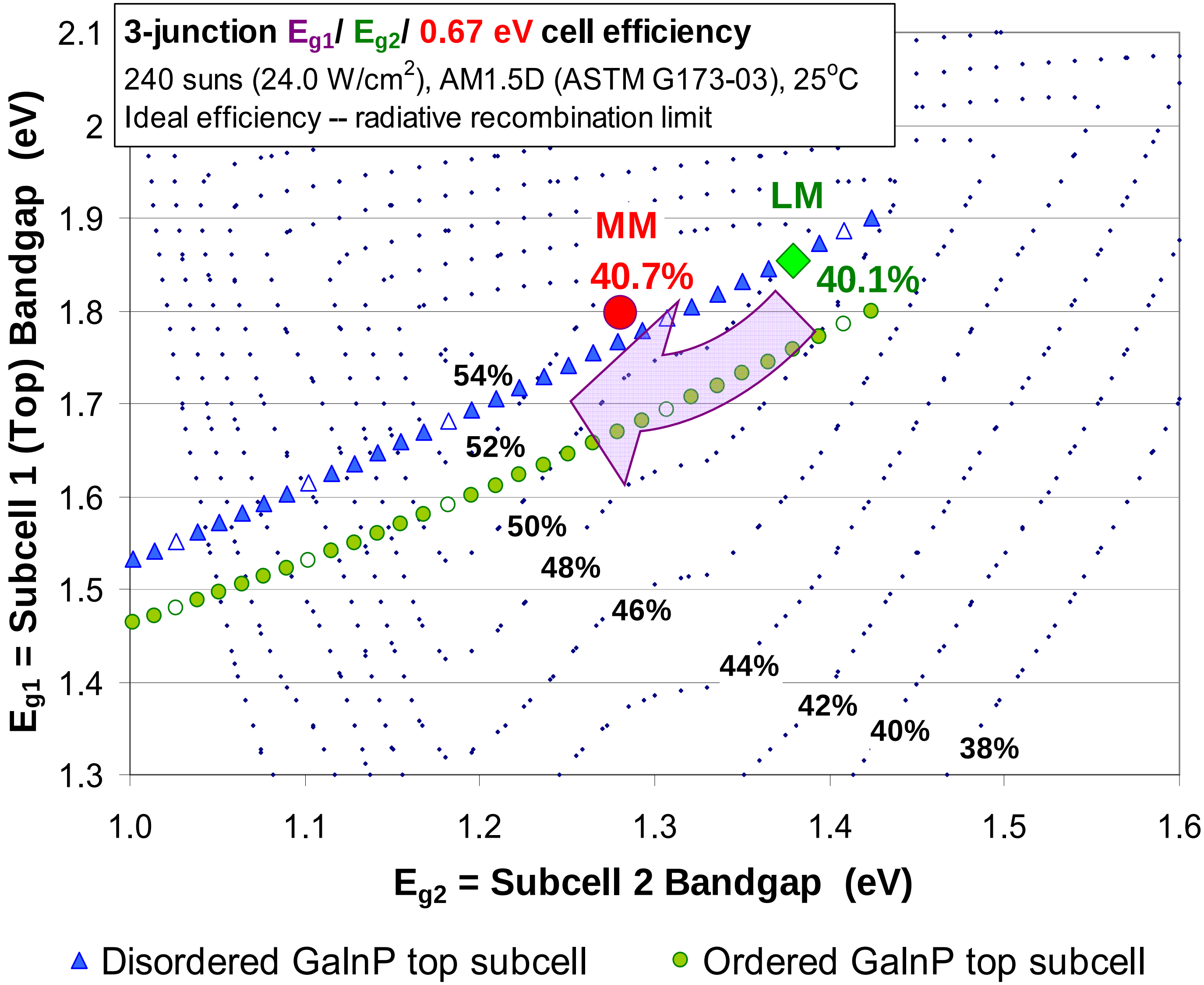
Metamorphic (MM) 3-Junction Solar Cell



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

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Record 40.7%-Efficient Concentrator Solar Cell

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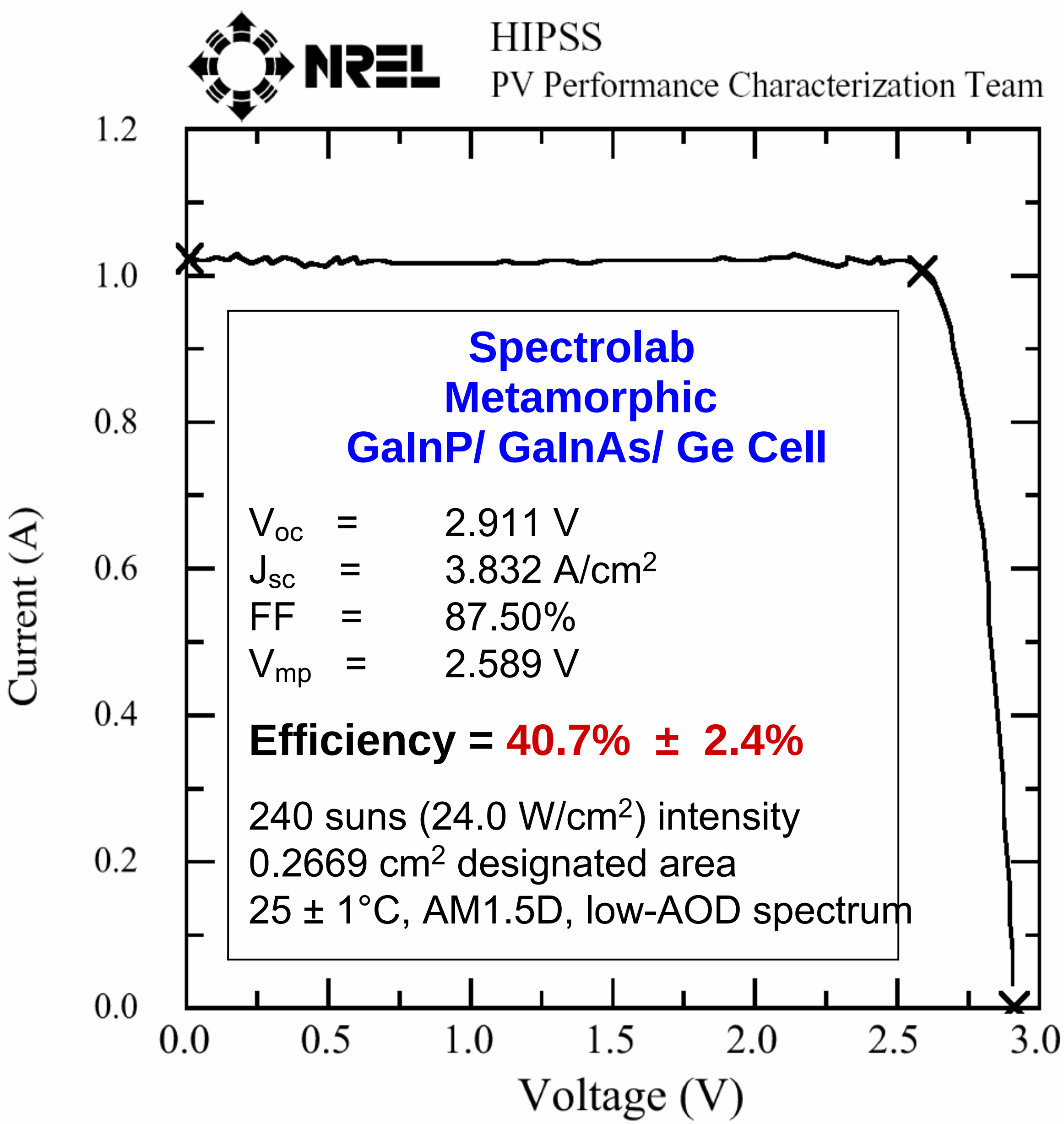
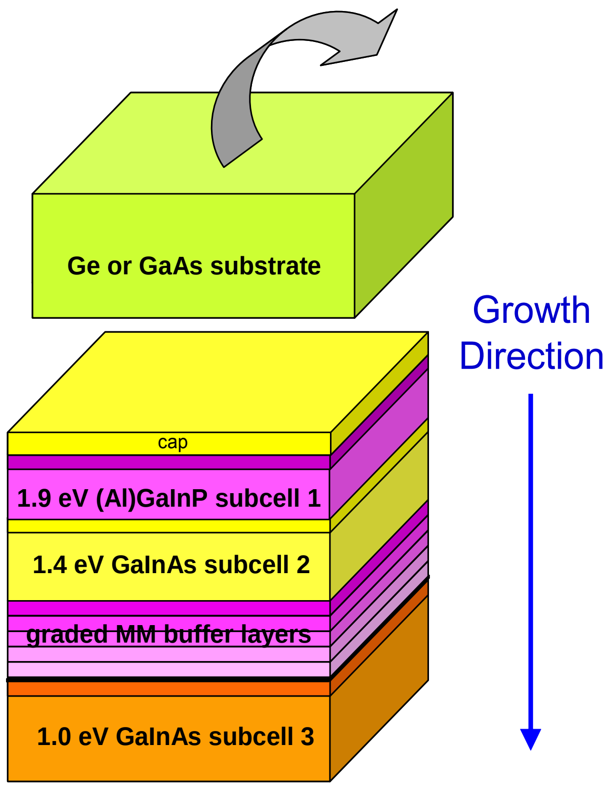


- **First solar cell of any type to reach over 40% efficiency**

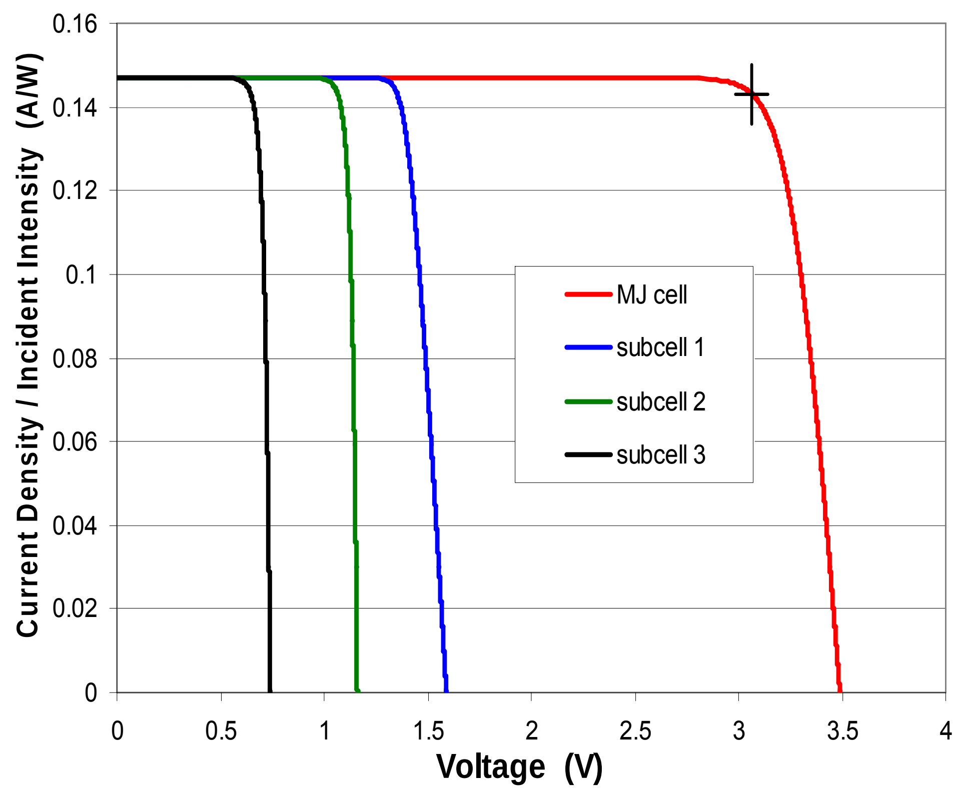
Ref.: R. R. King et al., *"40% efficient metamorphic GaInP / GaInAs / Ge multijunction solar cells,"*
Appl. Phys. Lett., ***90****, 183516, 4 May 2007.*

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

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)

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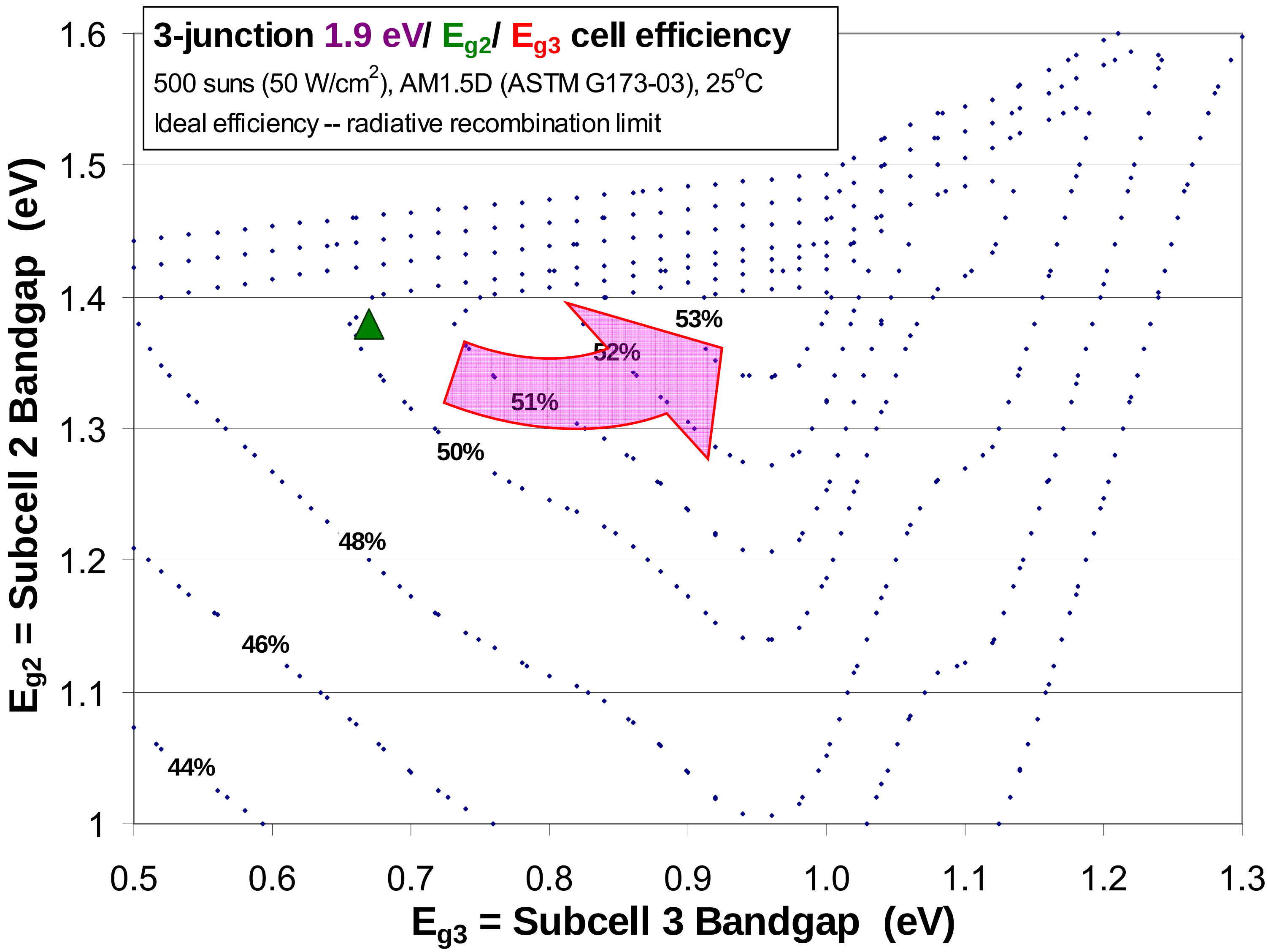
Inverted Metamorphic (IMM) 3-Junction Cell



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

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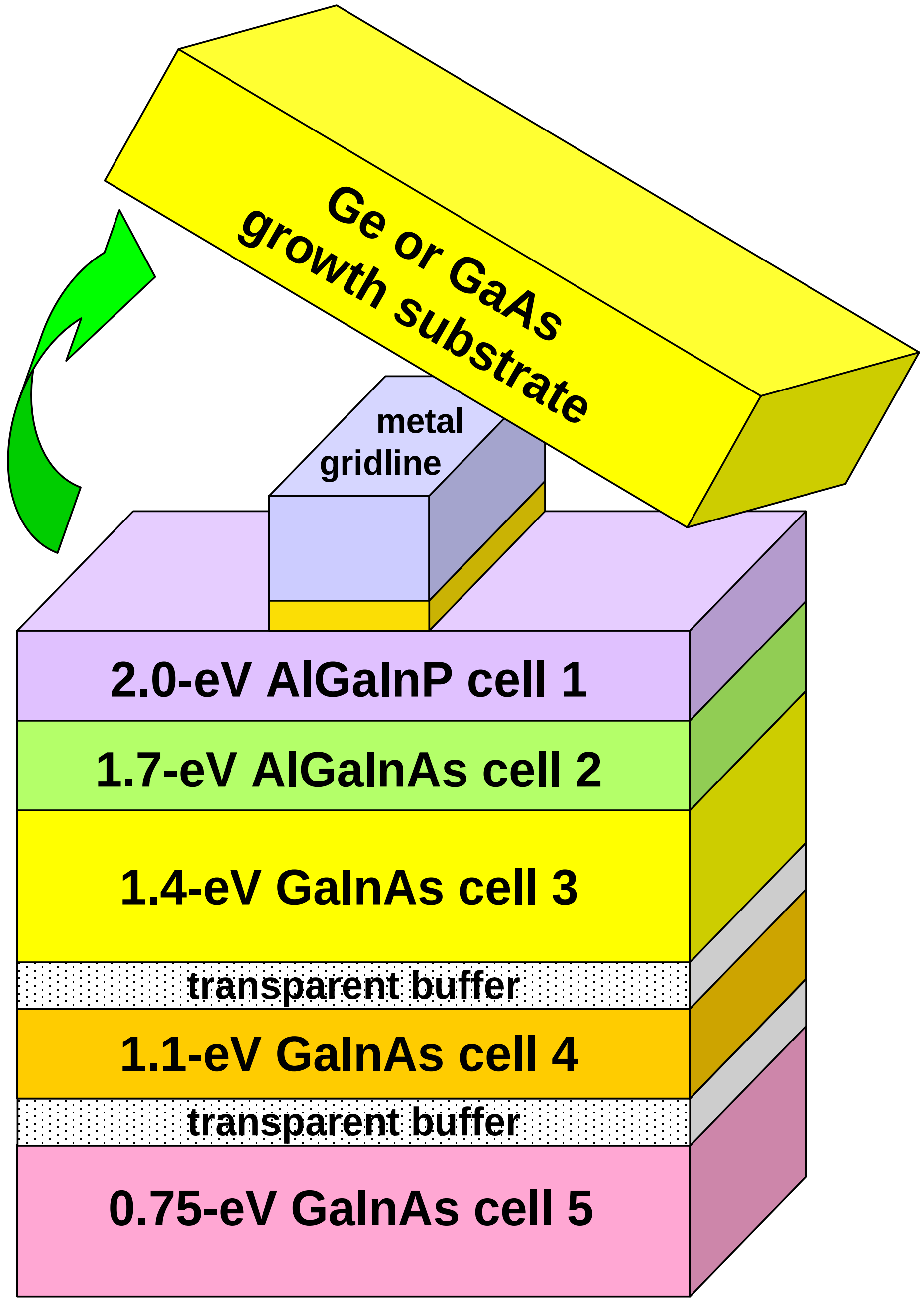
5-Junction Inverted Metamorphic (IMM) Cells



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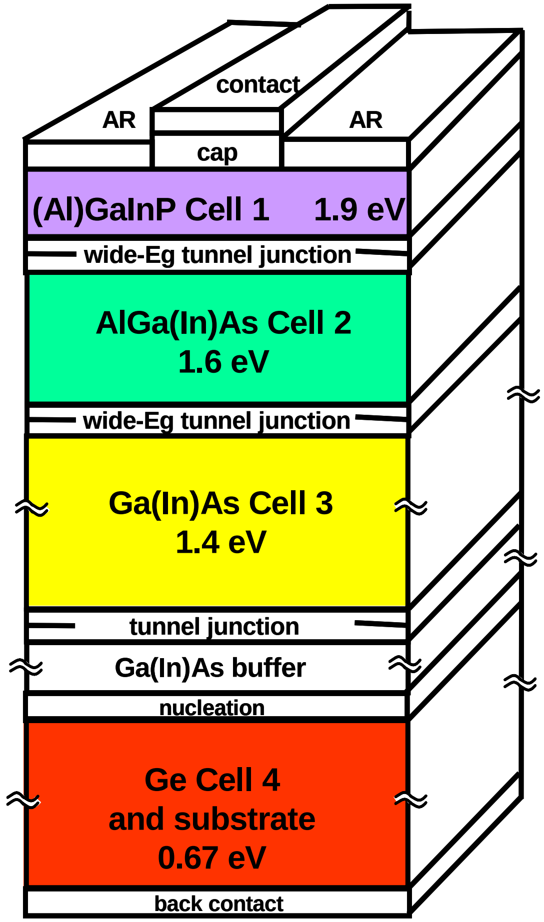
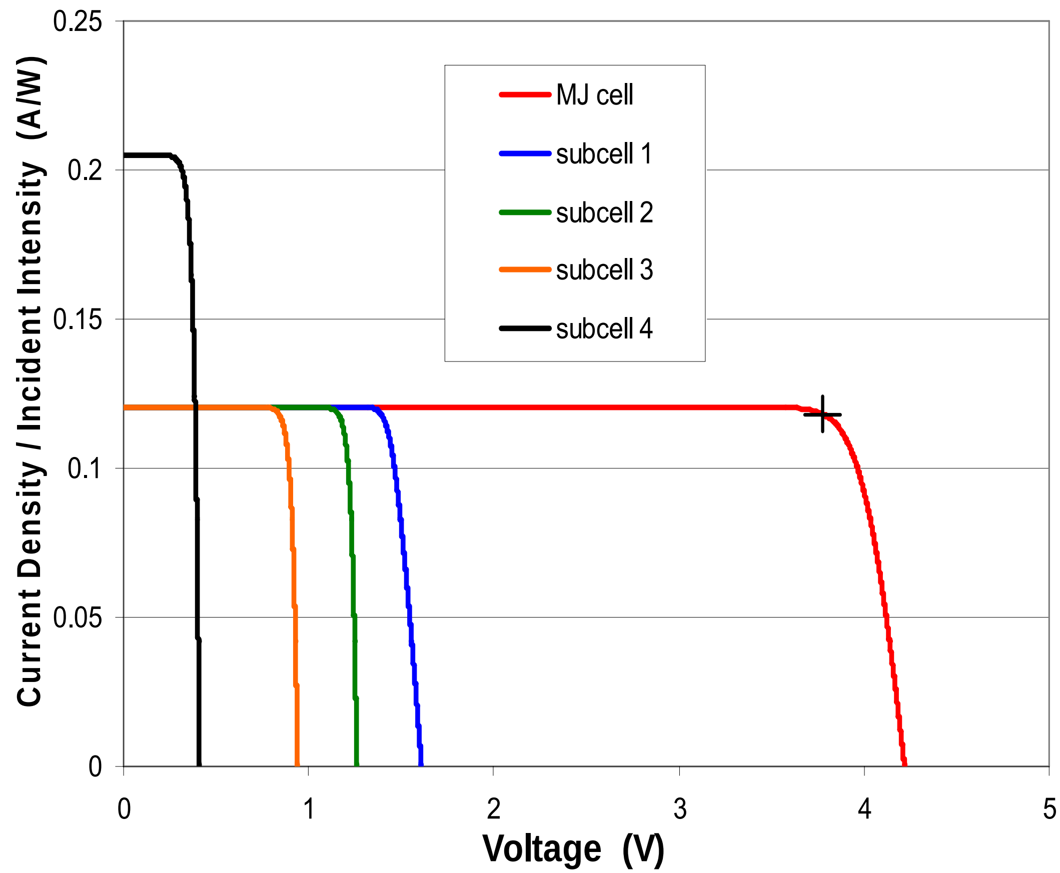
4-Junction Lattice-Matched Cell





- 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

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4-Junction Upright Metamorphic (MM) Terrestrial Concentrator Cell

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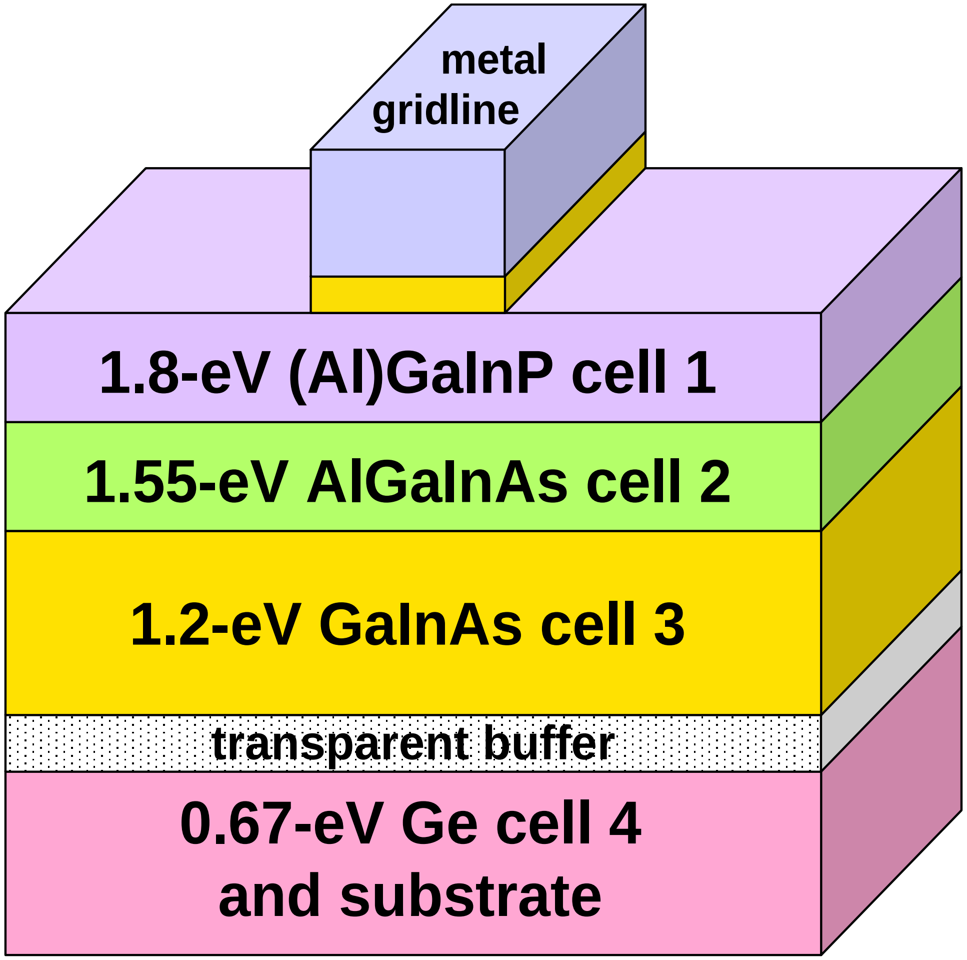

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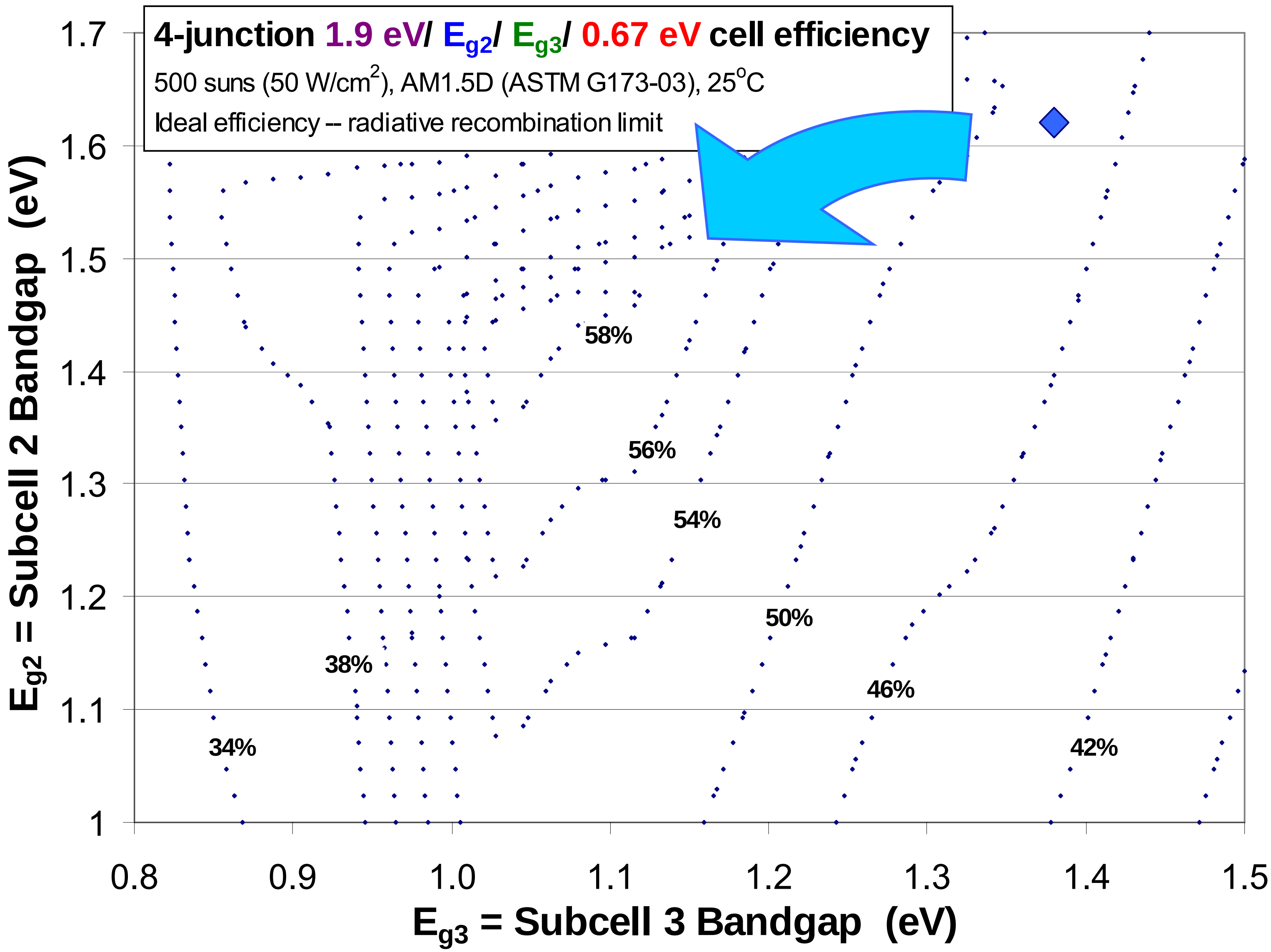
4-Junction Cell
Optimum Band Gap Combinations

BOEING



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

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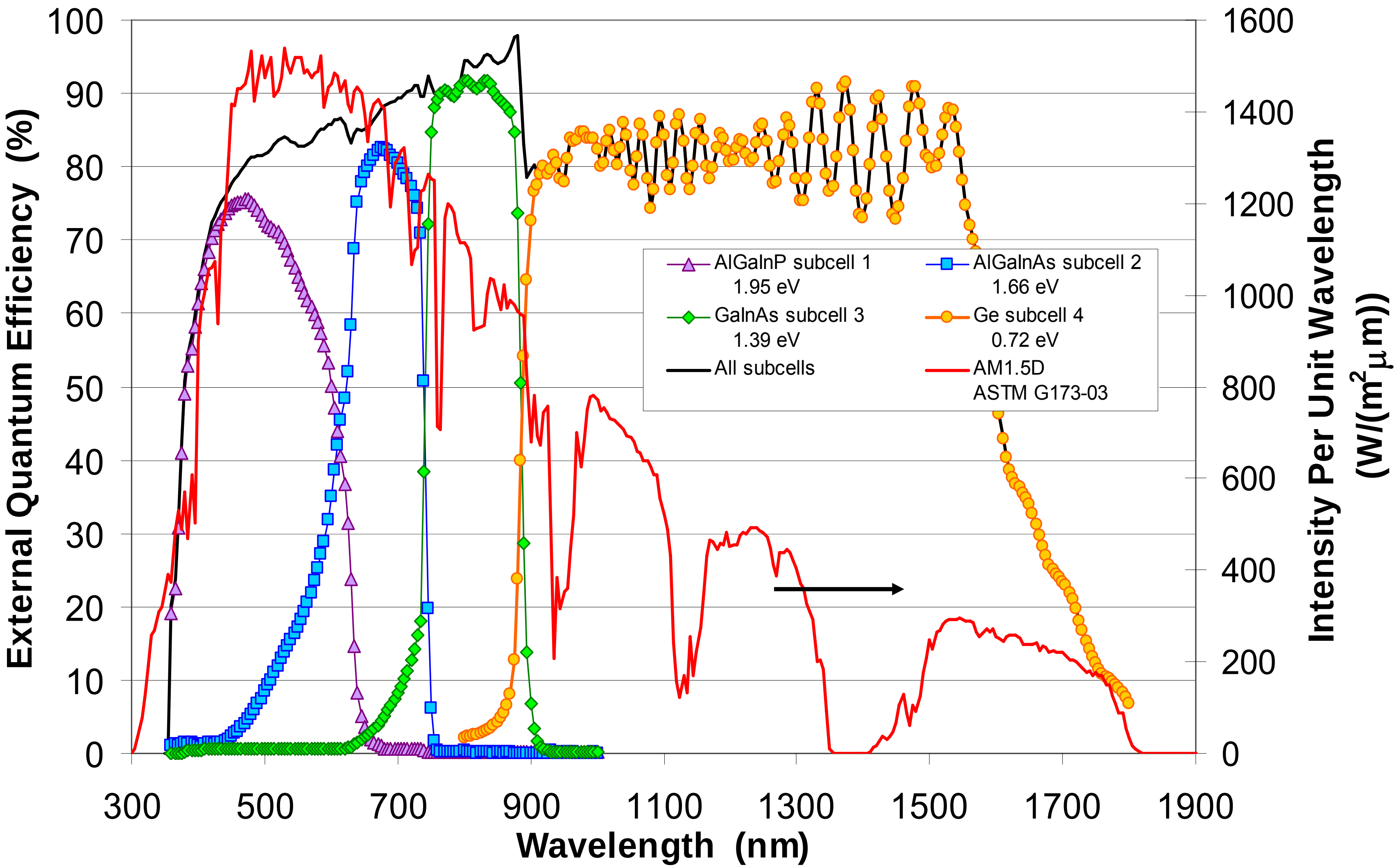
Measured 4-Junction Cell Quantum Efficiency



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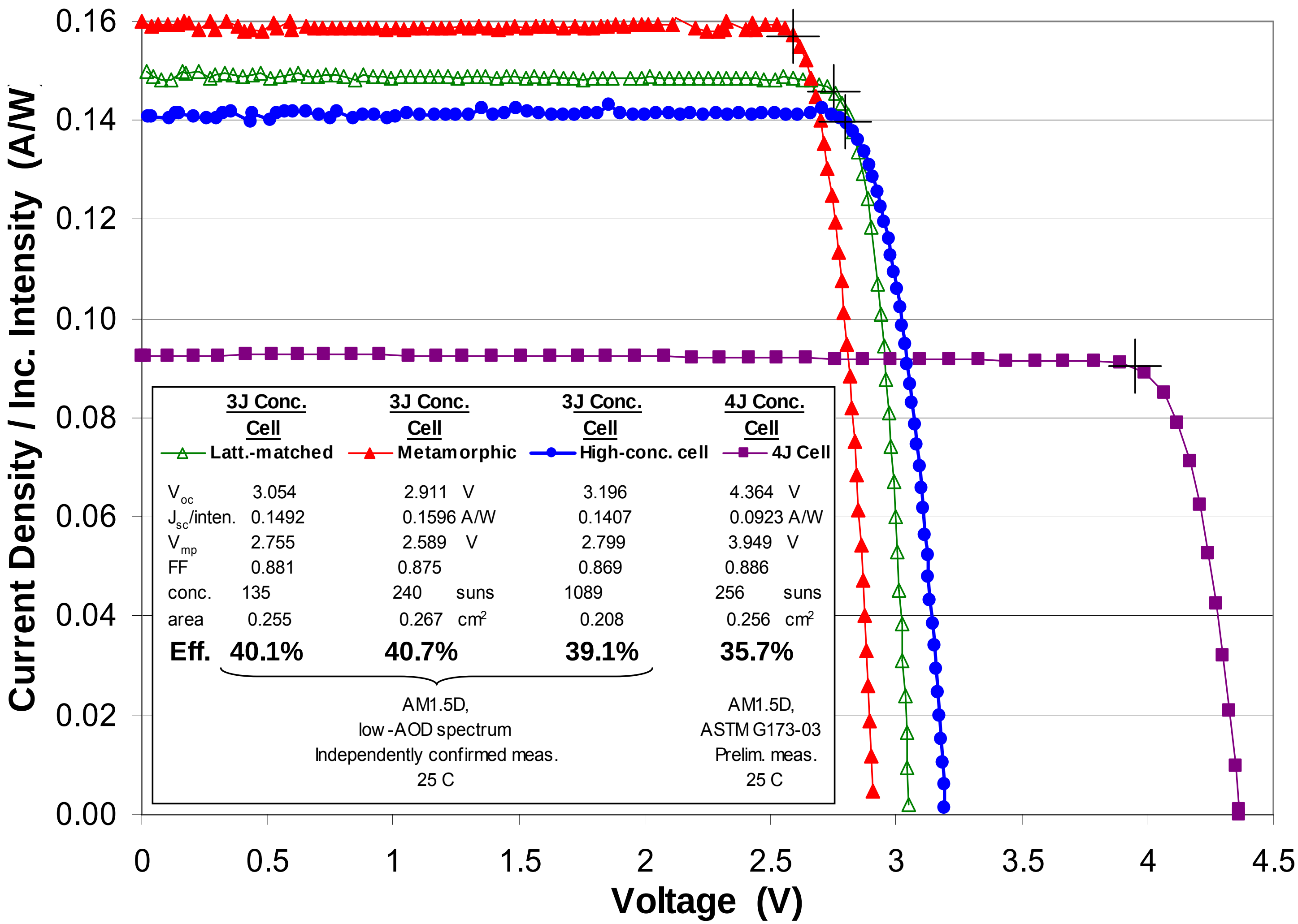
Light I-V Curves Record Efficiency Cells



- Light I-V curves for 3-junction upright MM (40.7%), 3J lattice-matched (40.1), 3J cell designed for >1000 suns (39.1%), and 4J LM cell (35.7%)

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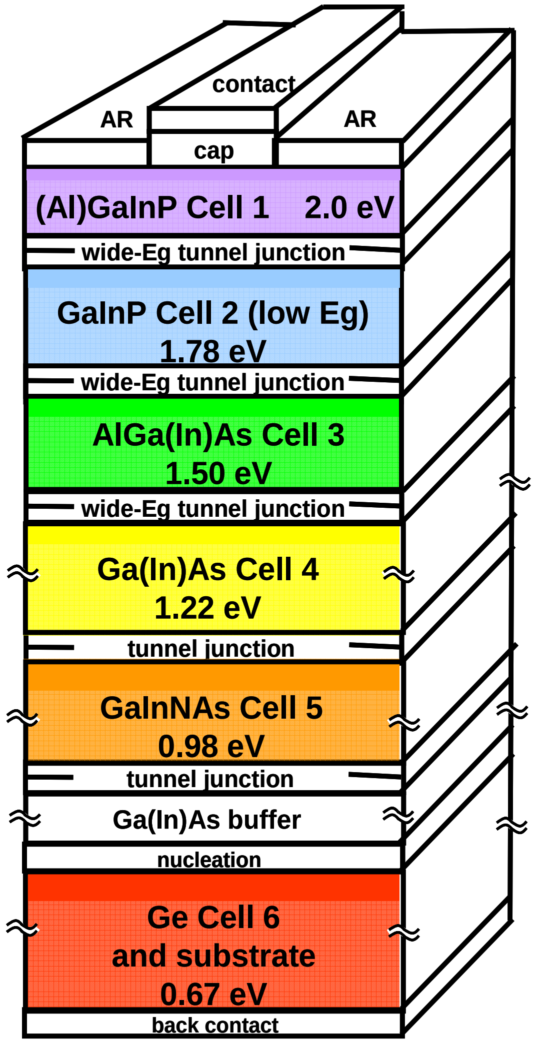
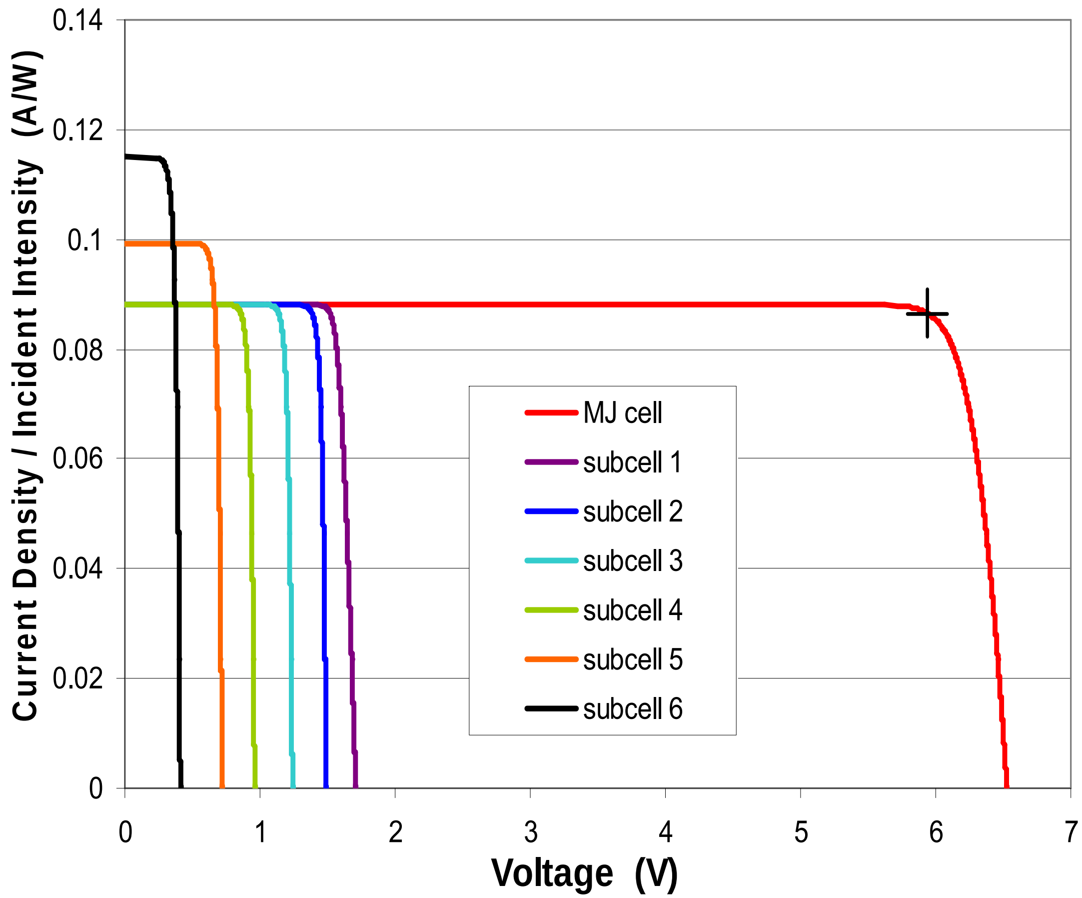
Electronic Materials for Renewable Energy





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Electronic Materials for Renewable Energy

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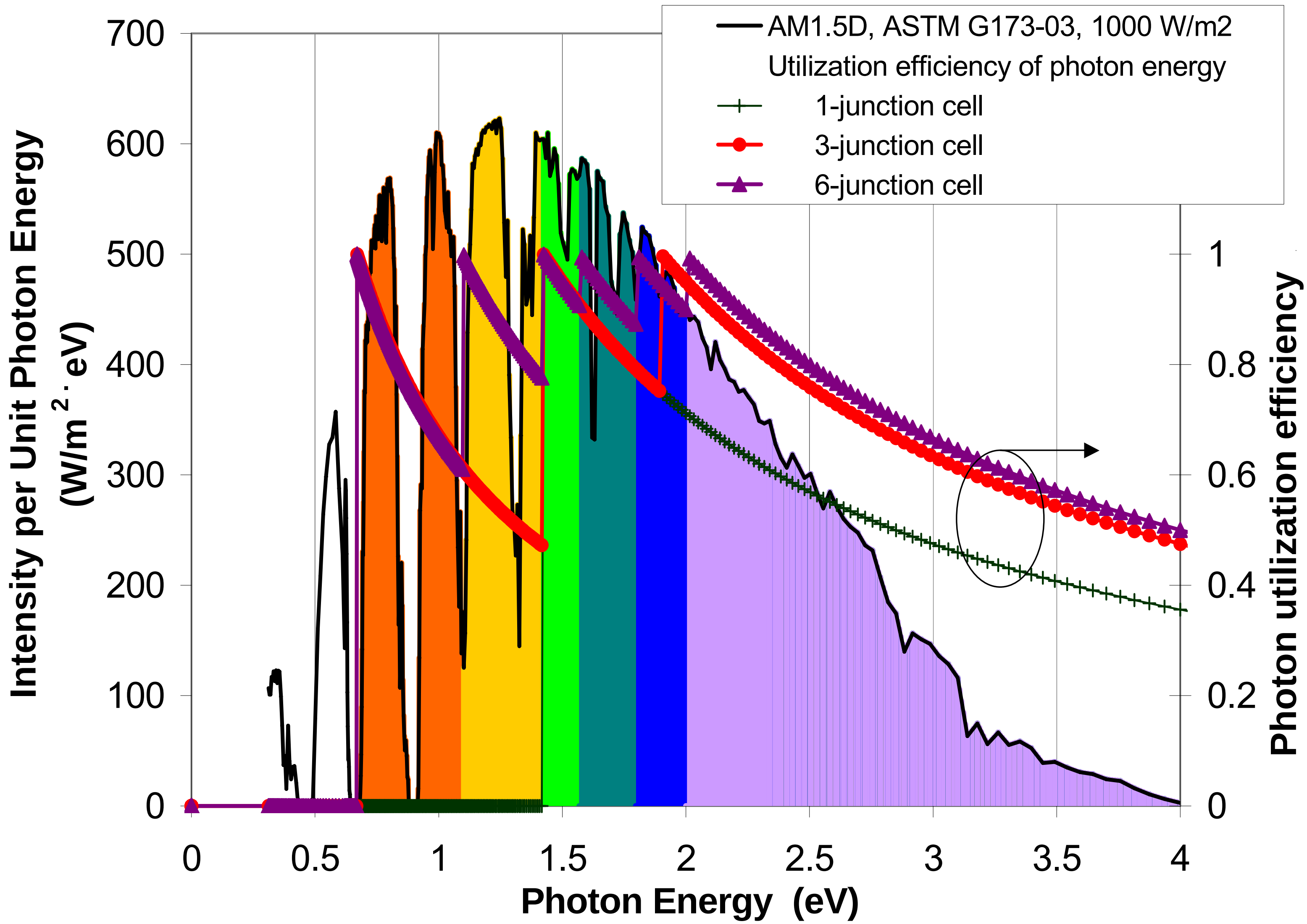

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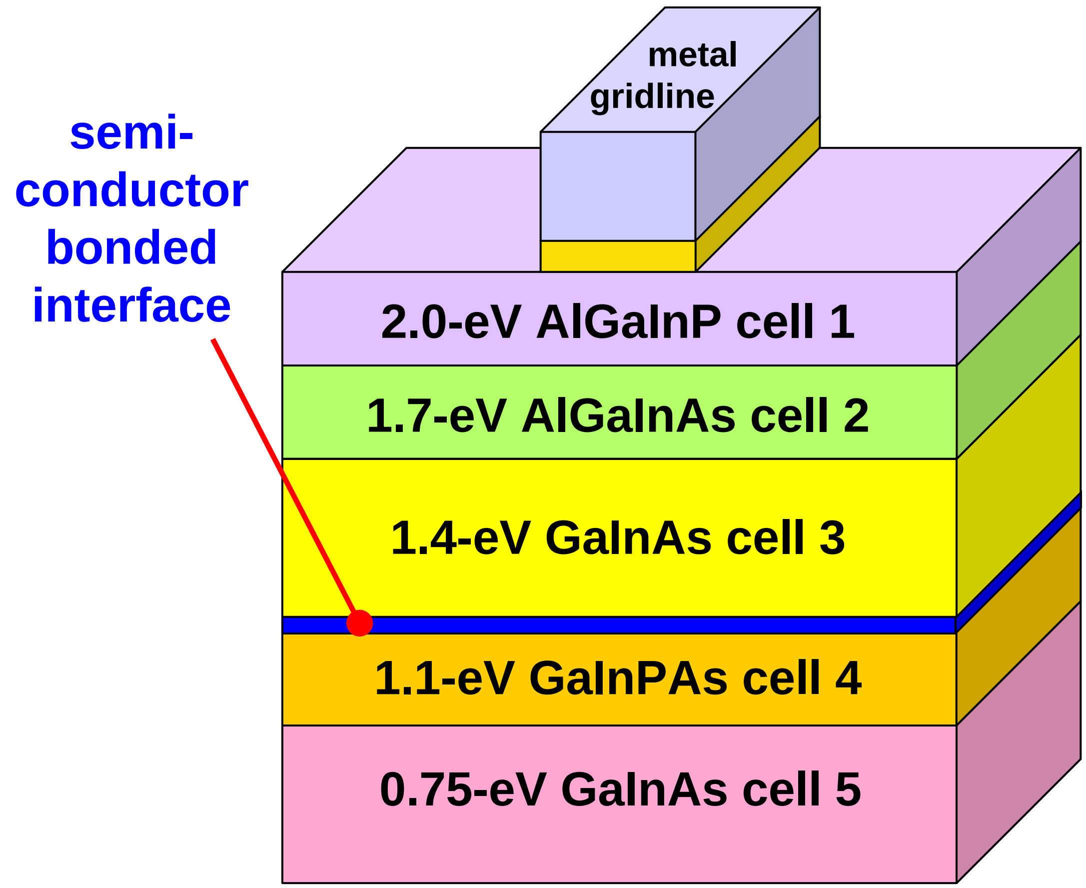
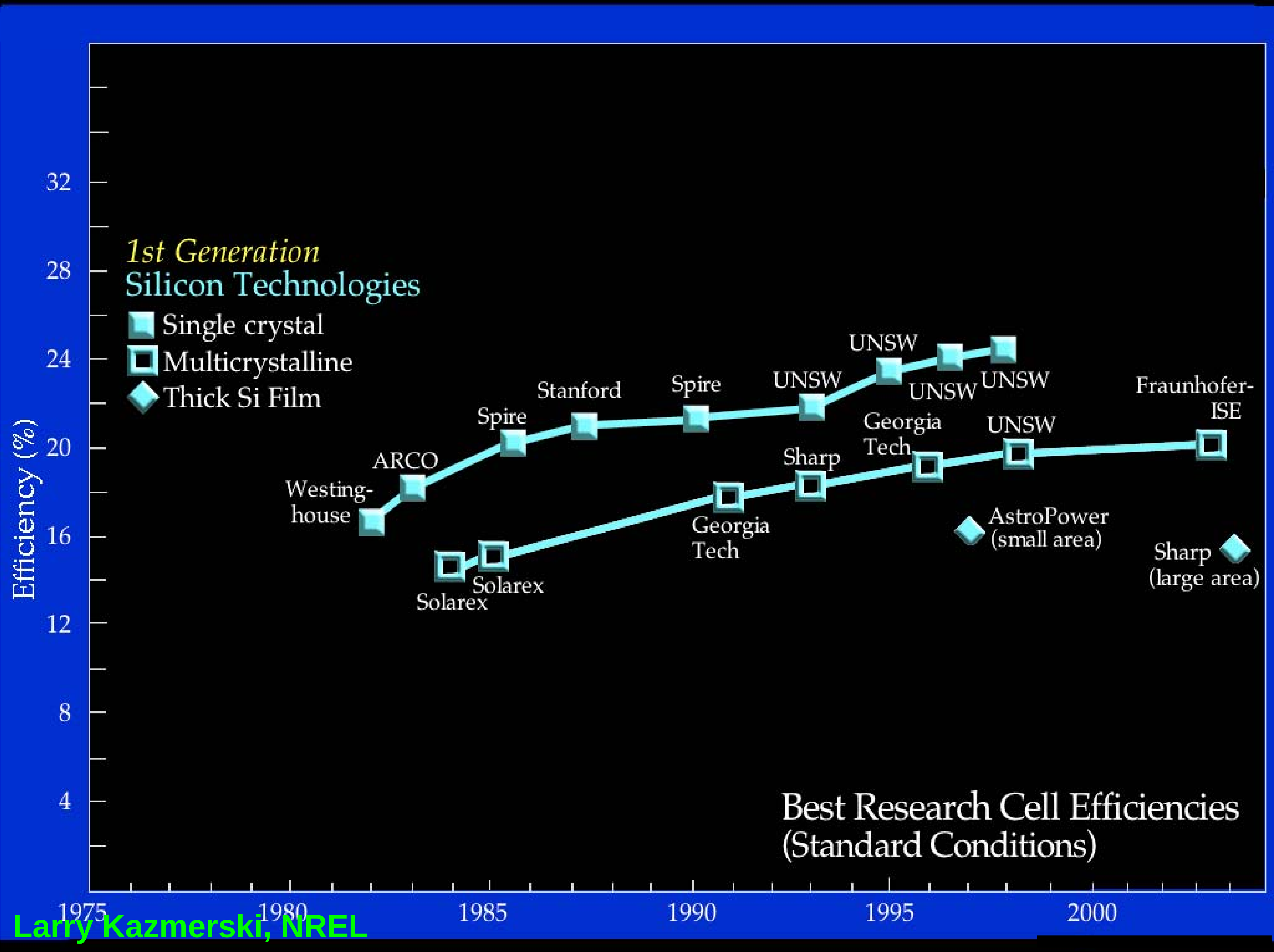
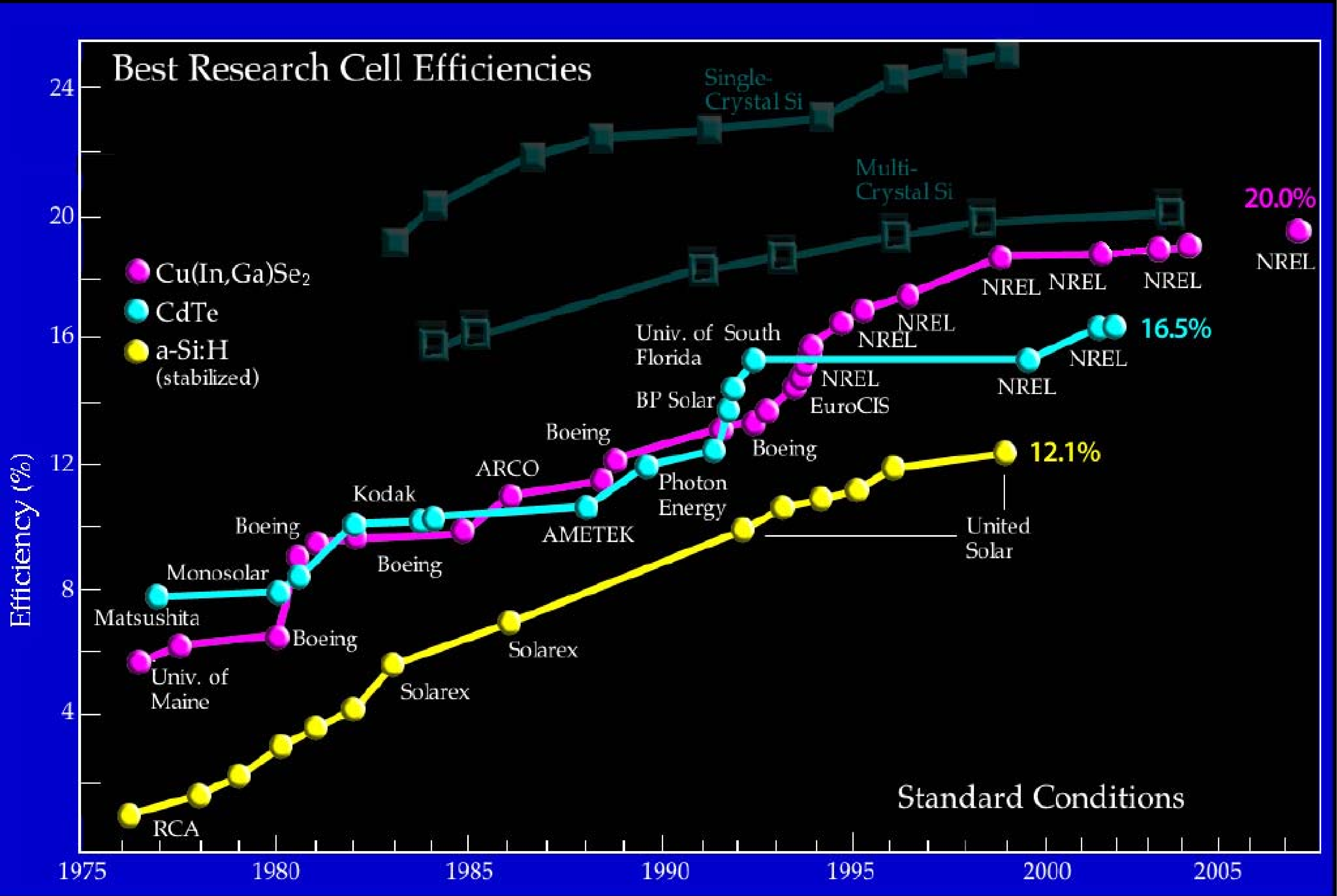
Semiconductor-Bonded Technology (SBT) Terrestrial Concentrator Cell

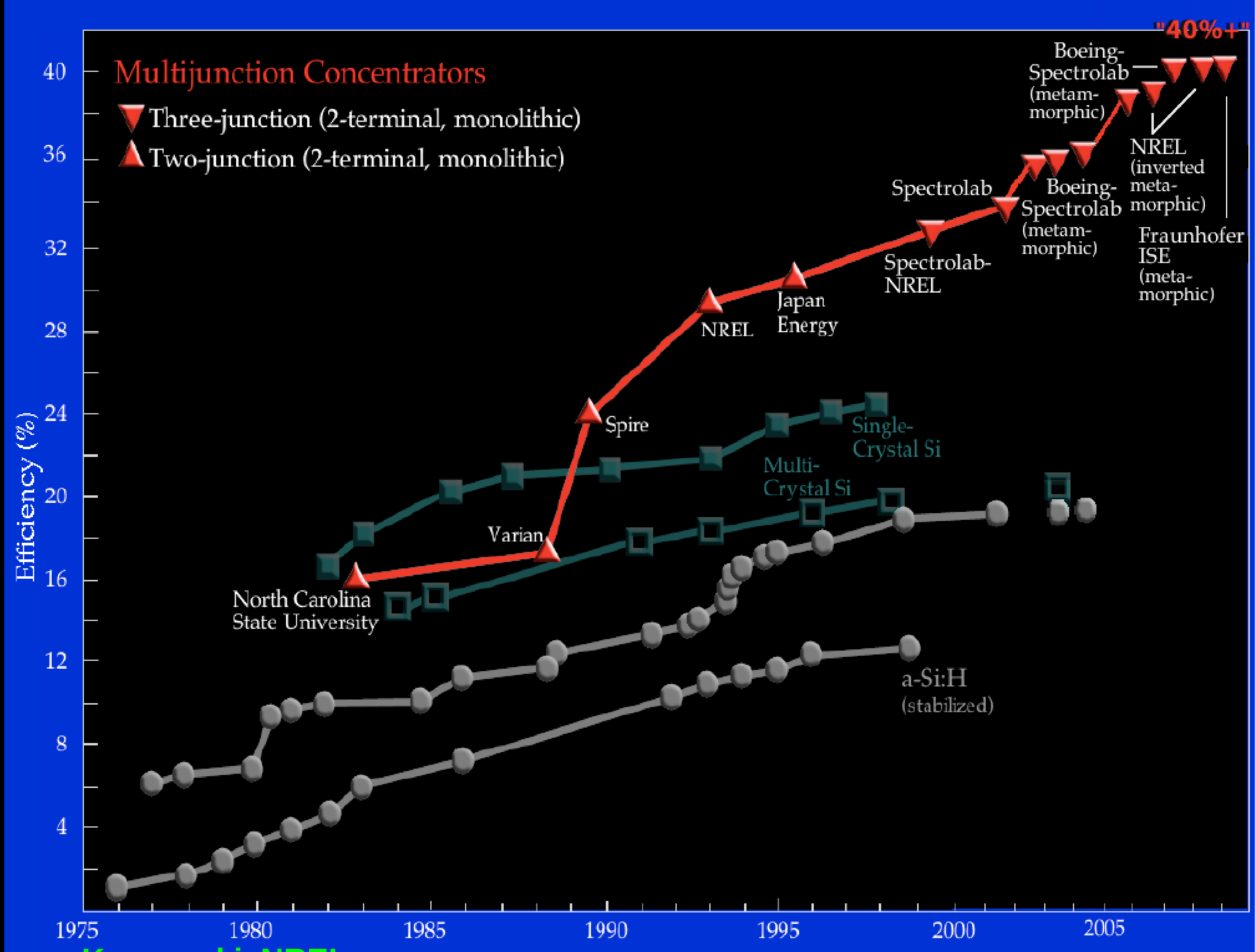
- **Wafer bonding for multijunction solar cells**
  - Low band gap cells for MJ cells using high-quality, lattice-matched materials
  - Epitaxial exfoliation and substrate removal
  - Formation of lattice-engineered substrate for later MJ cell growth
  - Bonding of high-band-gap and low-band-gap cells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




1st Generation
Silicon Technologies
Single crystal
Multicrystalline
Thick Si Film
Efficiency (%)
32
28
24
20
16
12
8
4
1975
1980
1985
1990
1995
2000
Westing-house
ARCO
Spire
Stanford
Spire
UNSW
UNSW
UNSW
UNSW
Solarex
Solarex
Georgia Tech
Sharp
Georgia Tech
UNSW
Fraunhofer-ISE
AstroPower (small area)
Sharp (large area)
Best Research Cell Efficiencies
(Standard Conditions)
Larry Kazmerski, NREL



Larry Kazmerski, NREL



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Concentrator Photovoltaic (CPV) Systems

and

Economics

Concentrator PV Systems with Multijunction Cells

- 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.

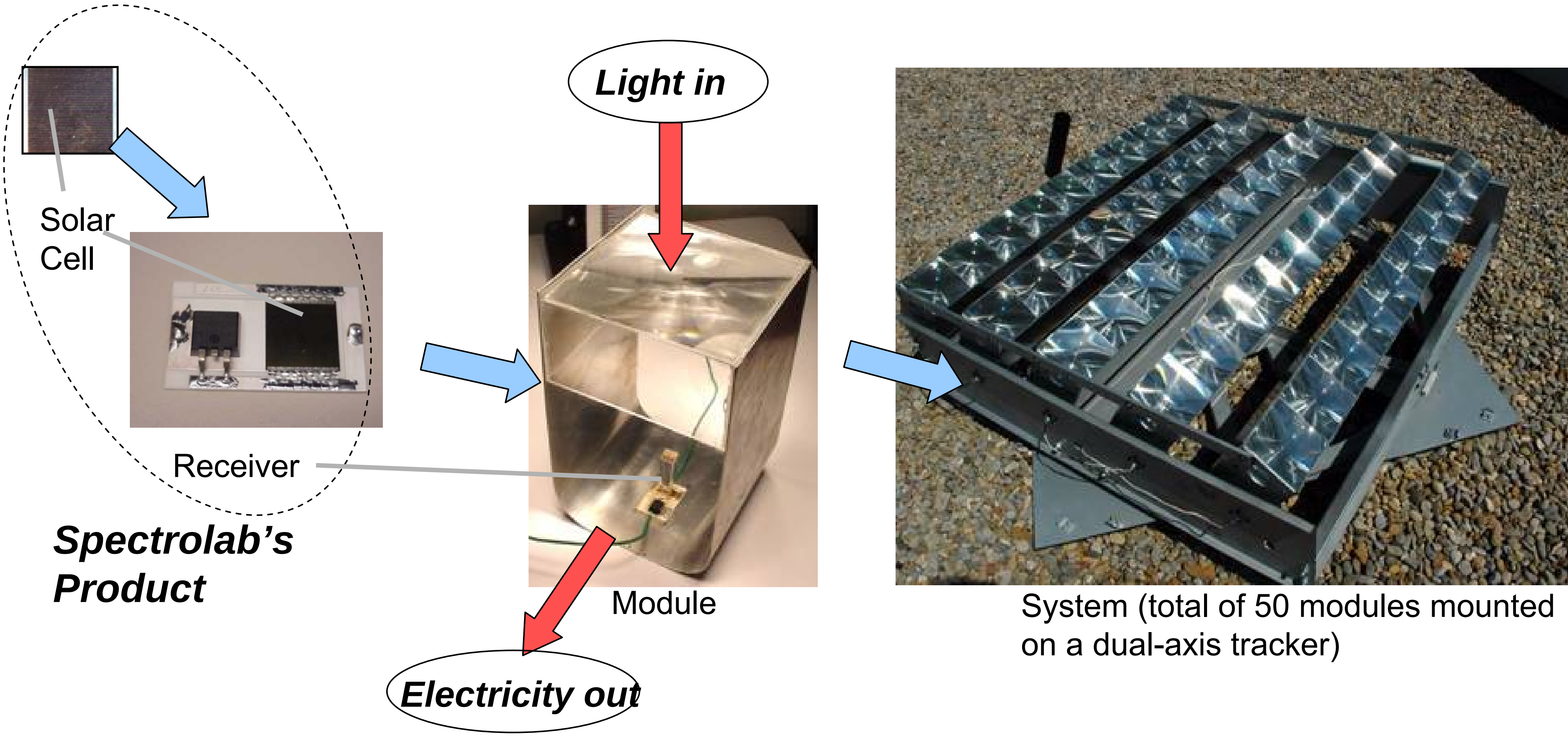
MJ cells are replaced by less expensive optics and common materials.

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

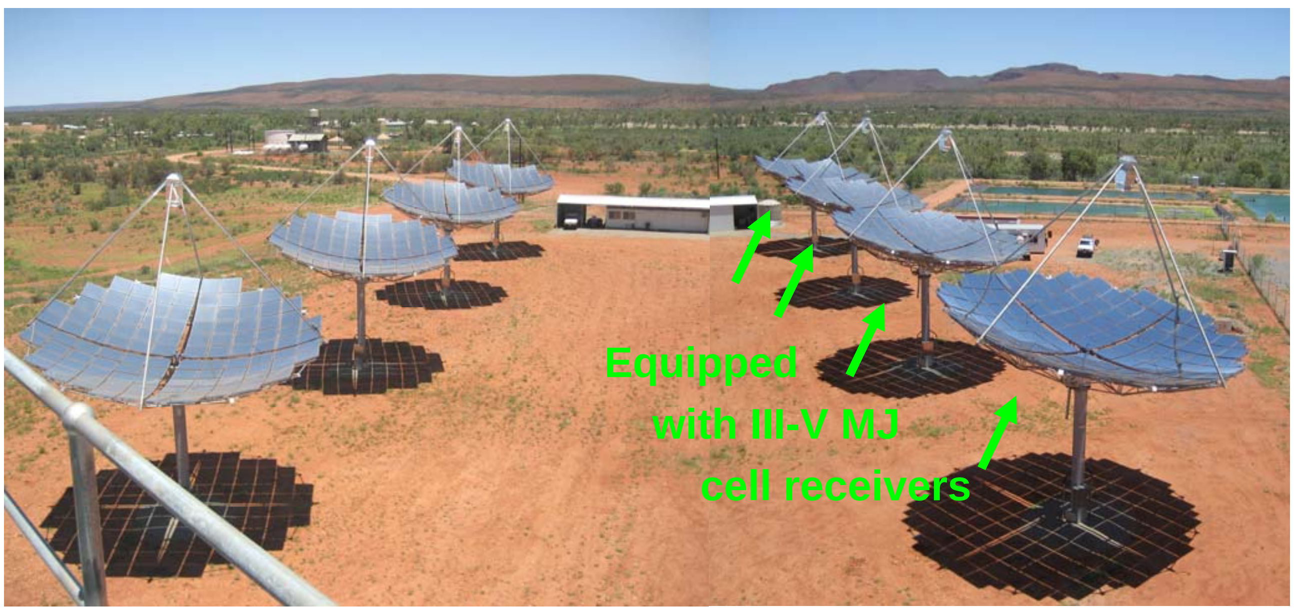
R. R. King, 51st Electronic Materials Conf., University Park, PA, June 24-26, 2009

Elements of a CPV System

Solar cells = Semiconductor converting light into electricity
Receiver = A collection of one or more solar cells mounted on substrates
Module = Receiver + optics to concentrate the light
BOS = Balance of System (everything else needed, e.g., tracker, inverter)



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

Optics

Cooling

Tracking

Structure

Operation and Maintenance

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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

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

Terrestrial PV System Cost vs. Cell Cost

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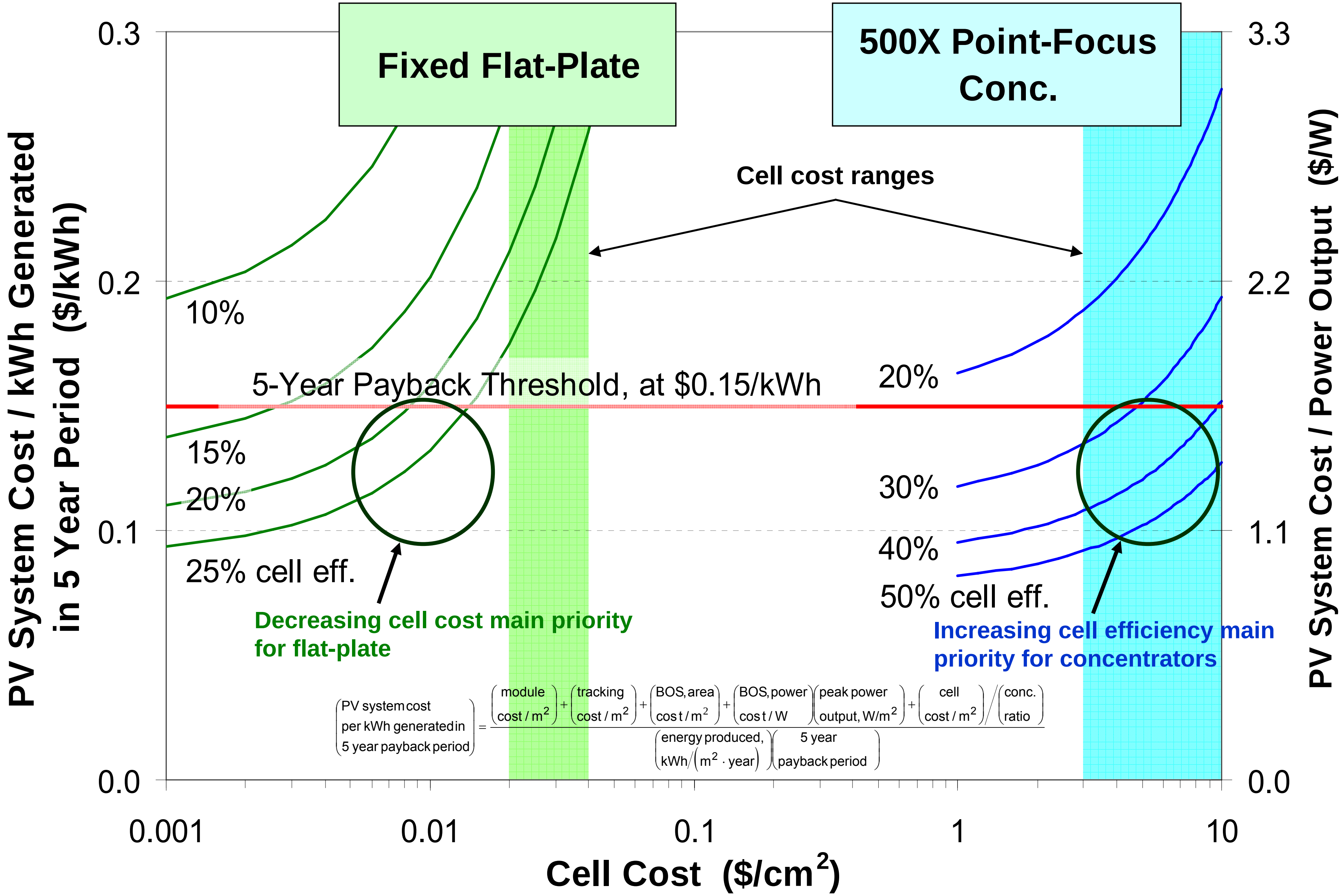
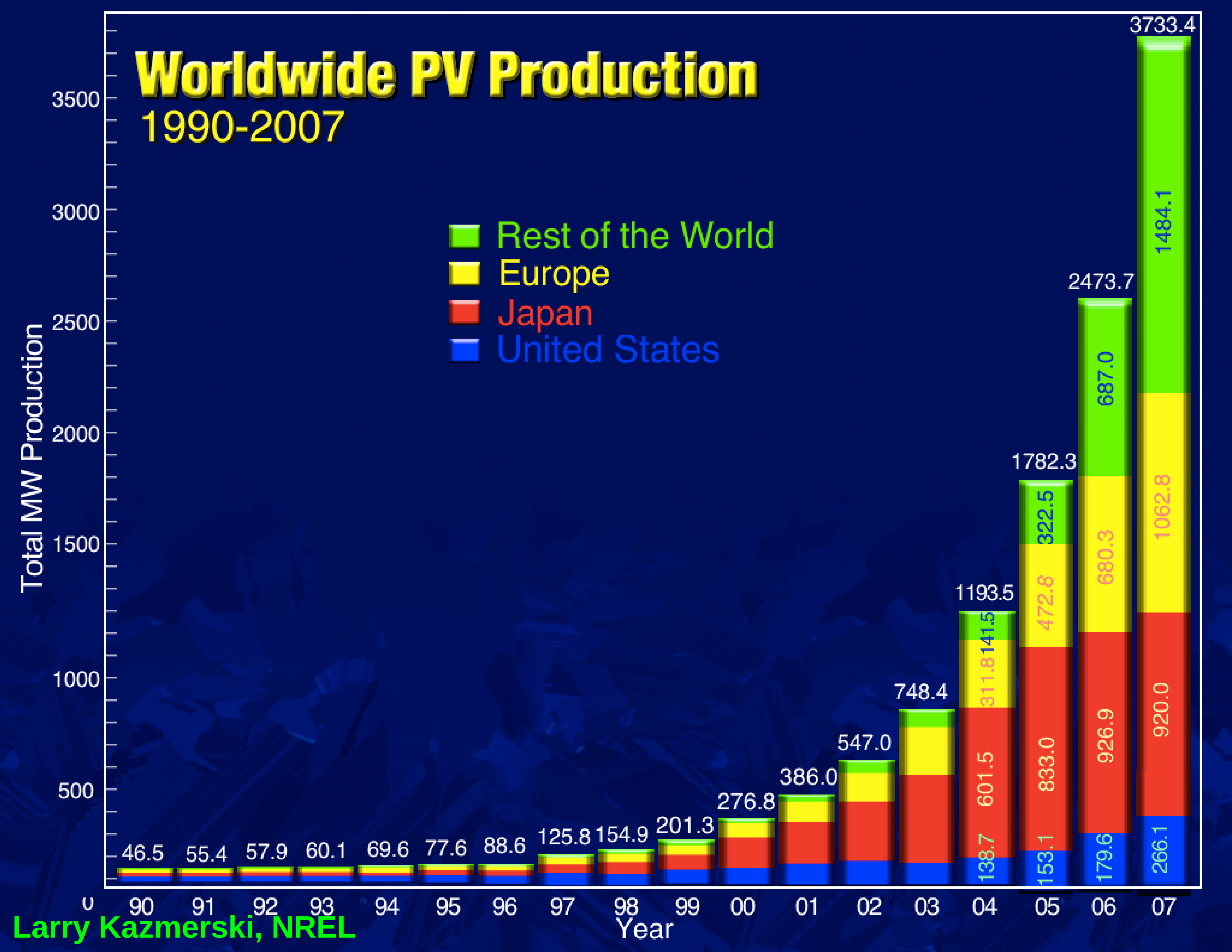
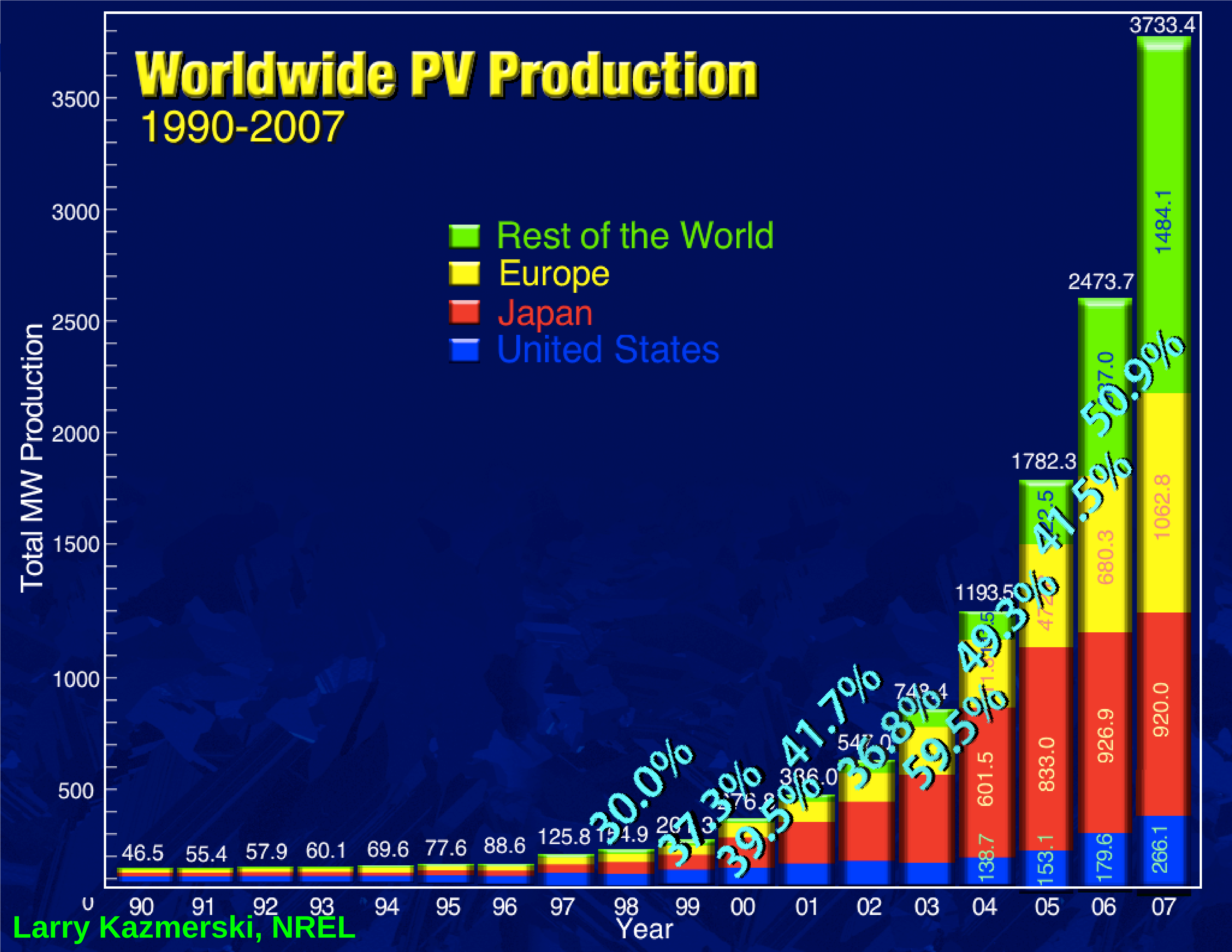


R. R. King et al.*, 3rd Int'l. Conf. on Solar Concentrators (ICSC-3), *Scottsdale, AZ, May 2005



Worldwide PV Production
1990-2007
Rest of the World
Europe
Japan
United States
Total MW Production
Year
3500
3000
2500
2000
1500
1000
500
0
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
154.9
201.3
276.8
386.0
547.0
748.4
1193.5
1782.3
2473.7
3733.4
141.5
311.8
601.5
138.7
322.5
472.8
833.0
153.1
687.0
680.3
926.9
179.6
1484.1
1062.8
920.0
266.1
Larry Kazmerski, NREL



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93
94
95
96
97
98
99
00
01
02
03
04
05
06
07
Year
46.5
55.4
57.9
60.1
69.6
77.6
88.6
125.8
386.0
547.0
748.4
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%
601.5
138.7
833.0
153.1
680.3
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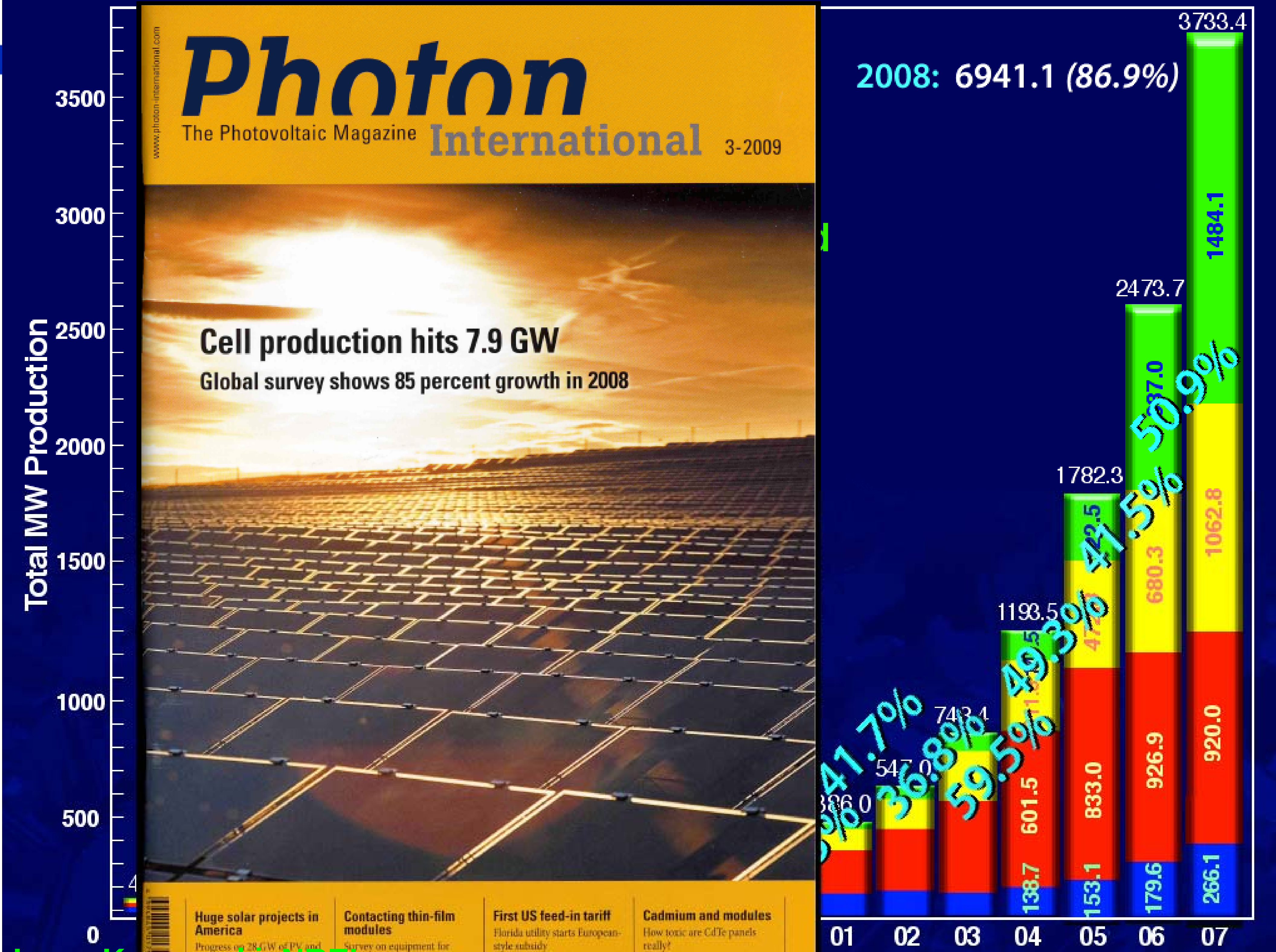

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Summary

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- **Urgent global need to address carbon emission, climate change, and energy security concerns → renewable electric power can help**
- **Electronic materials research has a huge opportunity to impact these challenges, by developing new materials, devices, processes to reach:**
  - 45-50% efficient single-crystal multijunction cells
  - 25% polycrystalline thin-film PV
  - better fuel cells, batteries, power and other renewable energy devices
- **Theoretical solar conversion efficiency**
  - Examination of built-in assumptions points out opportunities to reach higher terrestrial PV efficiency
  - Theo. solar cell η **> 70%,** practical η **> 50%** achievable
- **Metamorphic multijunction cells have begun to realize their promise**
  - **40.7%** metamorphic GaInP/ GaInAs/ Ge 3J cells demonstrated
  - First solar cells of any type to reach over 40% efficiency
  - Metamorphic 3J cells now over 41% efficiency
- **Solar cells with efficiencies in this range can transform the way we generate most of our electricity, and make the PV market explode**