# Single and Multi-junction Quantum Dot Solar Cells


***Seth Hubbard***
***Associate Professor***
***Physics/Microsystem Engineering***
***Rochester Institute of Technology***


NPRL NanoPower Research Laboratories
ROCHESTER INSTITUTE OF TECHNOLOGY

# Rochester Institute of Technology

NANOPOWER RESEARCH LABS


- Private university in upstate New York
  - ~18,000 students
  - 5.5 $km^2$ campus in suburban Rochester
  - Specialize in engineering and science

# NanoPV Group


- Steve Polly, Mike Slocum, Zac Bittner, Yushuai Dai, Brittany Smith and George Nelson: Microsystems Eng. PhD
- ***Alumni***: Dr. Chris Bailey (NRL), Chelsea Mackos (Emcore), Chris Kerestes (Emcore), Kristina Driscoll (RIT), Adam Podell (Photonics), Wyatt Strong (HRL), Mitch Bennett (NRL)

Research Support

# III-V Growth, Fabrication, Characterization


Aixtron 3x2” CCS MOVPE

Device Characterization

## III-V Epitaxial growth

- 50, 75, 100 mm capability
- Sources include: Ga, In, Al, P, As, Dopants include: Zn, Si, C and Te
- In-situ “Real-Temp” control and in-situ stress measurements

## III-V Processing technology

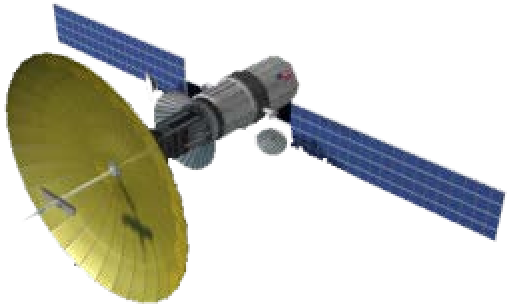
- Wet/Dry Etching, lithography
- Dedicated III-V metallization tools
- Annealing furnace up to 150mm

## Characterization

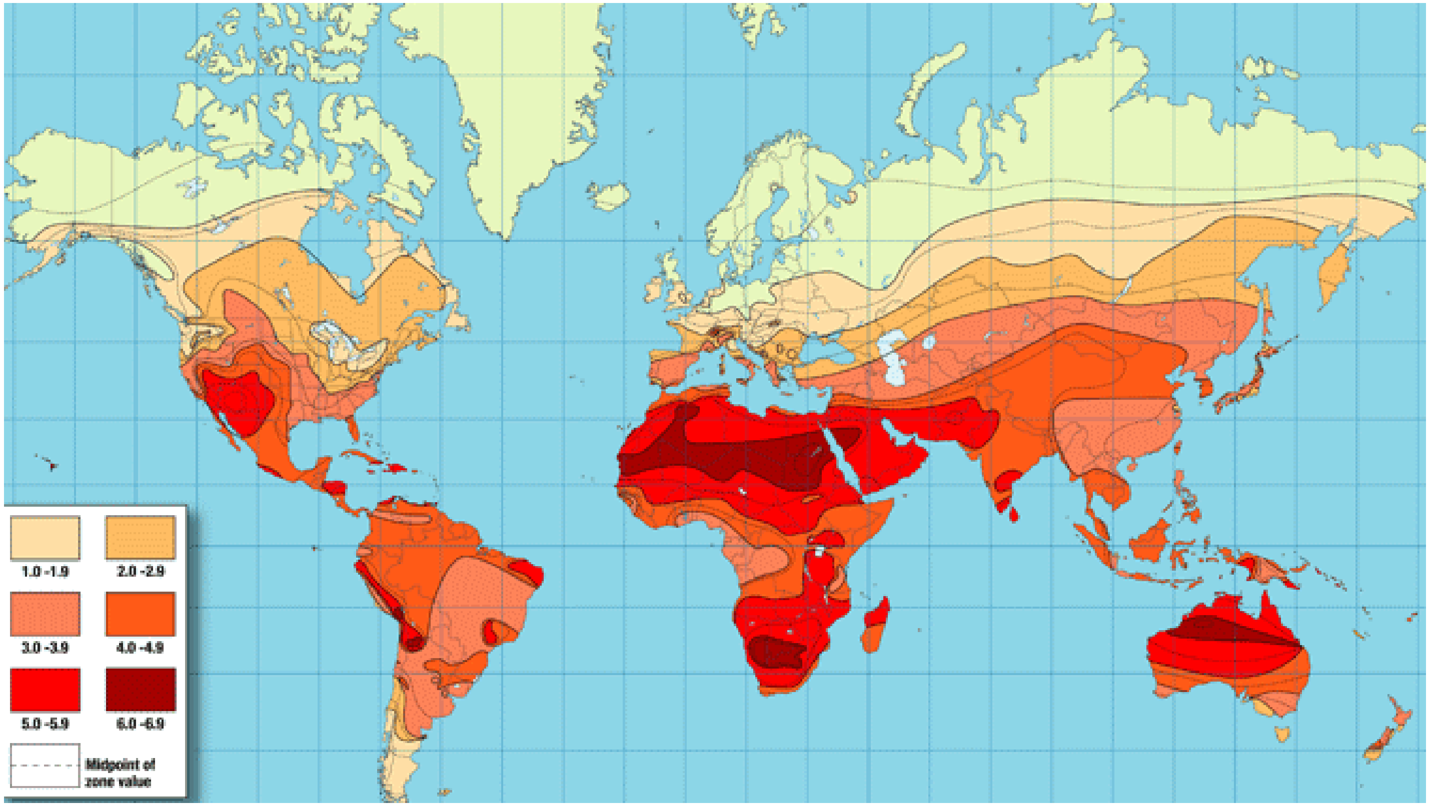
- TS Space systems 300 mm close-match solar simulator
- Bruker D8 HRXRD and XRR, Veeco D3100 AFM/STM
- Agilent B1500 Parametric Analyzer
- Cascade RF probe station
- Optronics and Newport spectral response
- Janis cryogenic (2K) probe station
- Photoluminescence and Photo-reflectance
- DLTS, FTIR, Raman, Hall
- Hitachi FE-SEM and Zeiss LEO SEM

# Outline

- Solar Energy Overview
- Nanostructured Photovoltaics
- SJ QD Solar Cells
- InAlAsSb Top Cells
- Conclusions



# Global Solar Energy Resource




Average insolation kWh/m$^2$/day

- Enough energy from the sun hits the Earth every hour to power mankind's entire energy needs for an entire year.
- The U.S. has the best solar energy resource of any industrialized country on the Earth.

# Solar Energy Potential



## Worldwide Solar Energy

Theoretical: 120,000 TW

*Energy in 1 hour of sunlight ⌚ 14 TW-yr*

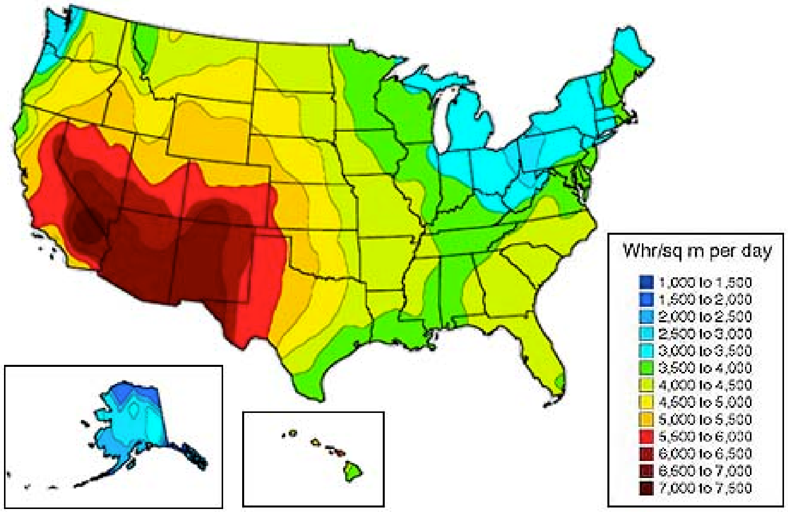
Practical: ≈ 600 TW

## Efficiency

| 10% | 20% | 30% | 40% |
| --- | --- | --- | --- |

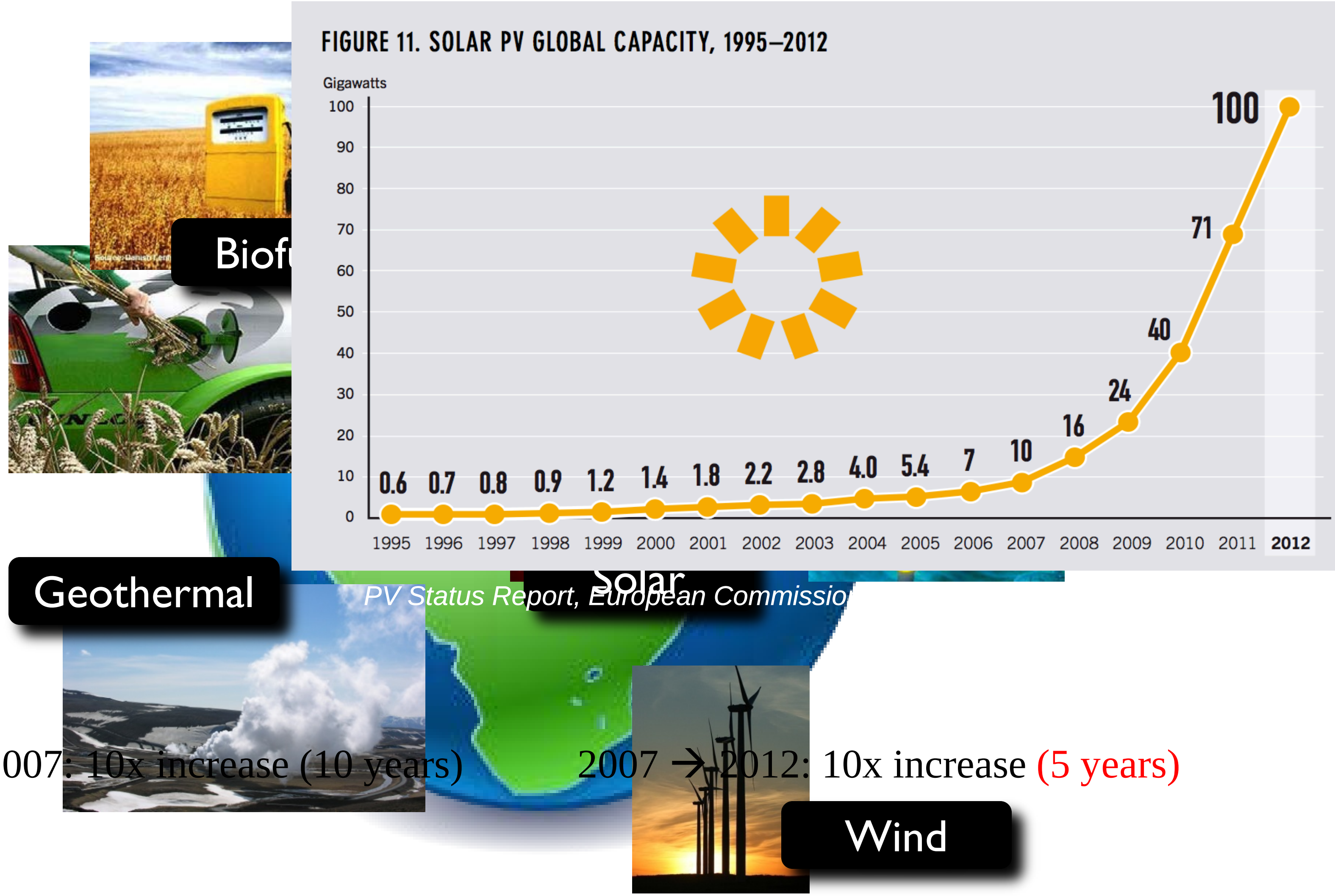
*3.6 TW US Consumption*


**Currently, solar provides less than 0.1% of the electricity used in the U.S.**




Solar resource for a concentrating collector

# Alternatives to Fossil Fuels

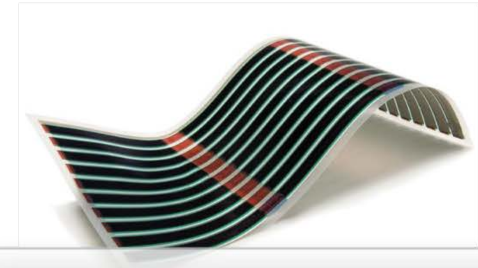


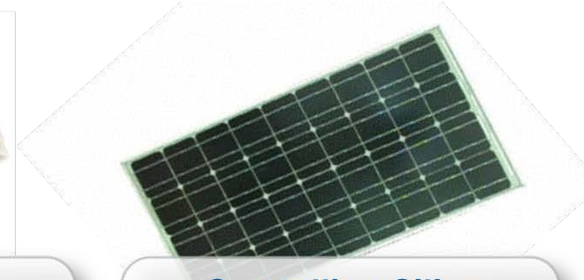

*PV Status Report, European Commissio*

1997 → 2007: 10x increase (10 years)

2007 → 2012: 10x increase (5 years)

# Photovoltaic Technologies

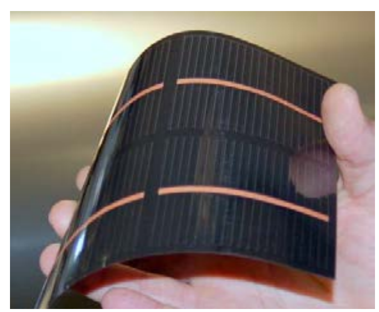


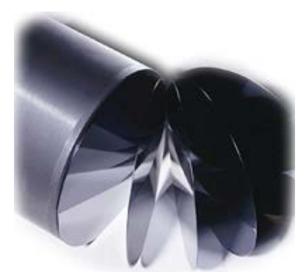


**CPV** — MARKET
- Ground Mounted
- Rooftop Mounted

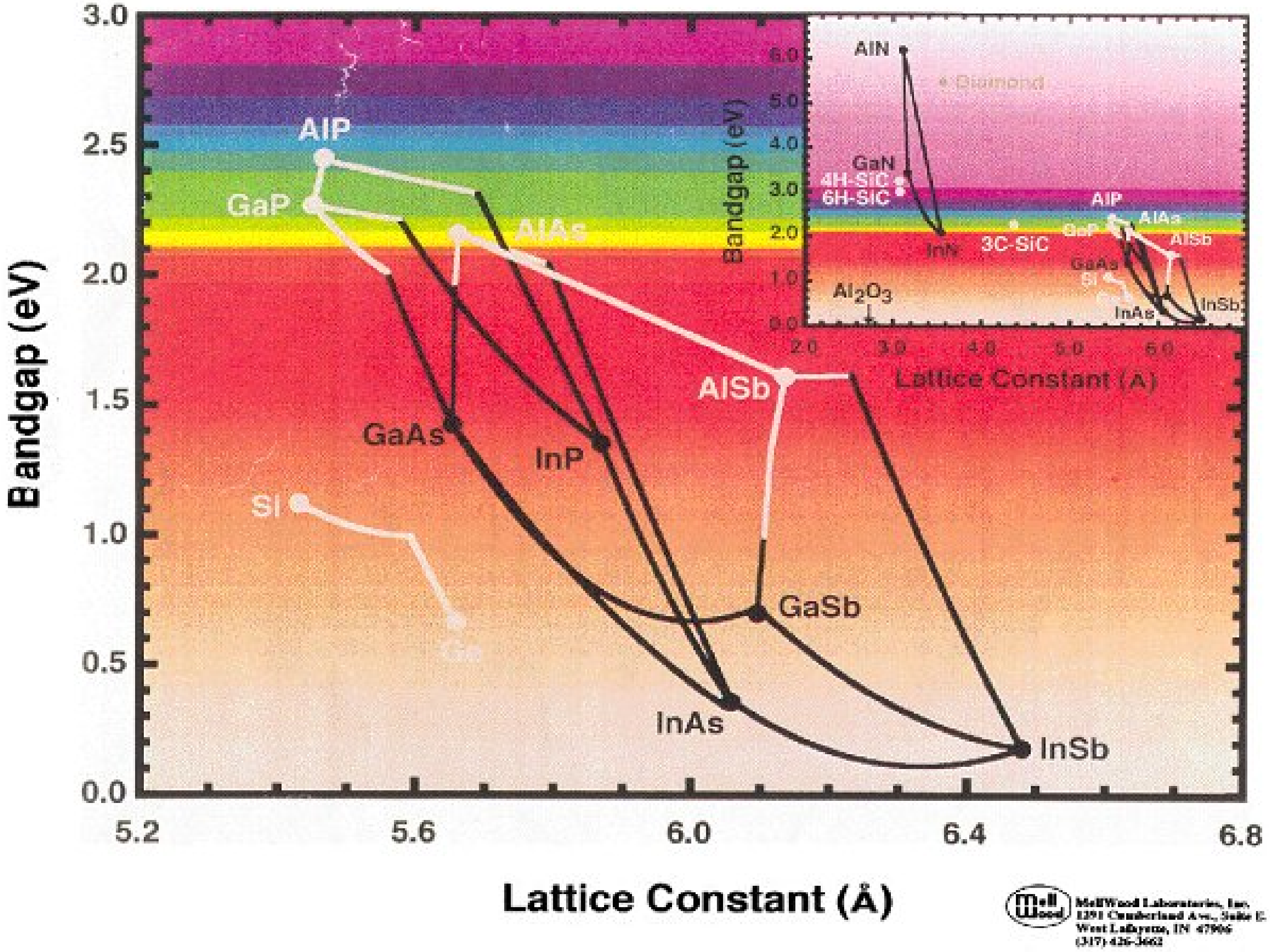
**Thin Films** — MATERIAL
- Amorphous Silicon
- CdTe / CIGS
- Organic

**Crystalline Silicon** — STRUCTURE
- Multi-Crystalline
- Mono-Crystalline

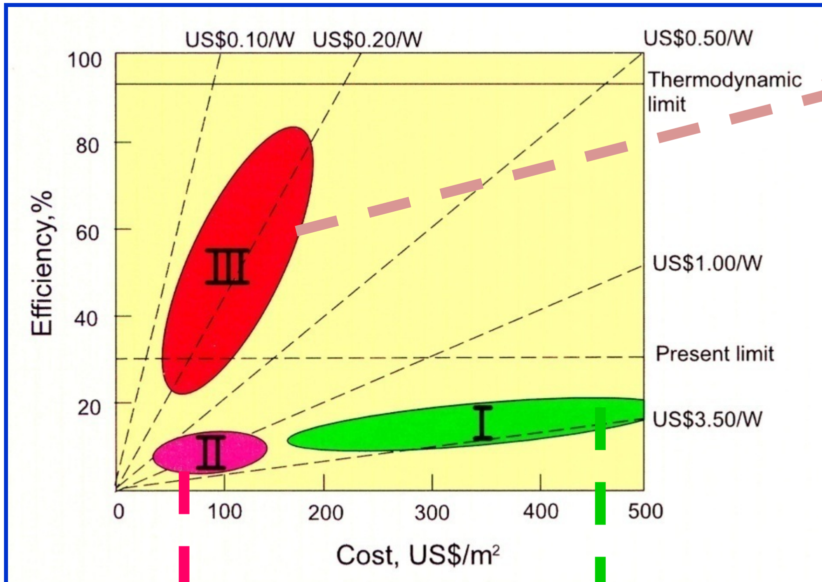




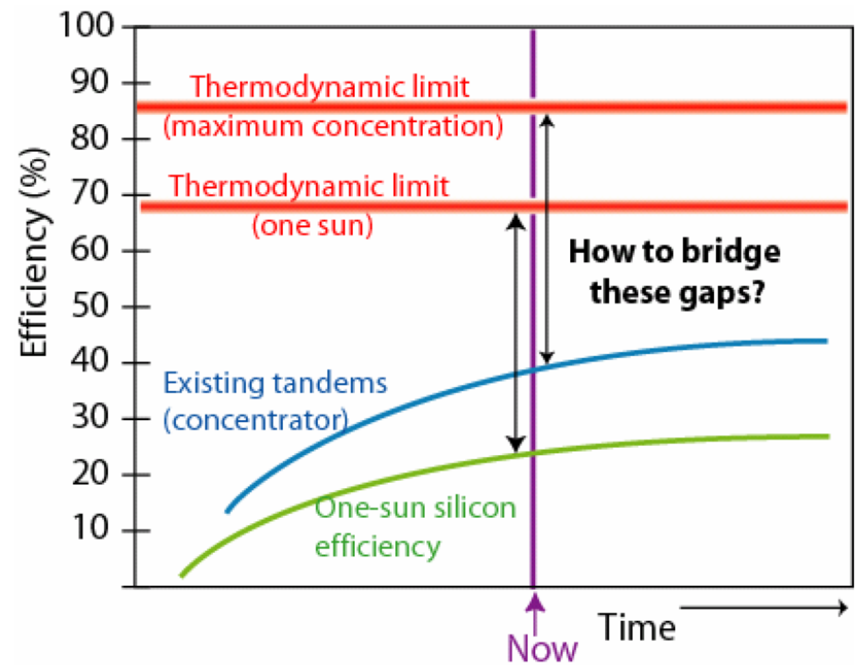
# Tailoring Materials for Color

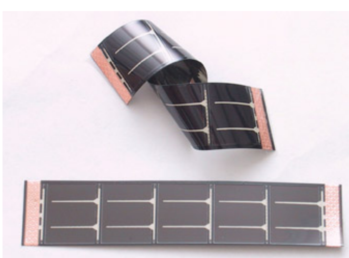


# Research…going forward




## Increased Efficiency and/or Lower Cost



**Amorphous Silicon, CdTe, CIGS**

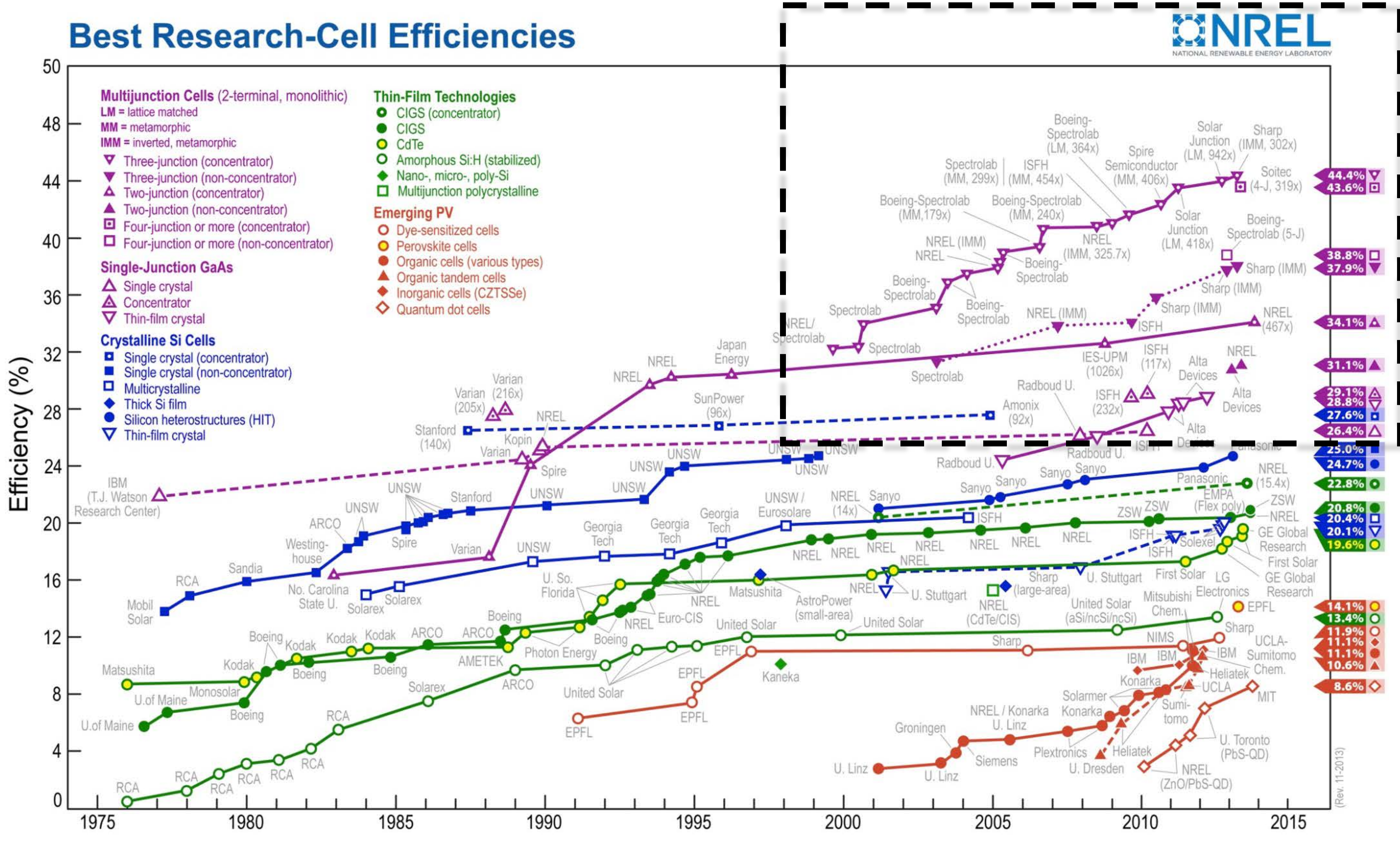
**Silicon**

# Next Generation Strategies

## Next Generation PV

- **Less Photovoltaic Materials**
  - *Concentration PV*
  - *Light Trapping*
- **Increased work per photon**
  - *Multi-junction III-V*
  - *Multi-exiton*
  - *IBSC*
- **Cheaper Photovoltaic Material**
  - *Thin Film PV*
  - *Organic materials*

# World Record Efficiencies



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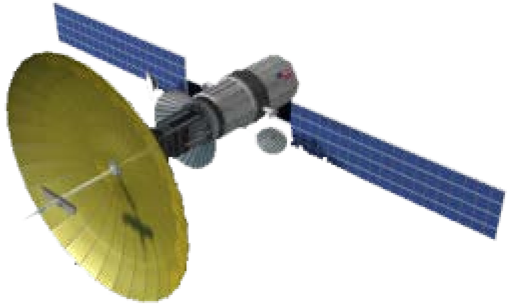
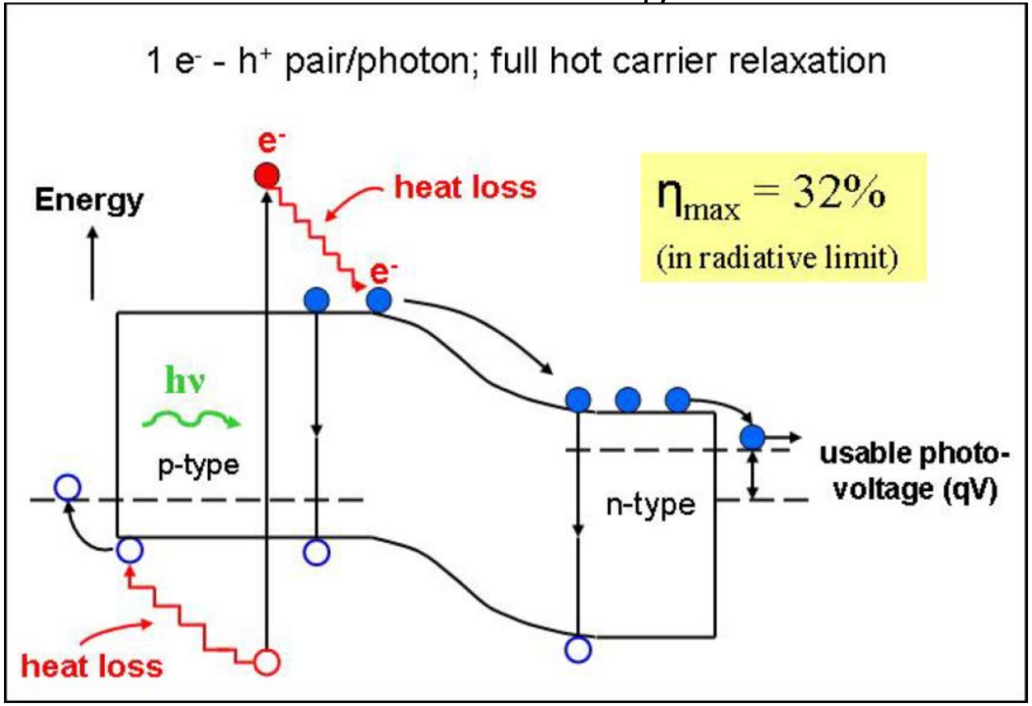
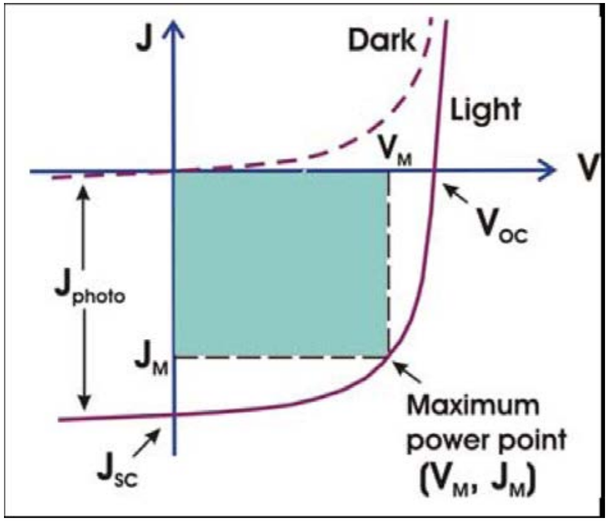


# Solar Cell Electrical Model

Single junction
solar cell band diagram




$$J = J_0(e^{qV/kT} - 1) - J_{SC}$$

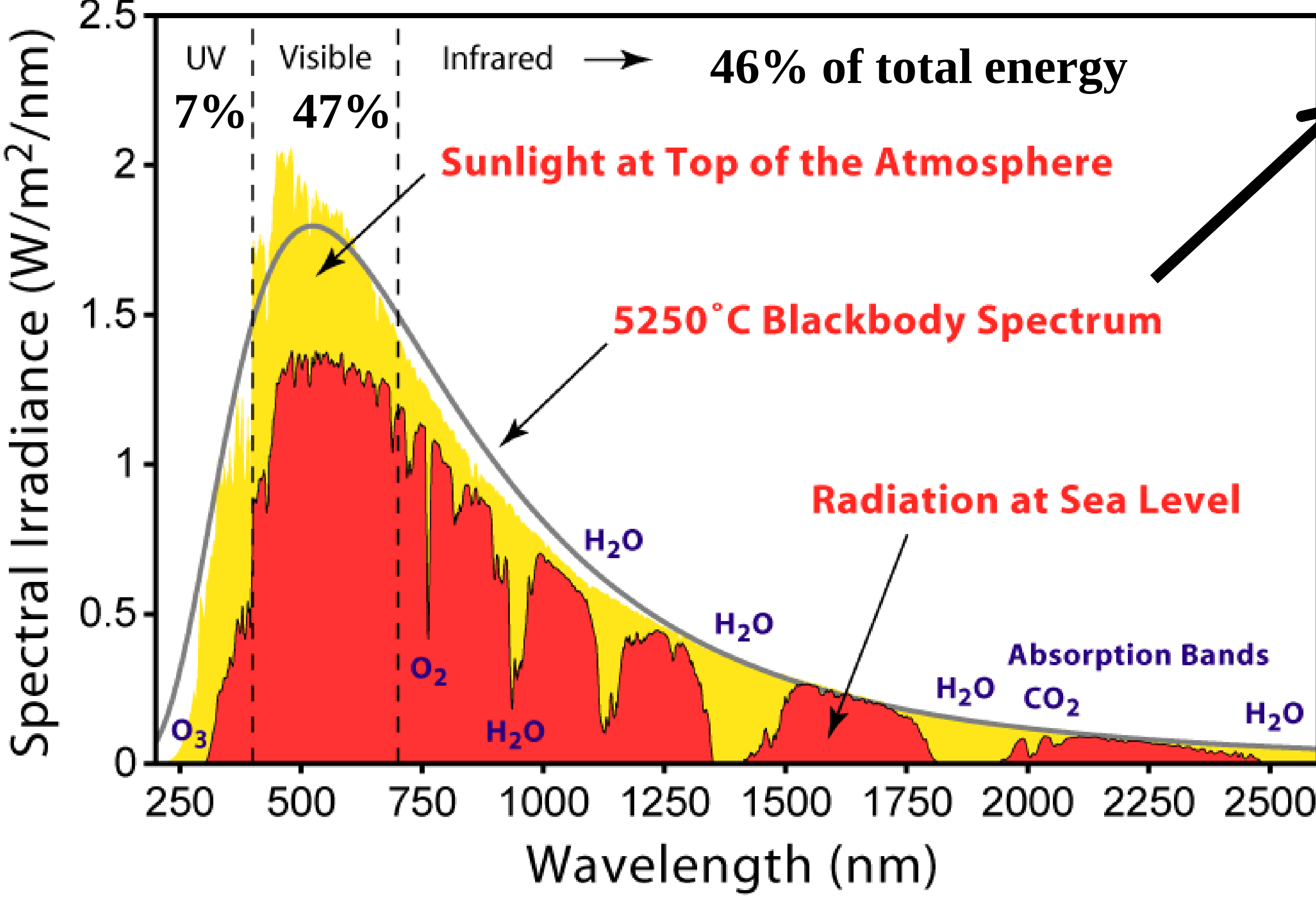
$$FF = \frac{P_{max}}{J_{sc}V_{oc}} = \frac{J_{max}V_{max}}{J_{sc}V_{oc}}$$

$$\eta = \frac{P_{max}}{P_{inc}} = \frac{J_{max}V_{max}}{P_{inc}}$$

- Solar Cell Loss Mechanisms
  1. Thermalization Loss (33%)
  2. hν<$E_g$ (23%)
  3. Carrier Recombination
  4. Contact and Junction Voltage

# Solar Spectrum

## Solar Radiation Spectrum




$$\frac{d\Phi}{dE} = \frac{2\pi E^2}{h^3 c^2} \frac{1}{e^{E/kT} - 1}$$

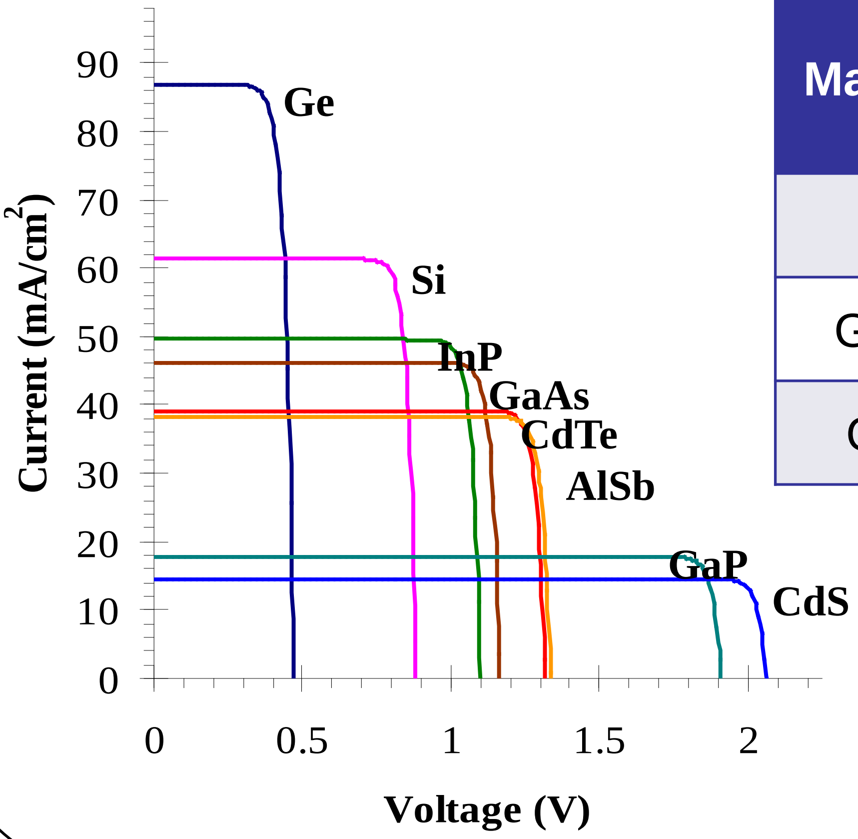
**Air Mass # = sec $\theta_z$**

**AM1.5 → $\theta_z$ = 48.19°**

**AM0 → Extraterrestrial**

# Single-Junction Limits

$$J(V) = f_\Omega \frac{2\pi q}{h^3c^2}\int_{\overline{E}_n} \frac{E^2 dE}{e^{E/kT_s}-1} - \frac{2\pi q}{h^3c^2}\int_{\overline{E}_n} \frac{E^2 dE}{e^{(E-qV)/kT_c}-1}$$



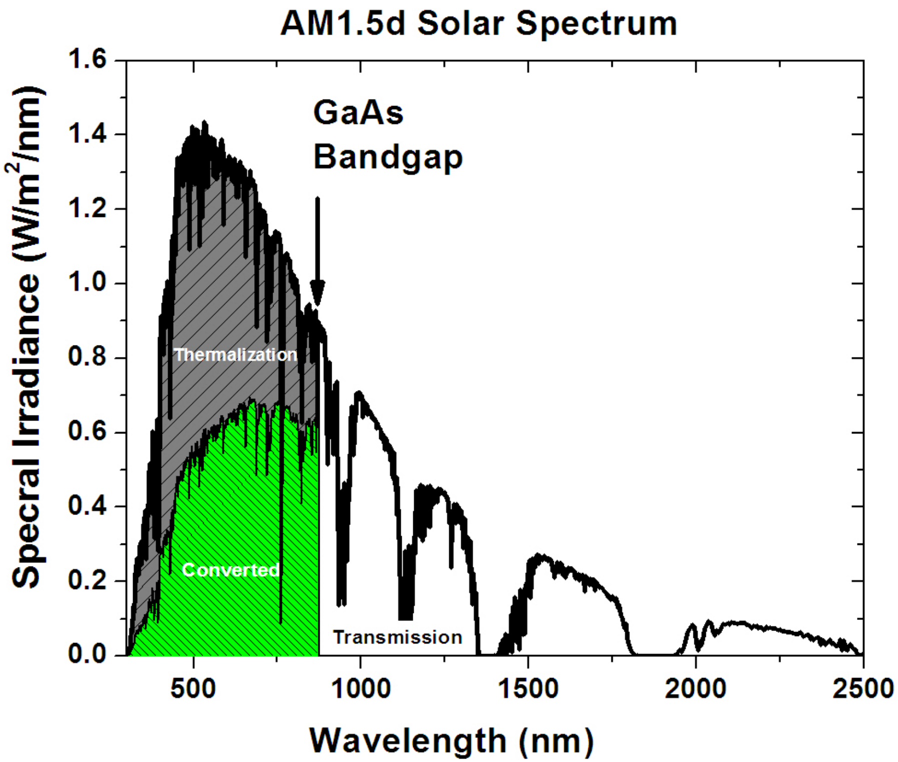

| Material | Bandgap (eV) | Short-circuit Current | Open Circuit Voltage |
|---|---|---|---|
| Si | 1.1 | 62 mA | .88V |
| GaAs | 1.4 | 46 mA | 1.16V |
| GaP | 2.2 | 18 mA | 1.81V |

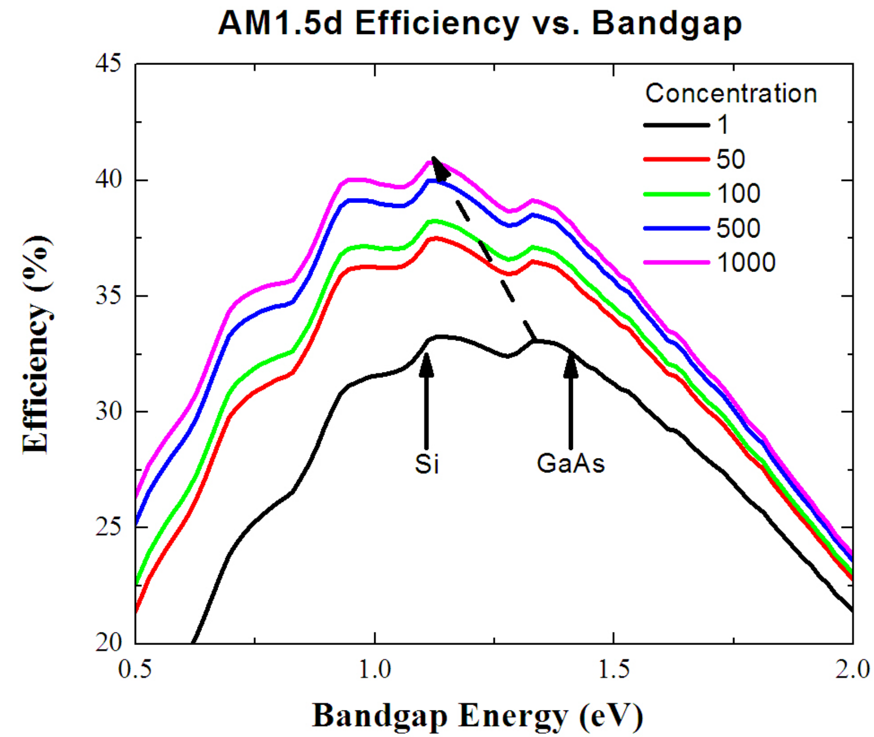
Solar concentrations: 1x, 10x, 100x, 518x, 1000x, 5180x, 10000x, 46198x

# Solar Cell Loss Mechanisms

Replace solar blackbody expression with ASTM solar data.

$$J(V) = f_\Omega \frac{2\pi q}{h^3 c^2} \int_{\overline{E}_n} \frac{E^2 dE}{e^{E/kT_s} - 1} - \frac{2\pi q}{h^3 c^2} \int_{\overline{E}_n} \frac{E^2 dE}{e^{(E-qV)/kT_c} - 1}$$




–Shockley-Queisser Limit approaches 40% at high Concentration

–Optimal bandgap approaches 1.2eV

•Bandgap tuning with QD or QW

# The Lattice Matched Triple Junction

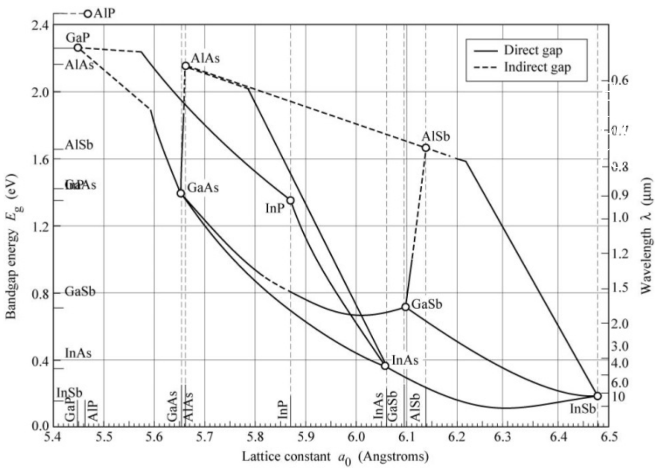
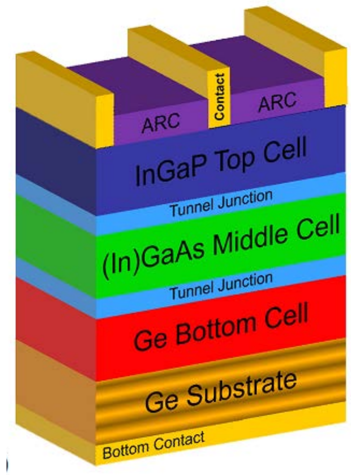



Fig. 12.6. Bandgap energy and lattice constant of various III–V semiconductors at room temperature (adopted from Tien, 1988).

E. F. Schubert
Light-Emitting Diodes (Cambridge Univ. Press)
www.LightEmittingDiodes.org

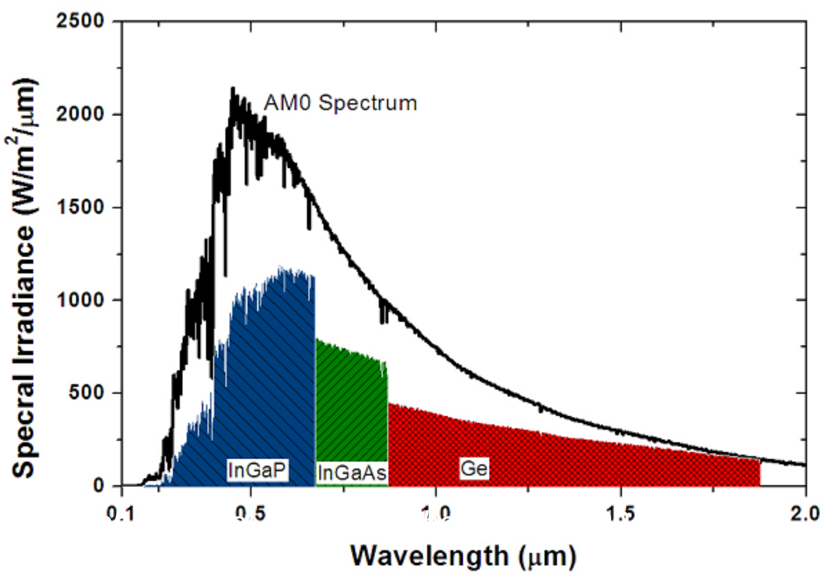
State of the art lattice matched triple junction

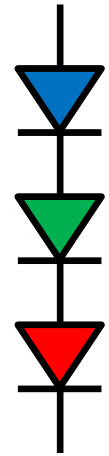



InGaP ~ 1.90 eV

GaAs = 1.42 eV

Ge = 0.66 eV

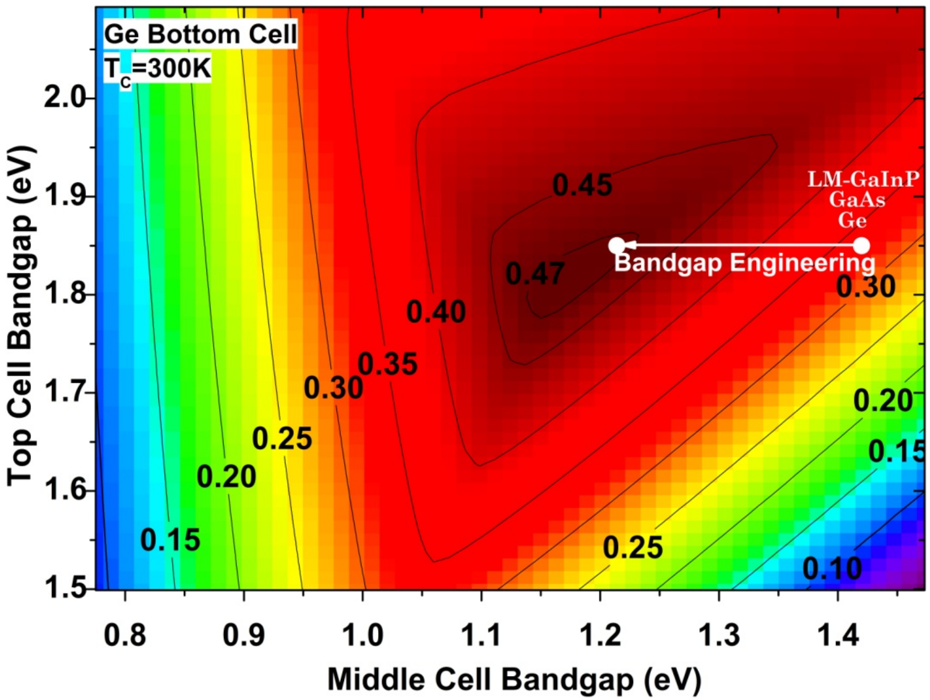


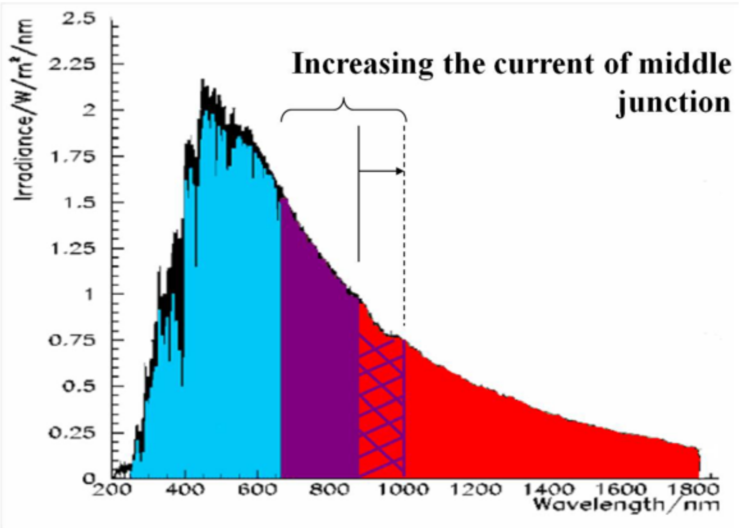



Three series connected diodes

Current-matching required

# The Bandgap Engineering Approach

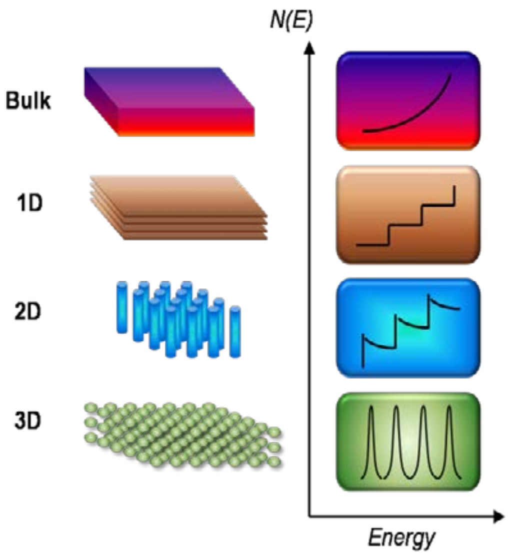


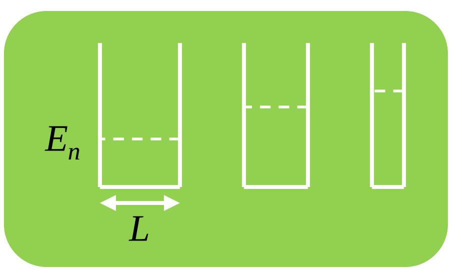




- Extra current generated from QW or QD regions can aid in current matching in multi-junction solar cells

# Nanostructured Absorption

Bohr radius $a_0 = \frac{4\pi\varepsilon_0\hbar^2}{me^2}$

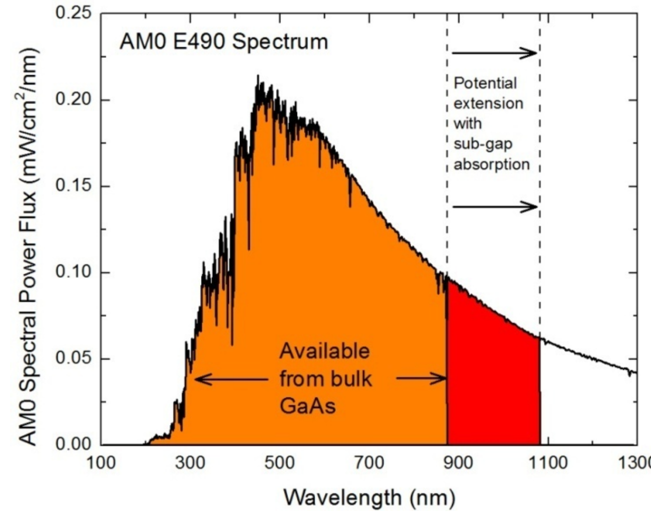



Size dependent absorption

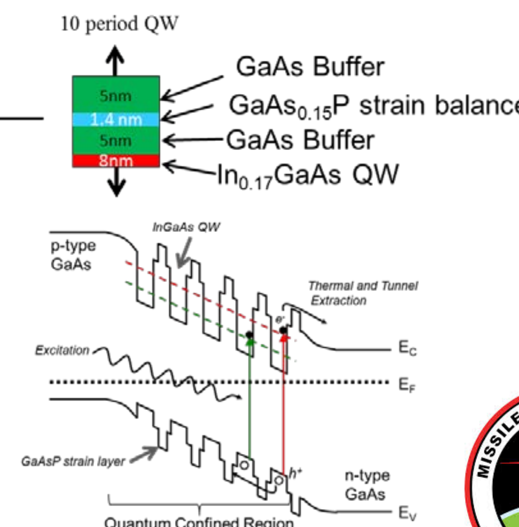
## Single Quantum Well:

$$E_n = \frac{\pi^2\hbar^2}{2m^*}\frac{n^2}{L^2}$$





QW GaAs *p-i-n* structure

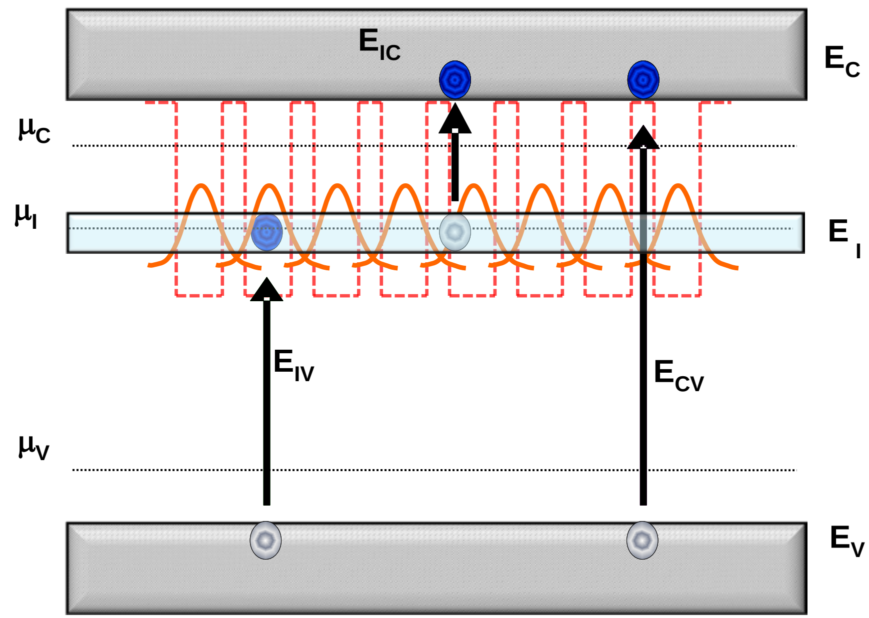


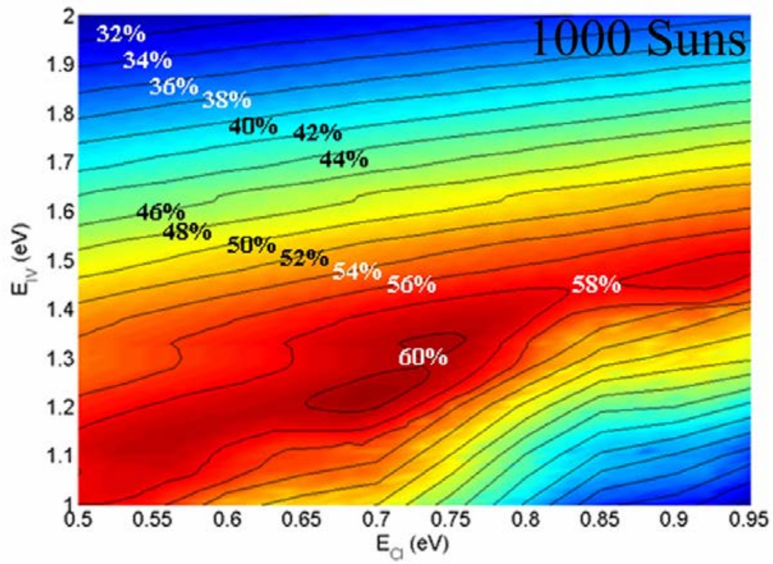

Multiquantum Well

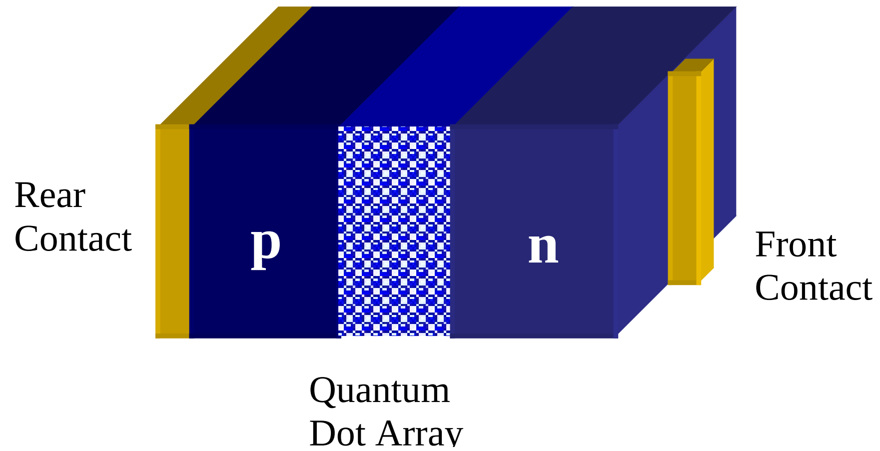
# A Revolutionary Approach to Bandgap Engineering

NPRL NANOPOWER RESEARCH LABS

- Intermediate band due to QD coupling.
  - A. Luque and A. Marti, Phys. Rev. Lett. 78, 5014 (1997).
- Allows for enhanced photogeneration mechanisms and two-photon effects
  - QD absorption
  - QD doping
  - QD carrier lifetime

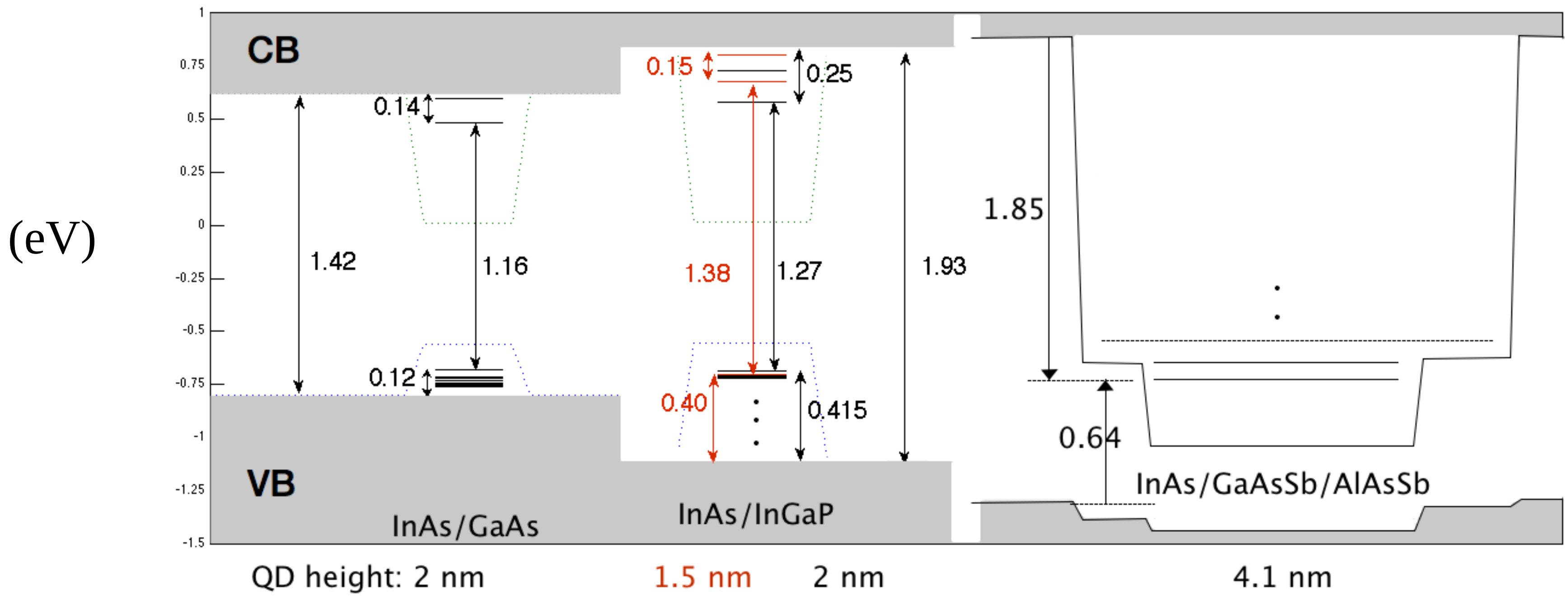


# Band lineups of current materials






- 8-band k.p simulation of materials systems currently under consideration
- For InAs in GaAs System, two-photon effect difficult due to thermal escape
  - Wider bandgap matrix or thicker GaAsP strain compensation?
- InAs in InGaP shows better confinement and match to IBSC bandgaps, but still many VB states.

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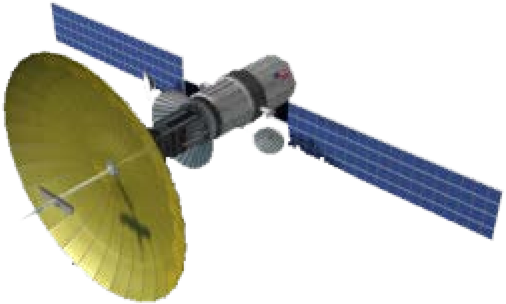
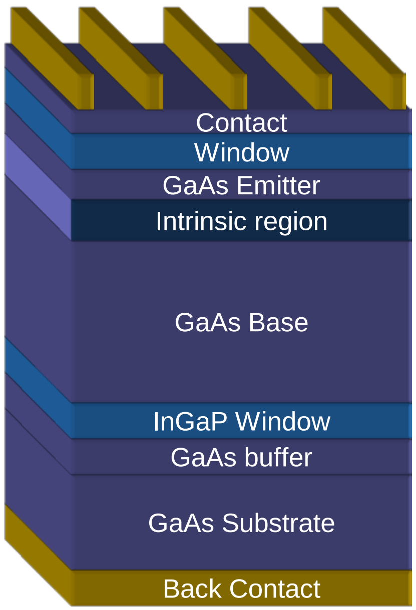
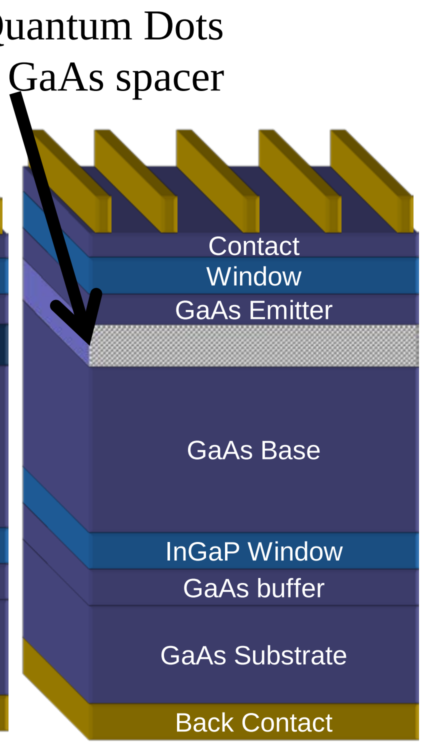


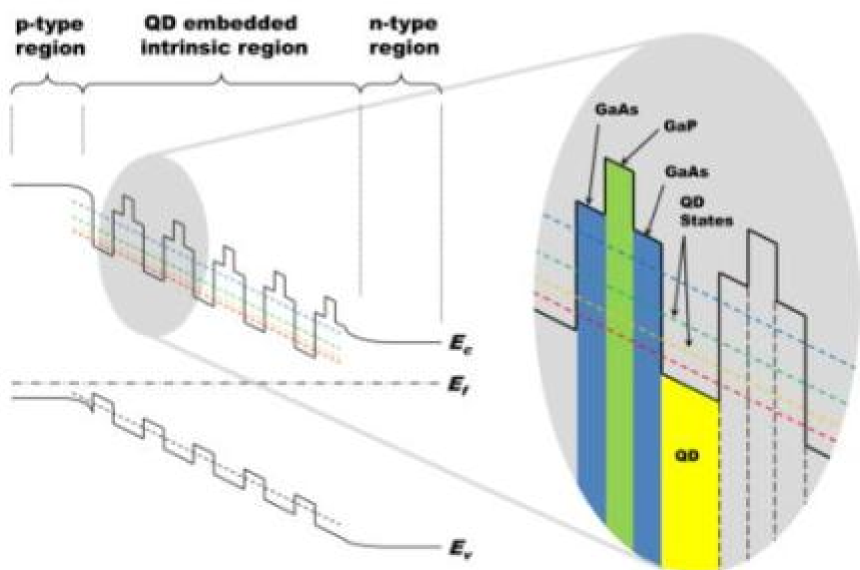
# InAs QD Enhanced GaAs Growth

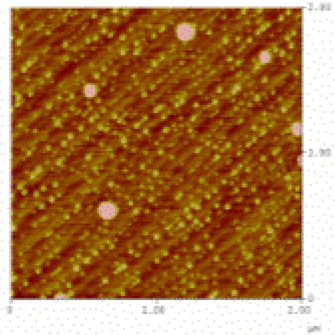



Baseline GaAs *p-i-n*




GaAs *p-i-n* with InAs QDs

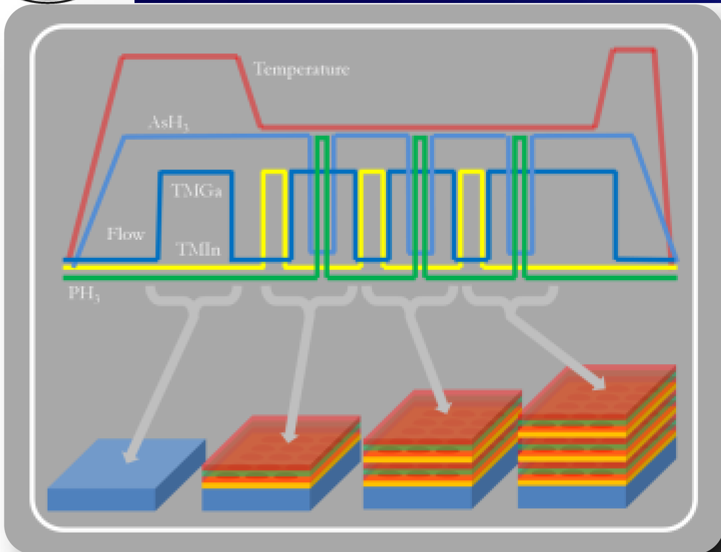



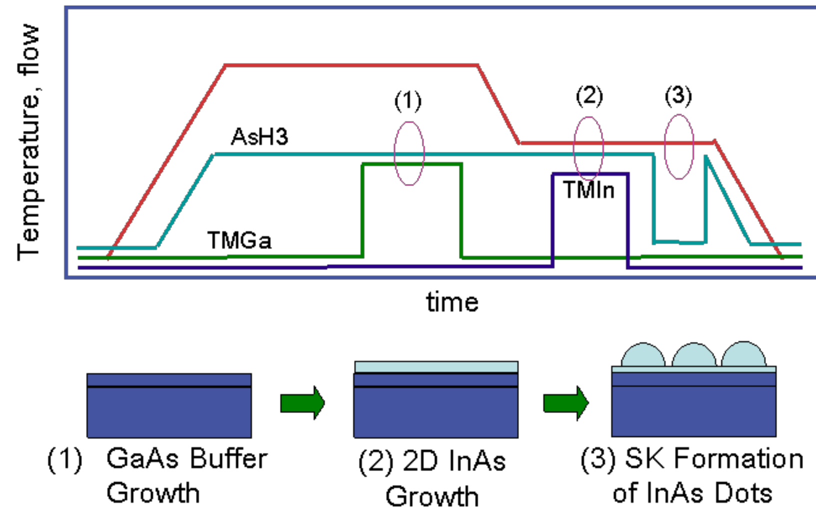
Dot Density:
$5\times10^{10}$ cm$^{-2}$
Dot Size:
5nm × 30nm

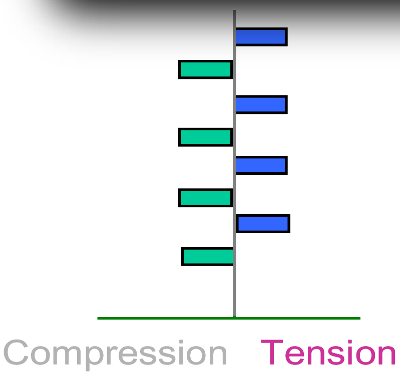
- Increased stacking to increase absorption

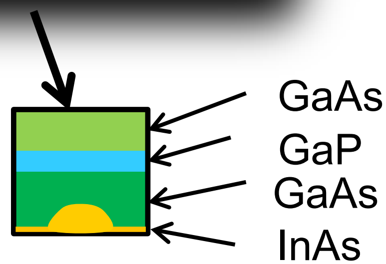
# QD Strain Compensation




~7.2% compressive mismatch, InAs on GaAs
~3.6 % tensile mismatch, GaP on GaAs



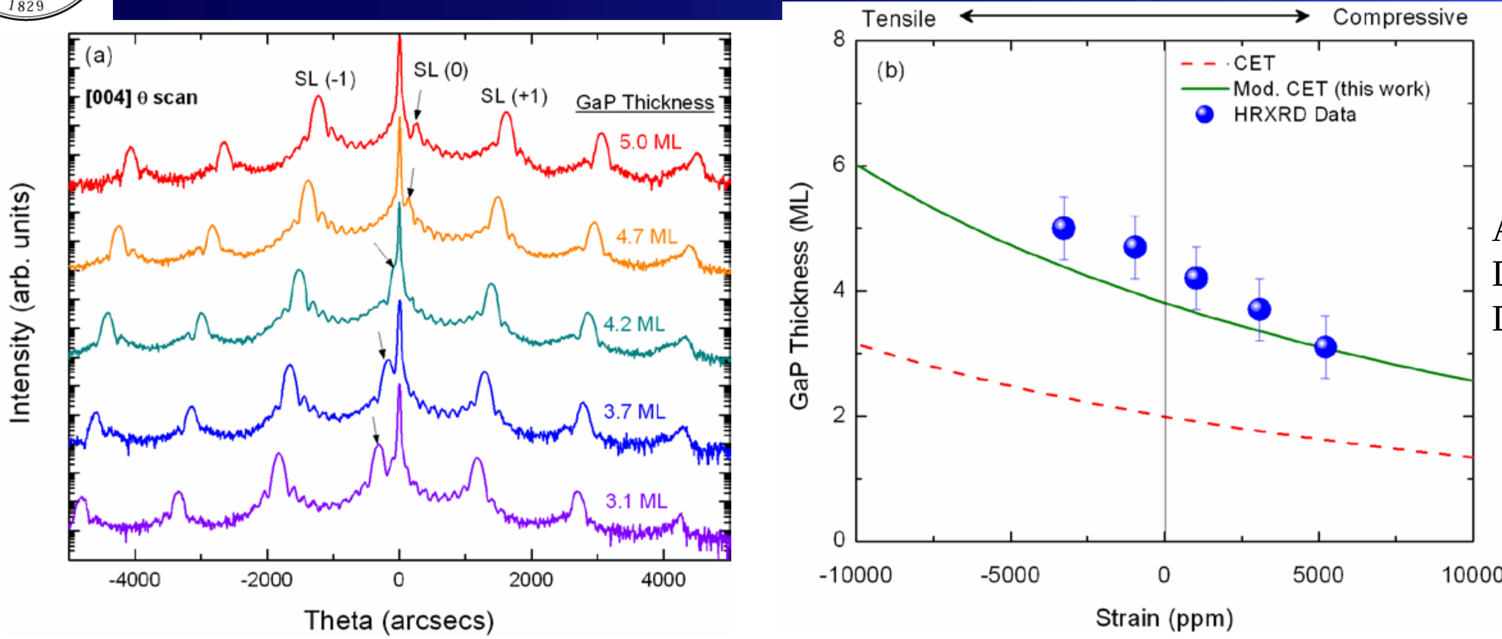




- QD weighted stress minimization
  – Target single QD size and density

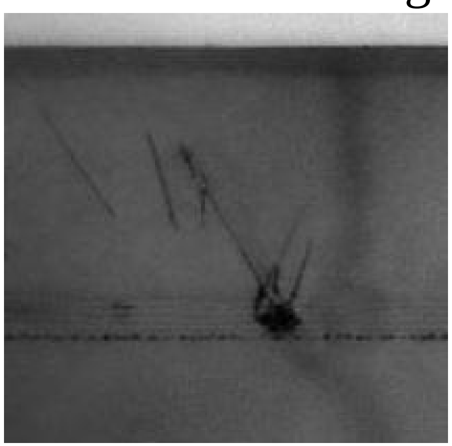
S.M. Hubbard, et al. *Appl. Phys. Lett* 92, 123512 (2008)
C.G. Bailey, S.M. Hubbard, et al., *Appl. Phys. Lett, 95, 203110 (2009)*

# Strain Compensation of InAs QDs

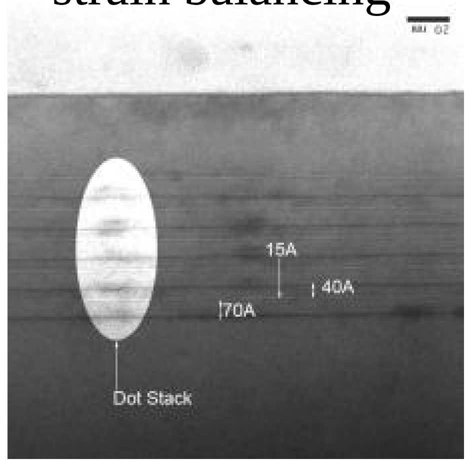


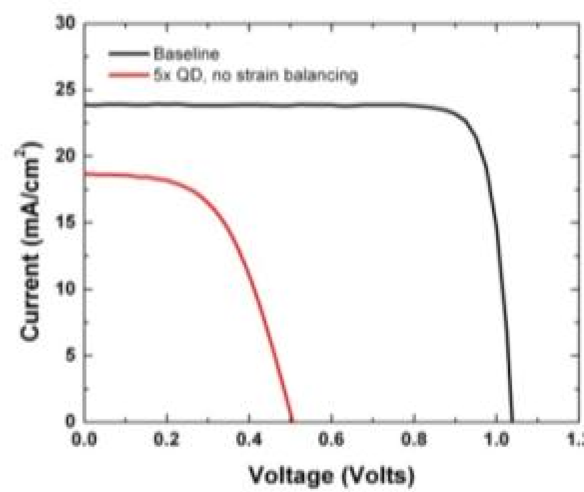

Assumptions:
Dot Size=6nm
Density=5X10$^{10}$ cm$^{2}$

No strain balancing

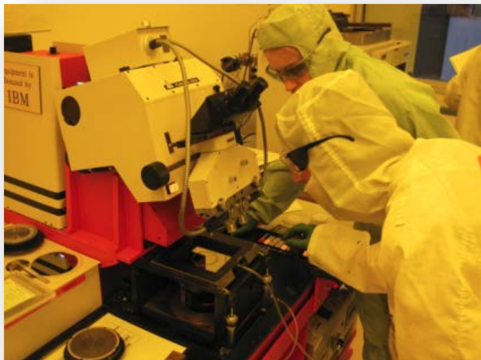


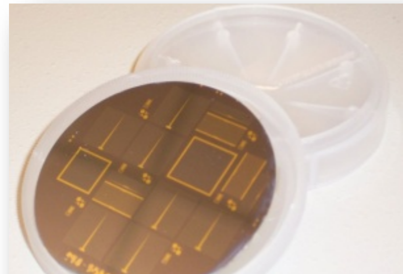
strain balancing



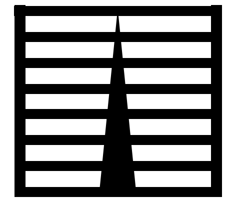



# Cell Fabrication and Testing

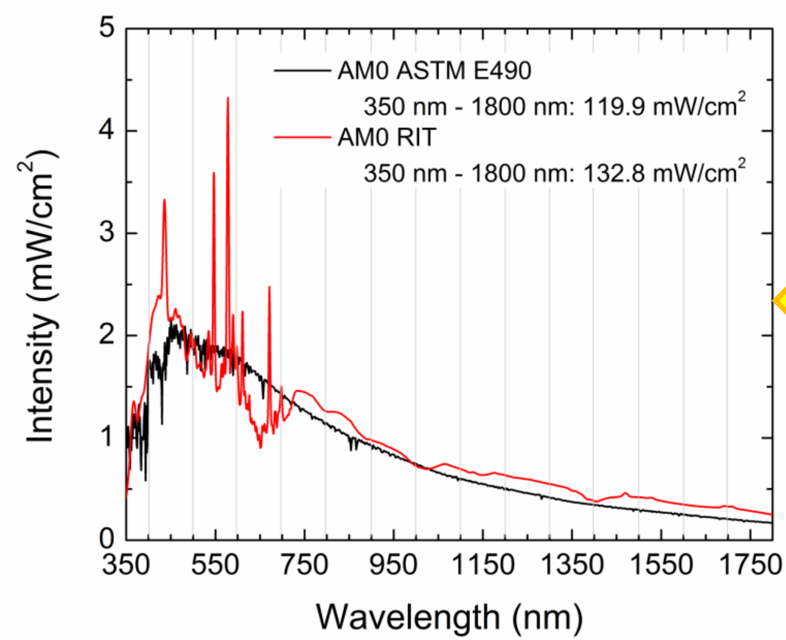




No ARC

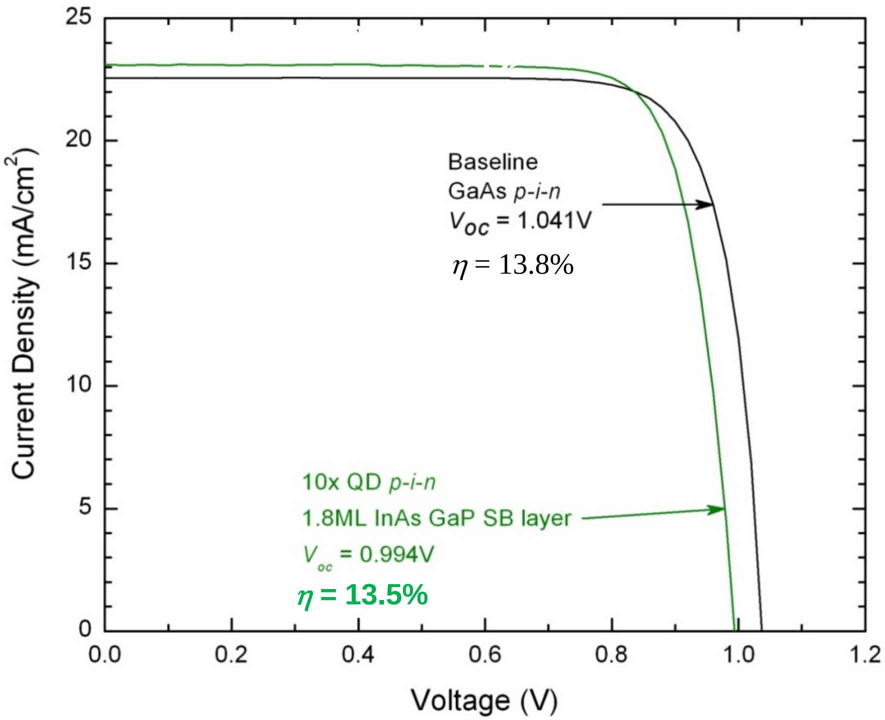


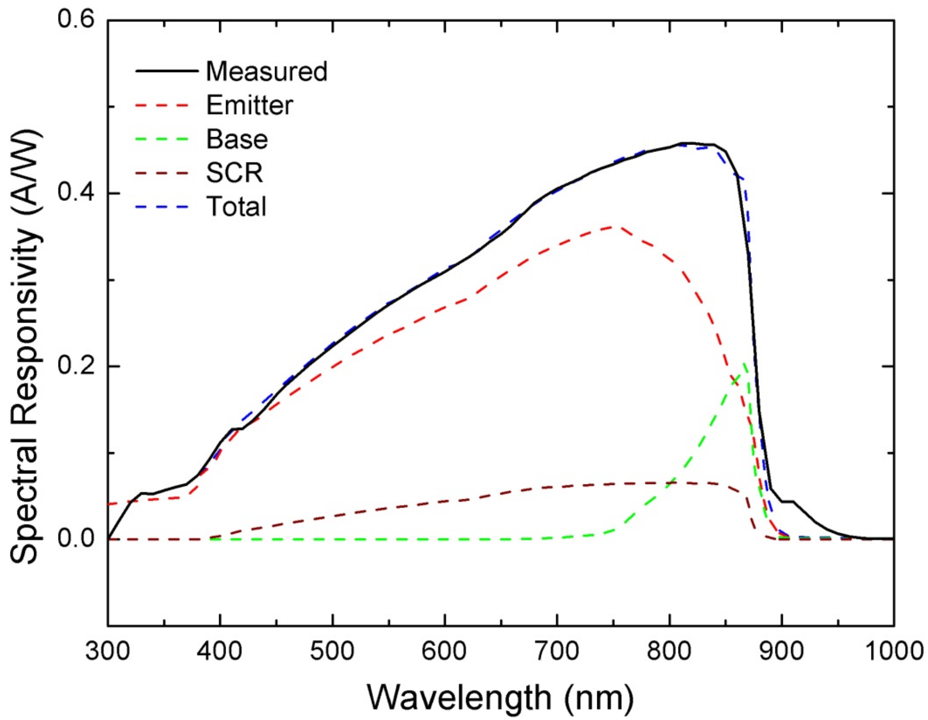
1 $cm^2$ cells, 4% grid shadowing




**TS Space Systems Dual Source**

# Effect of Strain Balancing



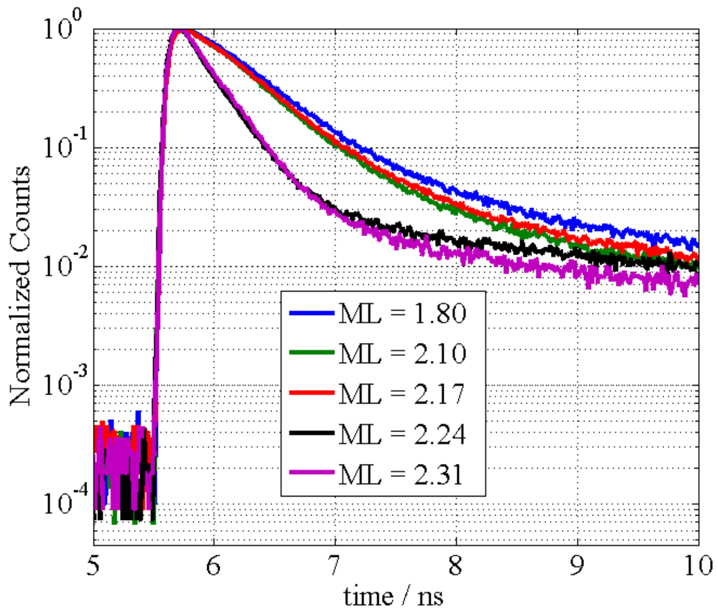




| $\tau_e$ (ns) | $\tau_b$ (ns) | $\mu_e$ ($cm^2/Vs$) | $\mu_b$ ($cm^2/Vs$) | $L_e$ (μm) | $L_b$ (μm) |
|---|---|---|---|---|---|
| 1 | 40 | 1500 | 350 | 1.70 | 5.70 |

- **Fit indicates no emitter degradation**

# Time Resolved Photoluminescence

QD emission 1000 nm



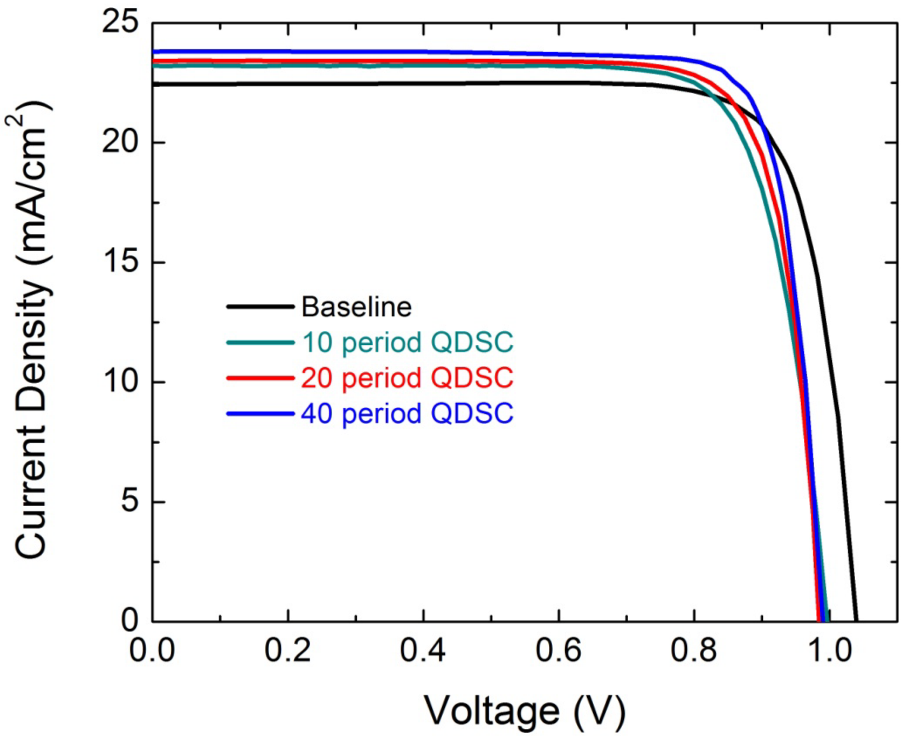

| ML | $\tau_0$(ns) |
|---|---|
| 1.8 | 0.93 |
| 2.1 | 1.14 |
| 2.17 | 1.07 |
| 2.24 | 0.17 |
| 2.31 | 0.18 |

- Parasitic recombination processes increase at ML coverage above ML = 2.2

**<u>Working hypothesis</u>: fast non-radiative processes scale with QD areal density and coalescence.**

# AM-0 Illuminated *J-V*

Non-AR-coated AM0

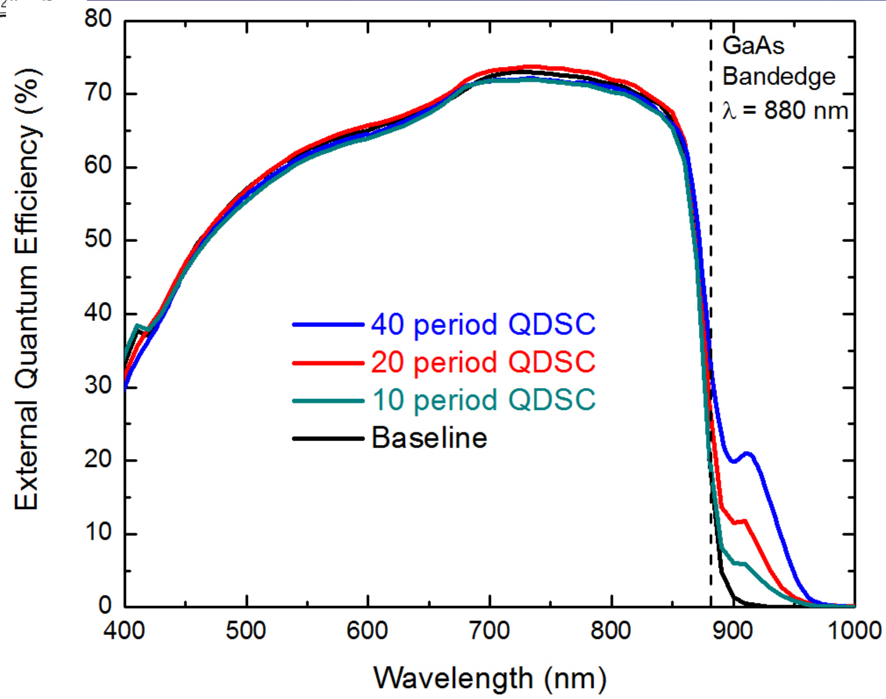


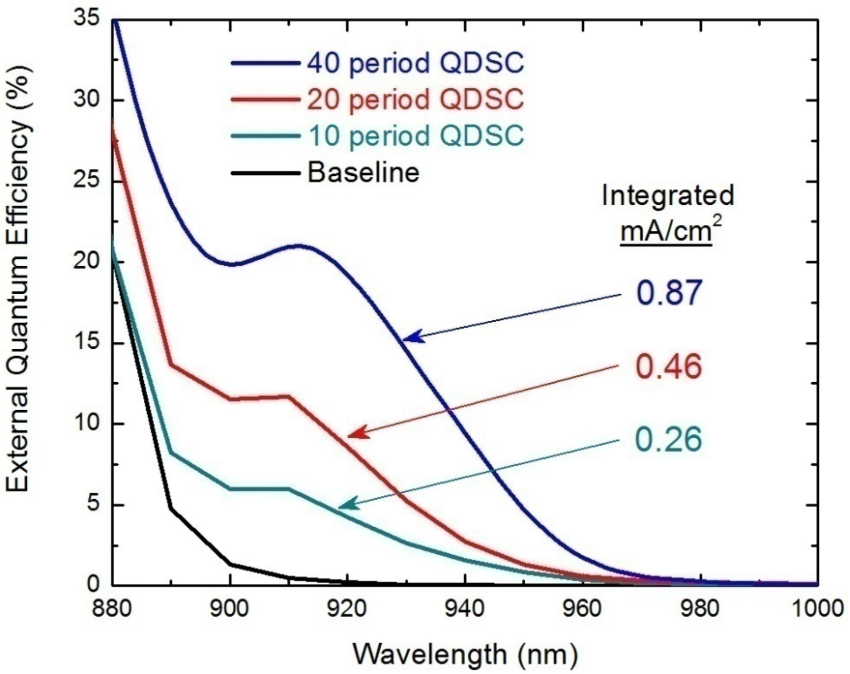

| | $I_{sc}$ (mA/cm$^2$) | $V_{oc}$ (V) | FF (%) | η (%) |
|---|---|---|---|---|
| Control | 22.47 | 1.039 | 80.0 | 13.8 |
| 10x | 23.21 | 0.997 | 78.5 | 13.4 |
| 20x | 23.42 | 0.986 | 80.8 | 13.7 |
| 40x | 23.78 | 0.990 | 82.3 | 14.3 |

**40 period QD solar cell showed a 0.5% abs (3.6% rel) efficiency improvement over control GaAs cell**

***C.G. Bailey et. al., IEEE Journal of Photovoltaics, v.2, 2012***

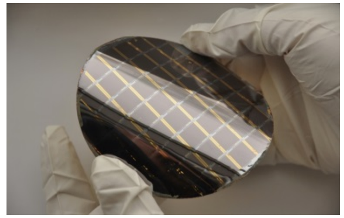
# External Quantum Efficiency

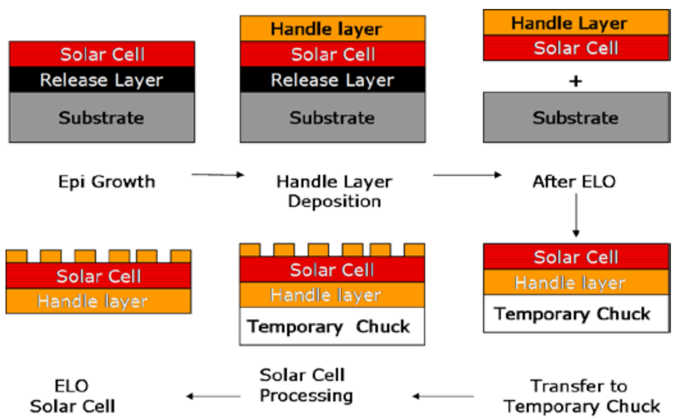


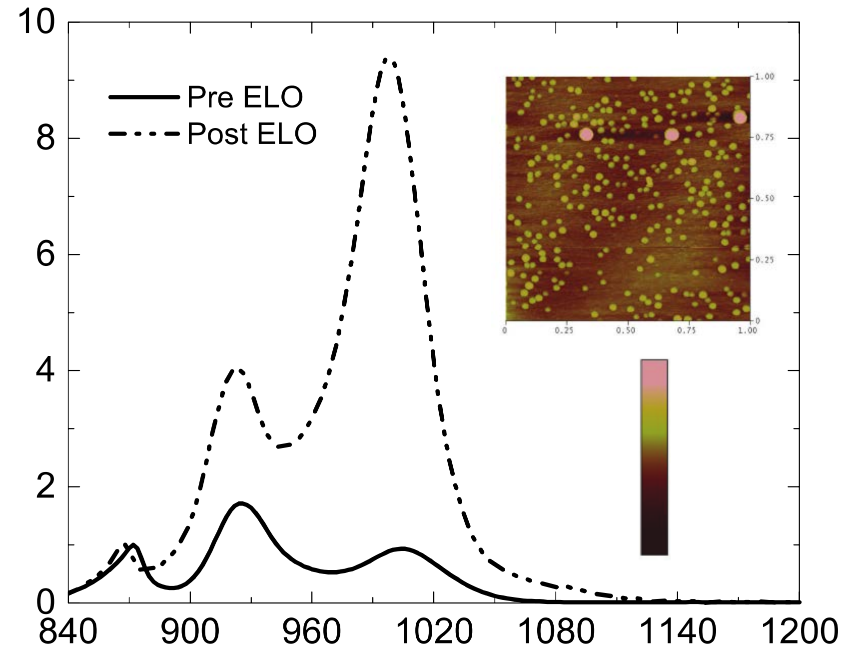




**Consistent improvement in sub-GaAs-bandgap absorption with increasing # of QD layers**

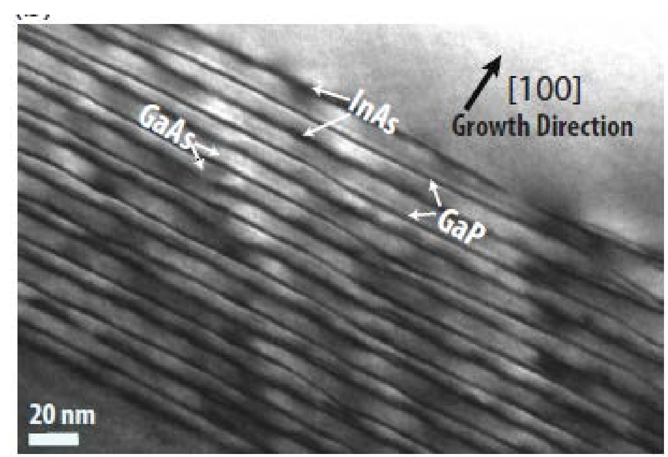
# Quantum Dot Epitaxial Lift-off



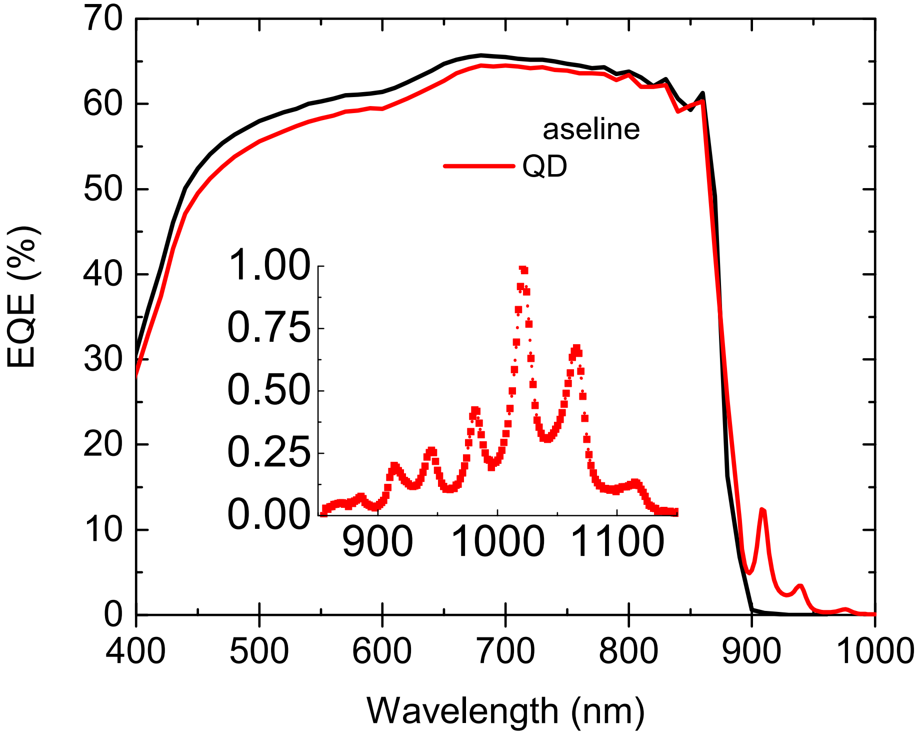


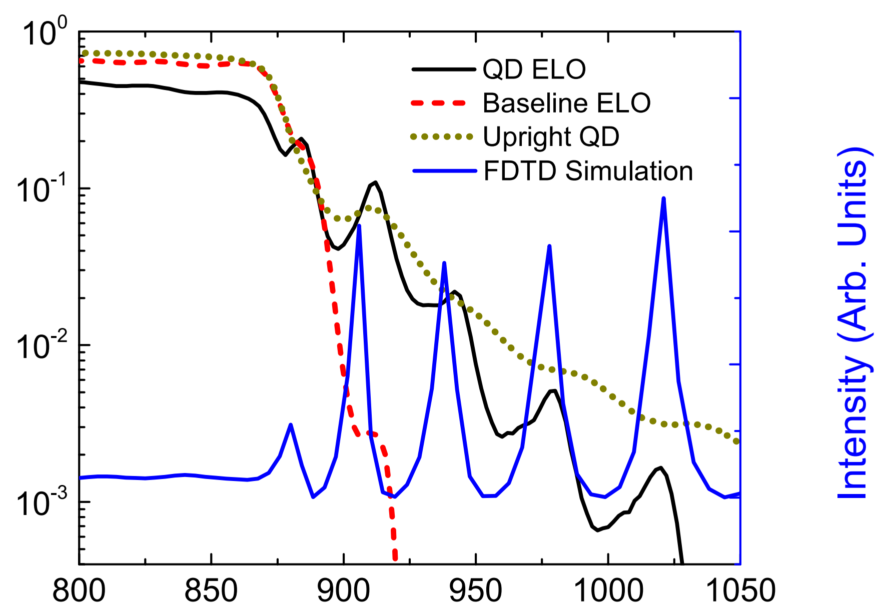

- Substrate removal allows for reduced weight and direct light management at rear surface to enhance QD absorption
- Other methods to improve absorption involve increasing the optical path length of light (OPL) through the QDs. This can be taken advantage of with a back reflector and a thin cell, which is accomplished through epitaxial lift-off (ELO).



# QD ELO Quantum Yield




- QD contribution to short circuit current density past the GaAs bandedge is 0.23 mA/cm$^2$ for QD ELO cell when compared to ELO baseline.




- Cavity resonance enhances QD absorption
- Further improvement in rear surface reflectance possible

# Conclusions

- Investigated strategic placement of QDs within the intrinsic region and how this affects device performance
  - Positional dependence of sub-Eg QE, $J_{SC}$, $V_{OC}$
  - Position and background doping must be considered in design and optimization of QD-enhanced solar cells
- Demonstrated QD doping using MOVPE
  - Successfully increased Voc of QD cell through reduction of SRH recombination
  - Explored minority carrier action as QDs are removed from a region of high electric field
  - Deeper confinement necessary for 2-photon effect at room temperature
- Epitaxial Lift-Off QD solar cells show enhanced absorption due to Faber-Perot cavity effects and enhanced backside reflectance