Principles of photovoltaic energy conversion and pathways to high efficiency

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U.S. Naval Research Laboratory

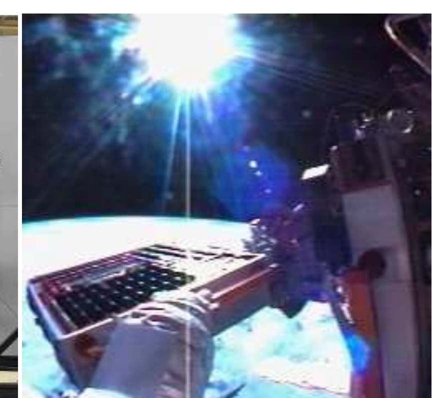
- The Naval Research Laboratory provides:
  - Primary in-house research for the physical, engineering, space, and environmental sciences

  Fundamentals → New capabilities → Field demonstration

  Theorist ⟶ Experimentalist ⟶ Test engineer

- Founded by Thomas Edison in 1923

  Key achievements:
  - First modern U.S. radar
  - First operational U.S. sonar
  - NAVSTAR GPS - based on the NRL TIMATION program
  - First US Earth orbiting spacecraft - Vanguard I
  - Semi-Insulating Gallium Arsenide Crystals - Technique for growing high-purity single crystals



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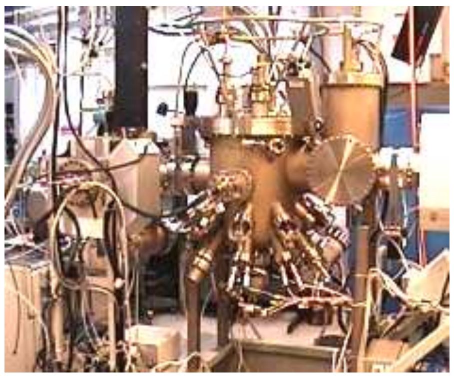
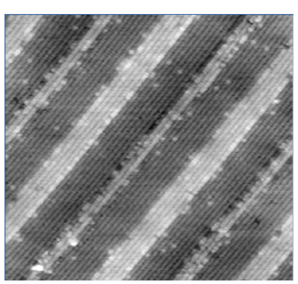
Opto-electronics and radiation effects

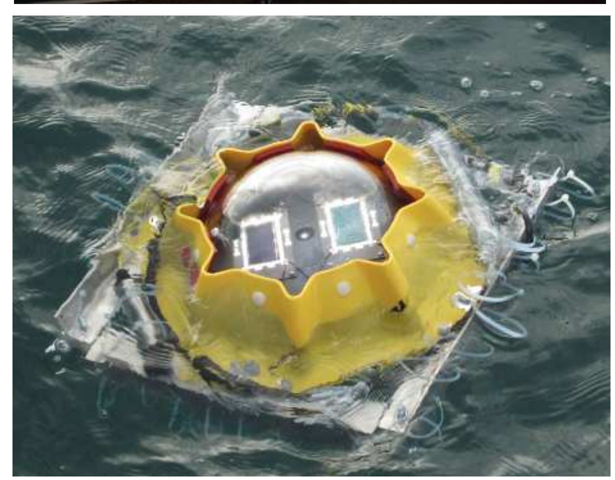
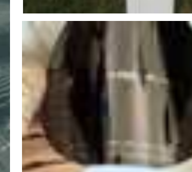
- III-V device design an fabrication
  - Simulation capabilities
  - Growth & characterization
  - 5000 ft^2 class 100 cleanroom



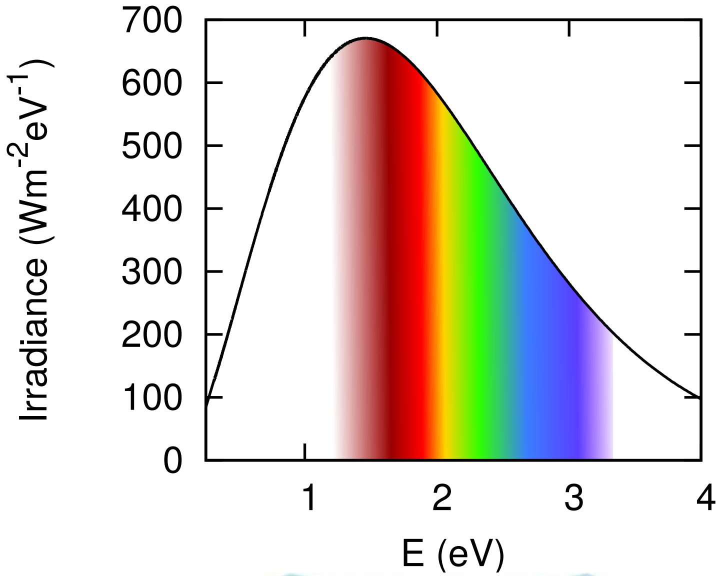

- Satellite space experiments
  - Design, build, operate, and post-flight analysis
  - Radiation effects
- Optical detectors for imager technologies
  - Night vision, thermal imaging, missile detection


- Photovoltaics
  - Innovation for high specific power and power density for specialized applications
  - Operation in extreme environments (e.g. space, underwater)
  - Large scale power generation

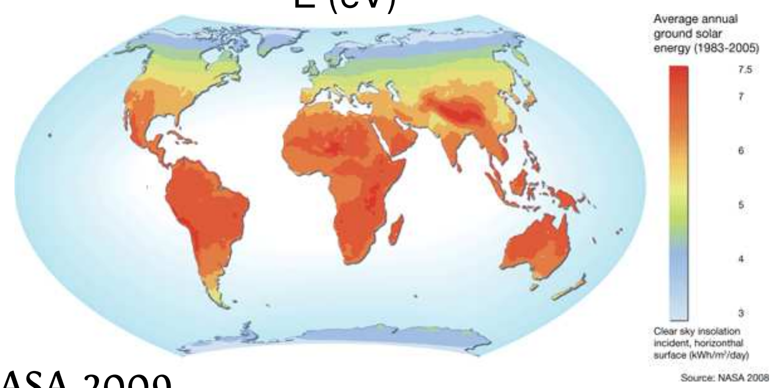

The Solar resource



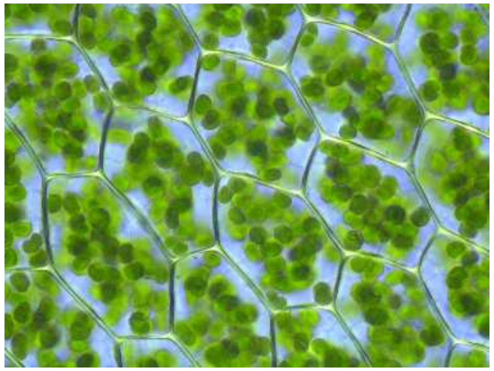
- The Sun is a blackbody with temperature ~6000 K

$$I(E) = \frac{2\Omega_A}{c^2h^3}\frac{E^2}{\exp(E/kT)-1}dE$$

- 1000 W.m^{-2} peak incident power



NASA 2009



- Solar energy use is innate
  - Directly as heat
  - Chemical, mechanical & electrical conversion
- Indrect an inefficient processes
- Photovoltaics provides direct conversion

Incumbent PV technology

- 1839 - Becquerel demonstration of photovoltaic effect
- 1954 - Bell Labs first ``high-power” Si solar cell (6%)
- Extremely fast growing industry - 38 GW capacity installed in 2013
- Si-wafer PV - 90% of 2013 production
- Multi-crystalline Si - 55% of total production
  - Record conversion efficiency for this technology is 20.4%
  - Most installed system ~15%
  - Extremely cheap - cells produced $0.2/W
    - Achieving grid parity in many parts of the world
    - US residential installations outstripping non-residential
    - 1/3 coming online without state incentives

Bell Labs, 1955

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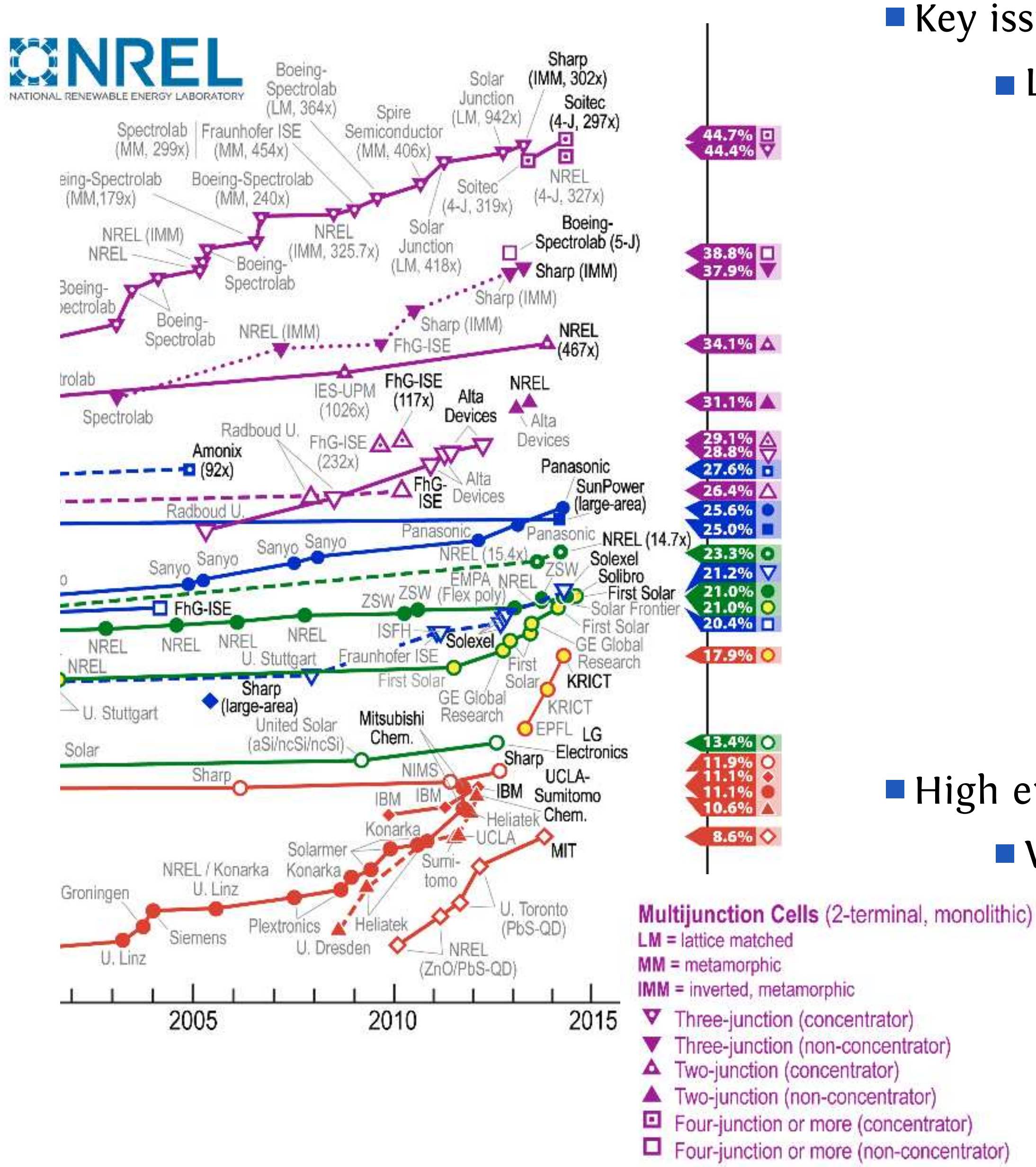
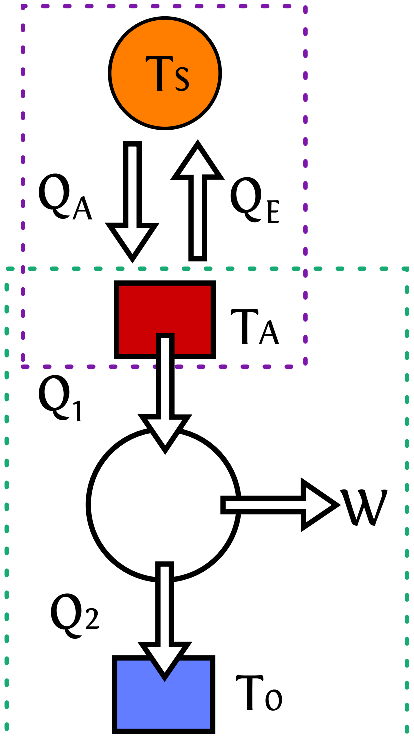
High efficiency PV

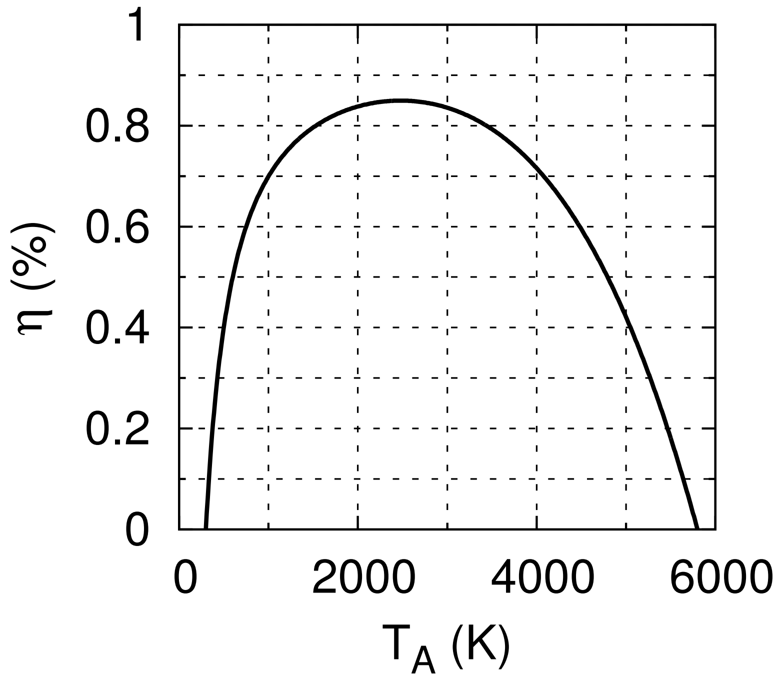


- Key issue with multi-crystalline Si:
  - Limited applications
    - ✓ Domestic power generation, suburban or rural residential installation
    - 22% energy consumption - residential (2011)
    - Industrial, commercial and transport
    - X Weight/area are significant
      - X Industrial architectures
      - X High power density requirements
      - X Portable
        - low power density (W/m^2)
        - low specific power (W/kg)
- High efficiency PV provides solutions
  - World record efficiency 44.7%

- Why is the efficiency of incumbent technology is fundamentally limited?
- Mechanisms for achieving high efficiency

Solar heat engine





- Absorber

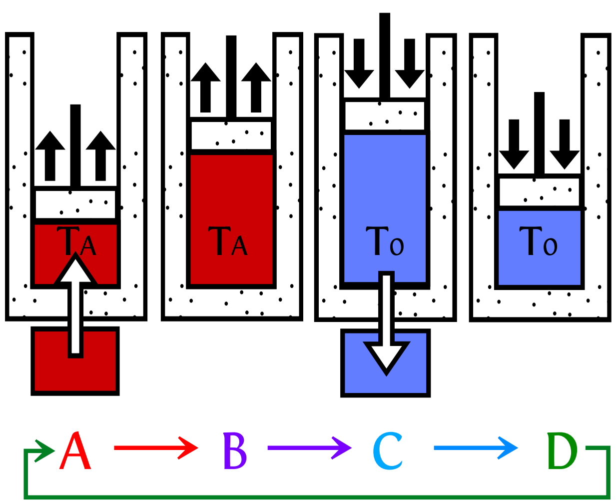
$$Q_A = A\sigma T_S^4 \quad Q_E = A\sigma T_A^4$$

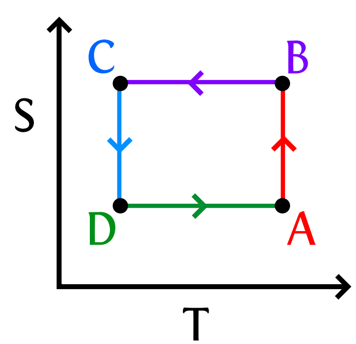
$$\frac{\text{Net energy flux}}{\text{Incident energy}} = \frac{Q_A - Q_E}{Q_A} = 1 - \frac{T_A^4}{T_S^4}$$

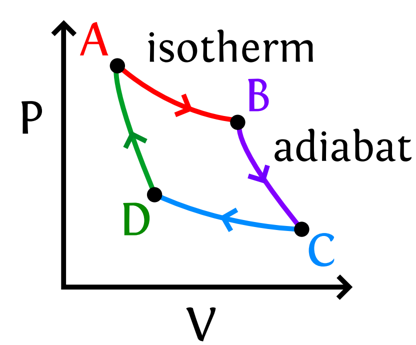
- Heat engine - transfer energy hot source to cold sink

$$\Delta S = -\frac{Q_1}{T_A} + \frac{Q_2}{T_0} \qquad \text{2nd law : } \Delta S \geq 0$$

$$\eta = \frac{W}{Q_1} = \frac{Q_1 - Q_2}{Q_1} = 1 - \frac{Q_2}{Q_1} = 1 - \frac{T_0}{T_A}$$







Carnot engine is isoentropic

$$\eta = \left(1 - \frac{T_A^4}{T_S^4}\right)\left(1 - \frac{T_0}{T_A}\right)$$

84.9% at $T_A = 2480$ K

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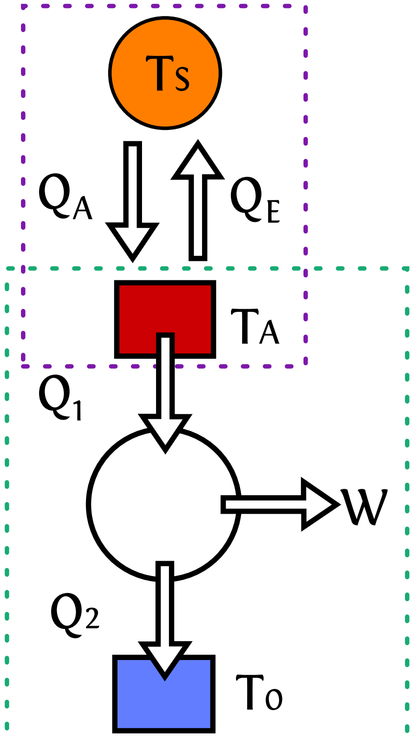
Solar heat engine: invalid assumptions

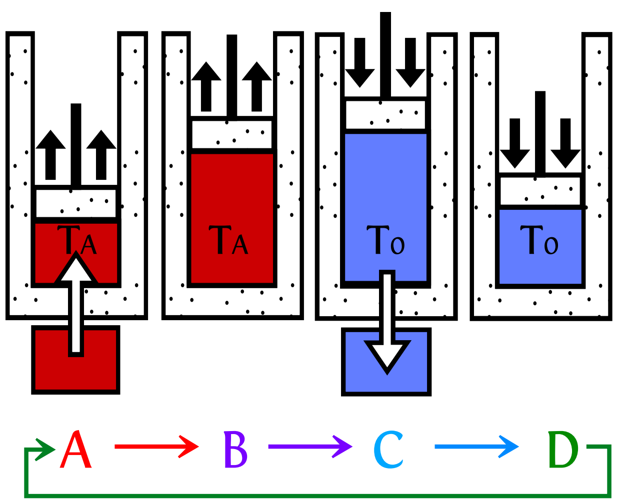


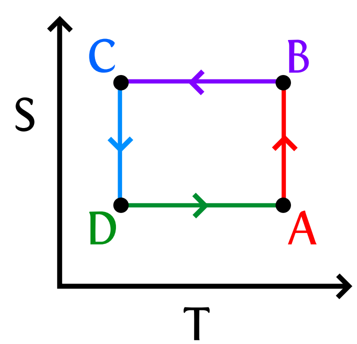
- How do current PV technologies deviate from the ideal?

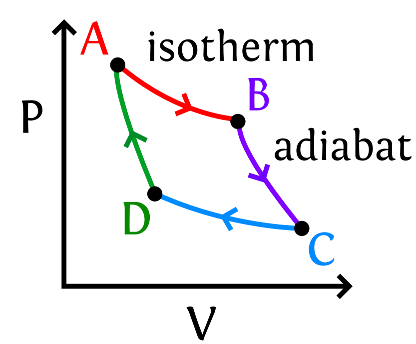
$$\eta = \left(1 - \frac{T_A^4}{T_S^4}\right)\left(1 - \frac{T_0}{T_S}\right)$$

84.9% at
T_A = 2480 K

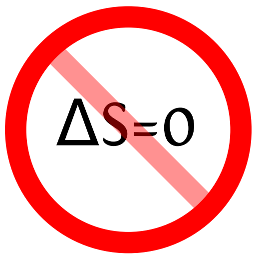
- Mismatch between absorption and emission angles
  -the terrestrial absorber is not a perfect blackbody cavity
- Some energy transfers from T_S to T_0 without being absorbed
- Some heat dissipation - dewar flasks are not perfect thermal insulators







- Non-isoentropic



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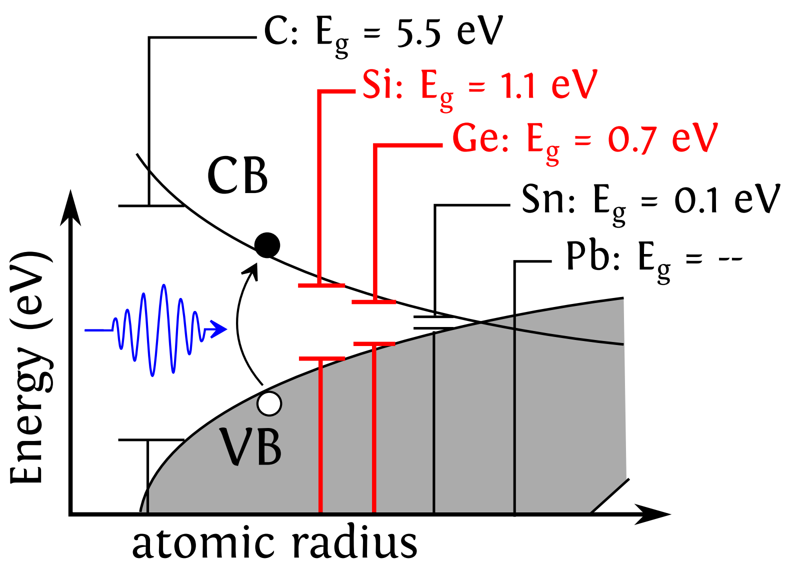
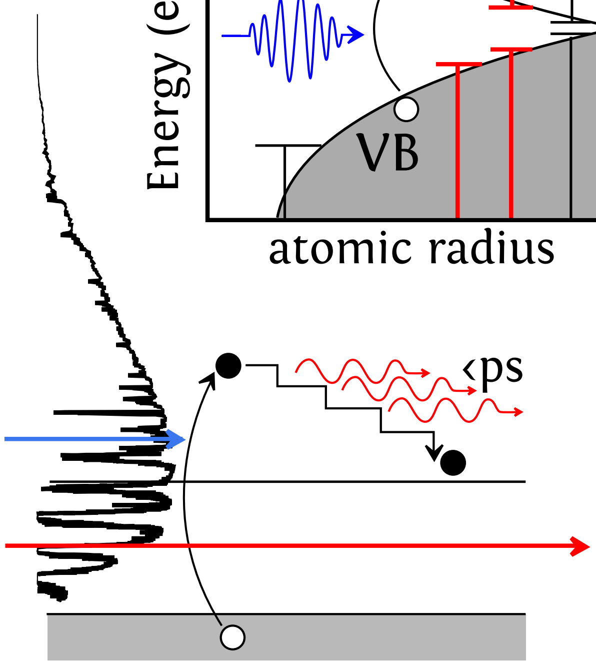
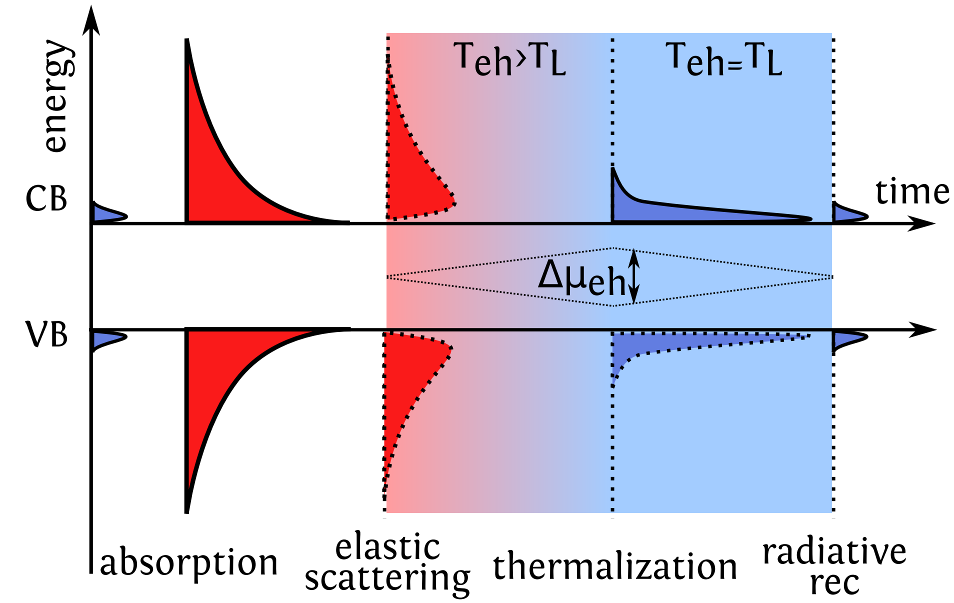
Semiconductors as absorbers



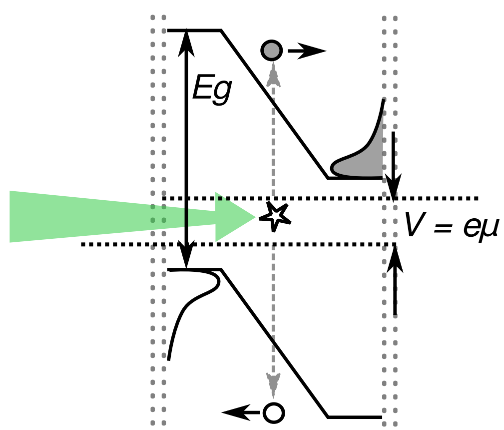


- Semiconductors have an bandgap
- Some transmission permitted to prevent total thermalization

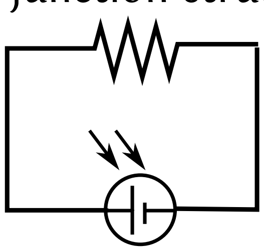
- Entropy free work is generated by thermalization



- Recitification: with charge separation, the chemical potential becomes a voltage across the device



- The Photovoltaic Effect
- Most often realized in a pn junction structure



Detailed balance limiting efficiency

- Detailed balance approach:

$$J = J_{abs} - J_{emit}$$

$$= e\int_0^\infty \alpha(E).n(E, T_S, \mu = 0, \Omega_S).dE$$

$$- e\int_0^\infty \alpha(E).n(E, T_A, \mu_A = eV, \Omega_{emit}).dE$$

- Generalized Planck equation

$$n(E, T, \mu, \Omega).dE = \frac{2\Omega}{c^2h^3}\frac{E^2}{\exp(E-\mu/kT) - 1}.dE$$

- Particle number conserved

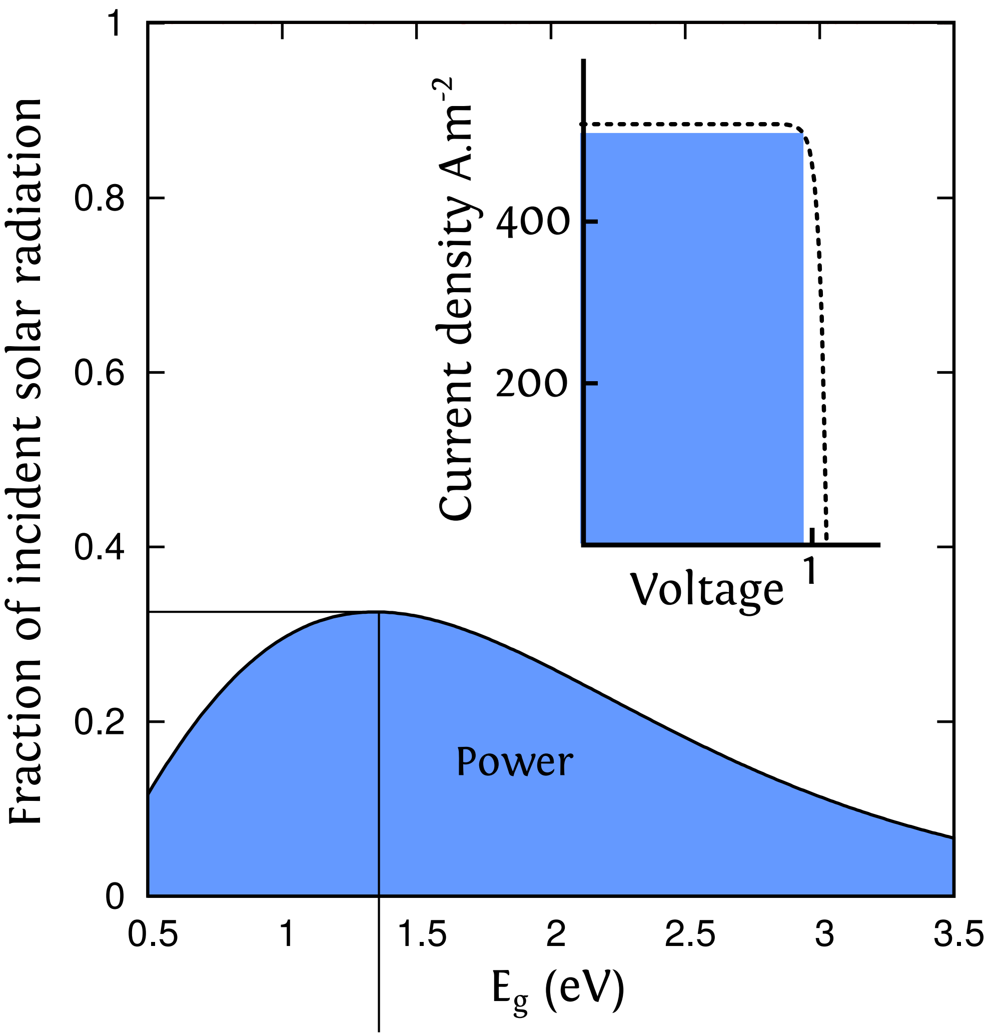
Unity absorptivity above Eg and zero below

All recombination radiative

Infinite carrier mobility

Maximum power point opperation

Boltzmann approximation: $(E-\mu)/kT \gg 1$



32.5% for Eg = 1.35
(31% for 1.31 eV numerical)

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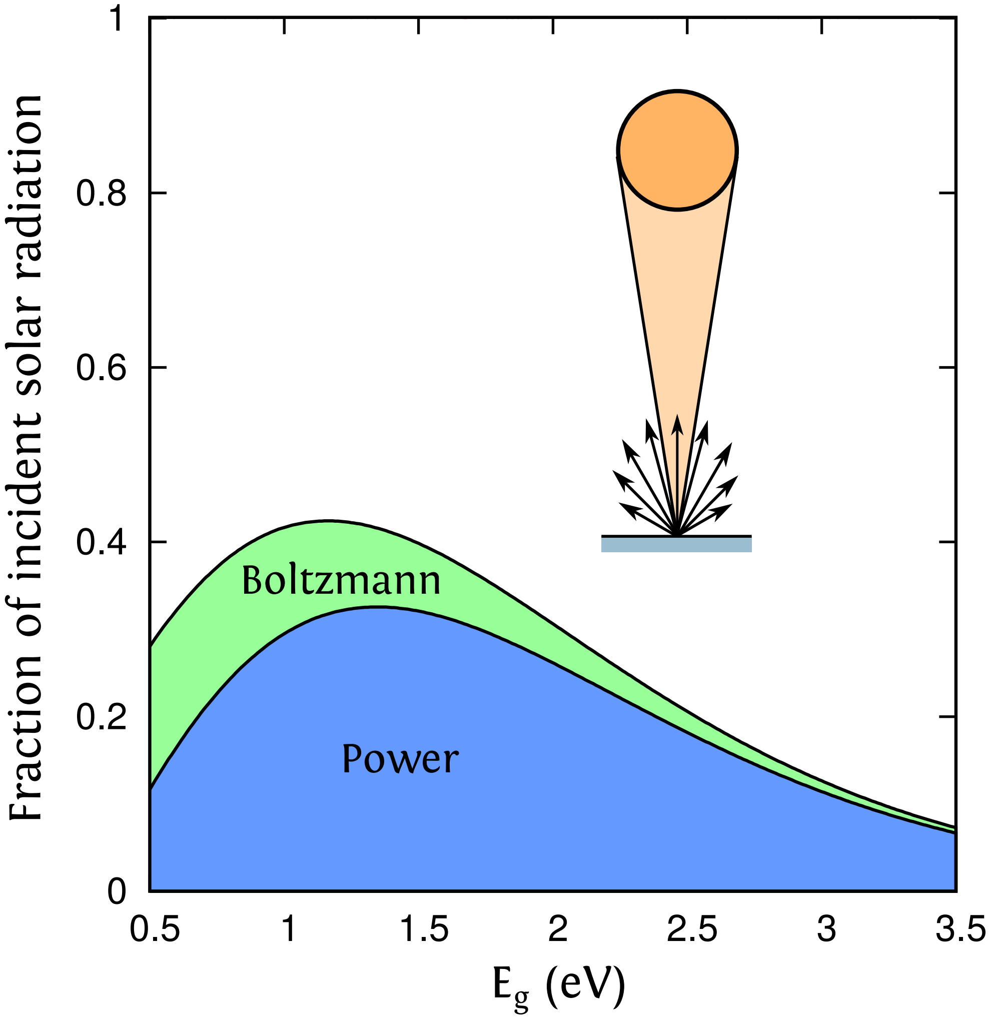
Intrinsic losses

- Mismatch between absorption and emission angles:

$$kT_A.\ \ln(\Omega_{emit}/\Omega_{abs}).\ J_{opt}$$



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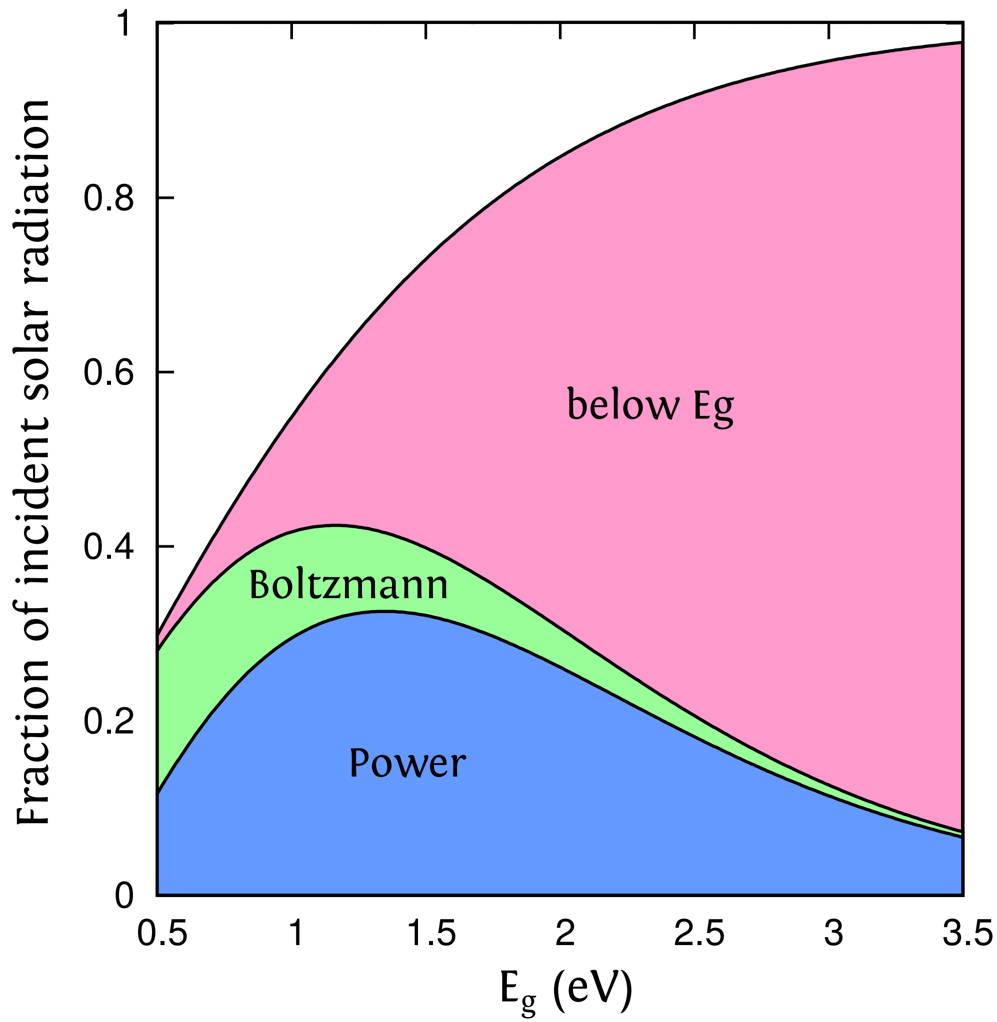
- Transmission of low energy photons

$$\int_0^{E_g} E.n(E, T_s, \mu=0, \Omega_S).dE$$

- Mismatch between absorption and emission angles:

$$kT_A.\ \ln(\Omega_{emit}/\Omega_{abs}).\ J_{opt}$$



Intrinsic losses

- Thermalization of high energy photons

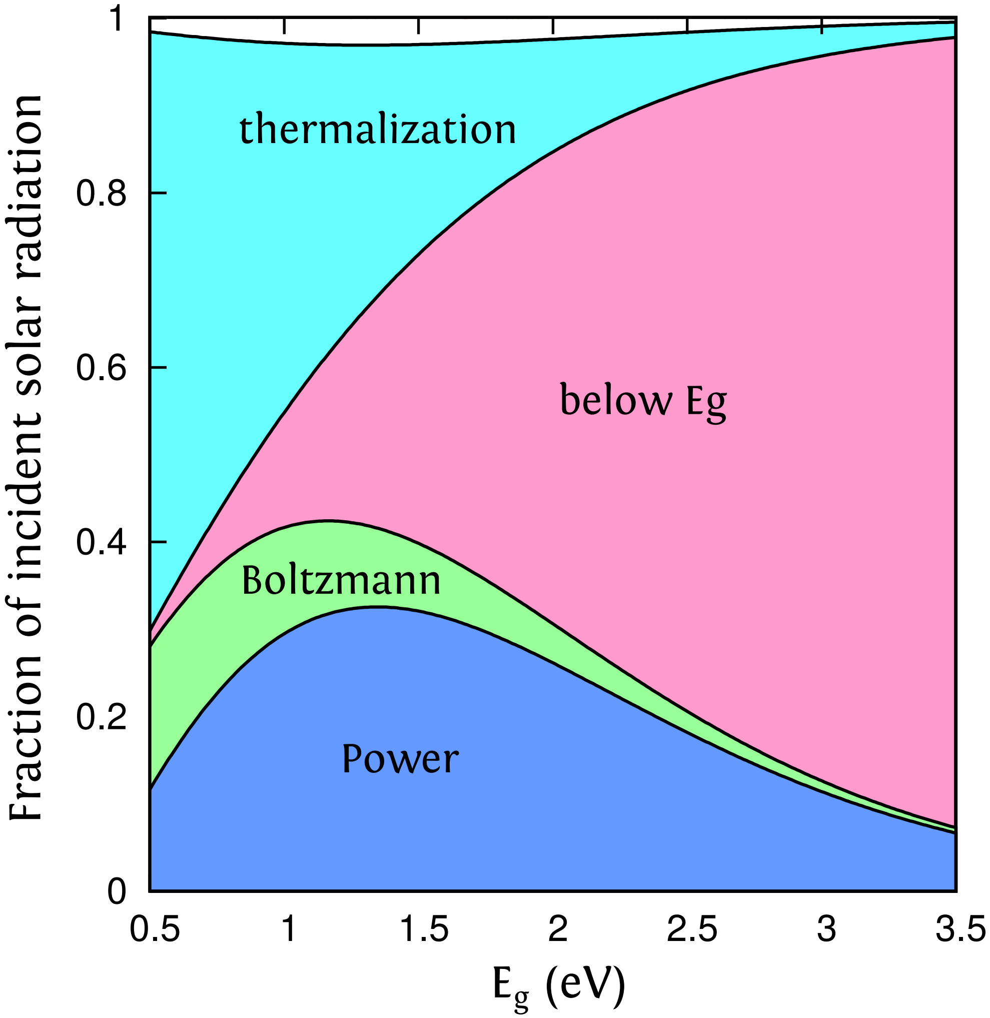
$$\int_{E_g}^{\infty} E.n(E, T_s, \mu=0, \Omega_S).dE \; - \; E_g . J_{abs}$$

- Transmission of low energy photons

$$\int_{0}^{E_g} E.n(E, T_s, \mu=0, \Omega_S).dE$$

- Mismatch between absorption and emission angles:

$$kT_A . \ln(\Omega_{emit}/\Omega_{abs}) . J_{opt}$$



Intrinsic losses

- Carnot

  $E_g(T_A/T_S).\,J_{opt}$

- Emission

  $E_g.\,J_{emit}$

- Thermalization of high energy photons

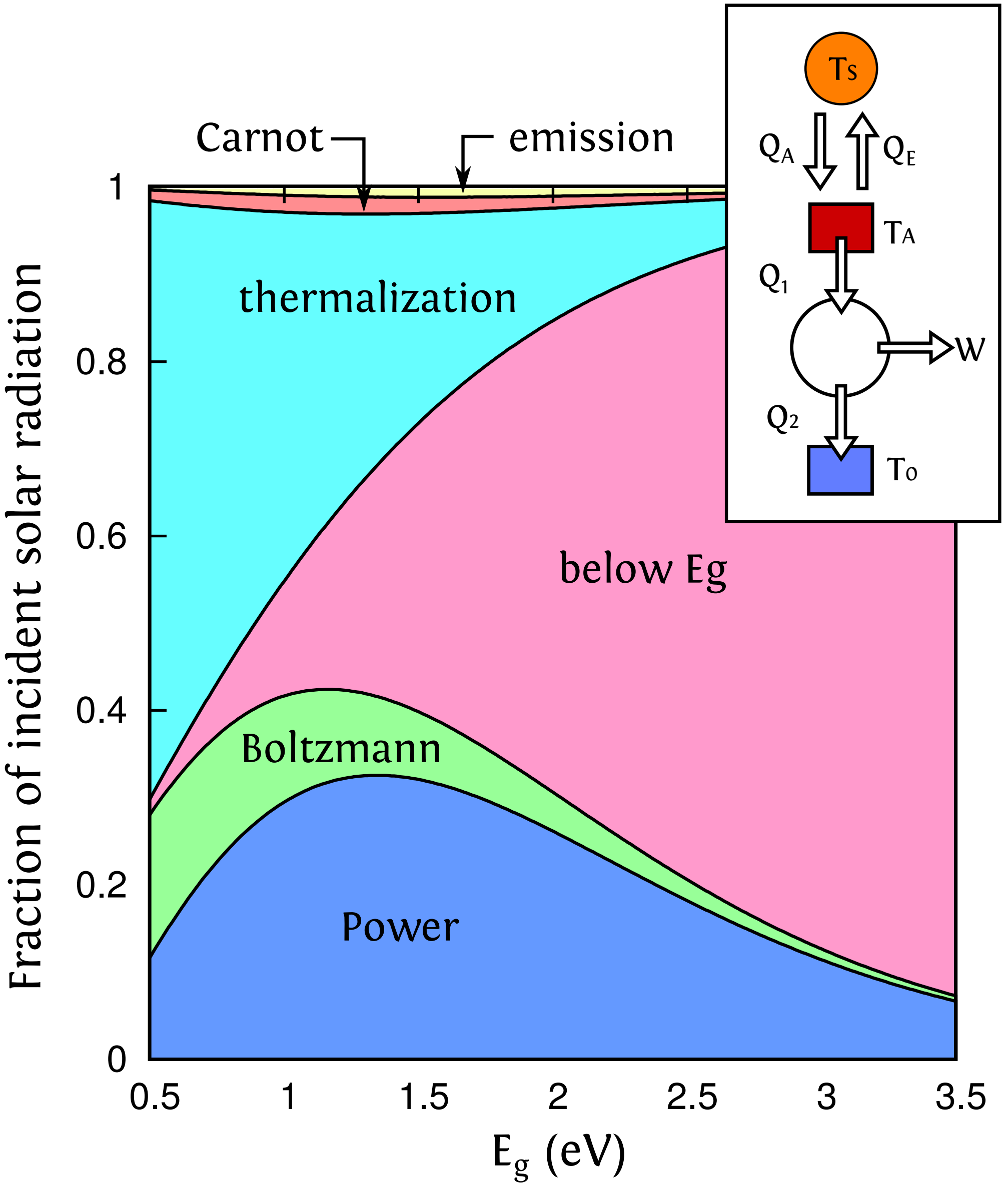
$$\int_{E_g}^{\infty} E.n(E, T_s, \mu=0, \Omega_S).dE \;-\; E_g.\,J_{abs}$$

- Transmission of low energy photons

$$\int_{0}^{E_g} E.n(E, T_s, \mu=0, \Omega_S).dE$$

- Mismatch between absorption and emission angles:

$$kT_A.\,\ln(\Omega_{emit}/\Omega_{abs}).\,J_{opt}$$



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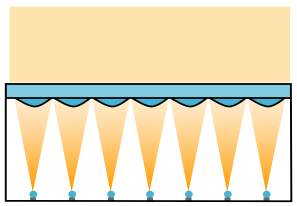
Pathways to high efficiency

- Target dominant intrsinsic loss mechanisms:

Boltzmann loss

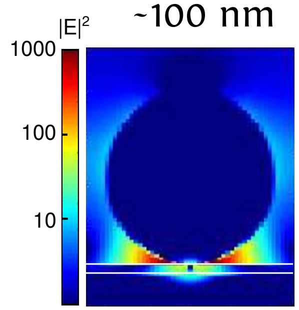
- Solar concentration

Focusing module



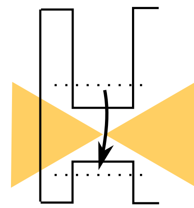
Furman et al., 35th IEEE PVSC, 475 (2010)

Field localization ~100 nm



Ciracì et al., Science 337, 1072 (2012)

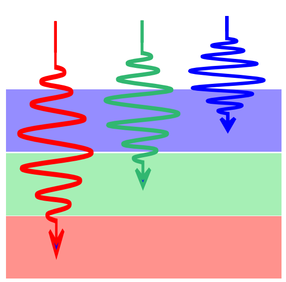
Directional emission



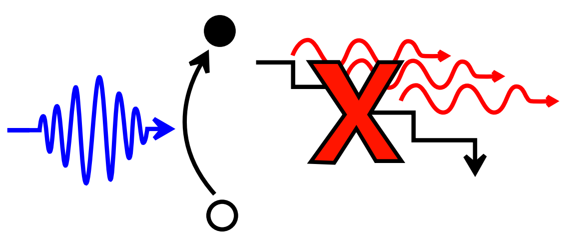
Adams et al., 35th IEEE PVSC, 1 (2010)

Thermalization & below Eg

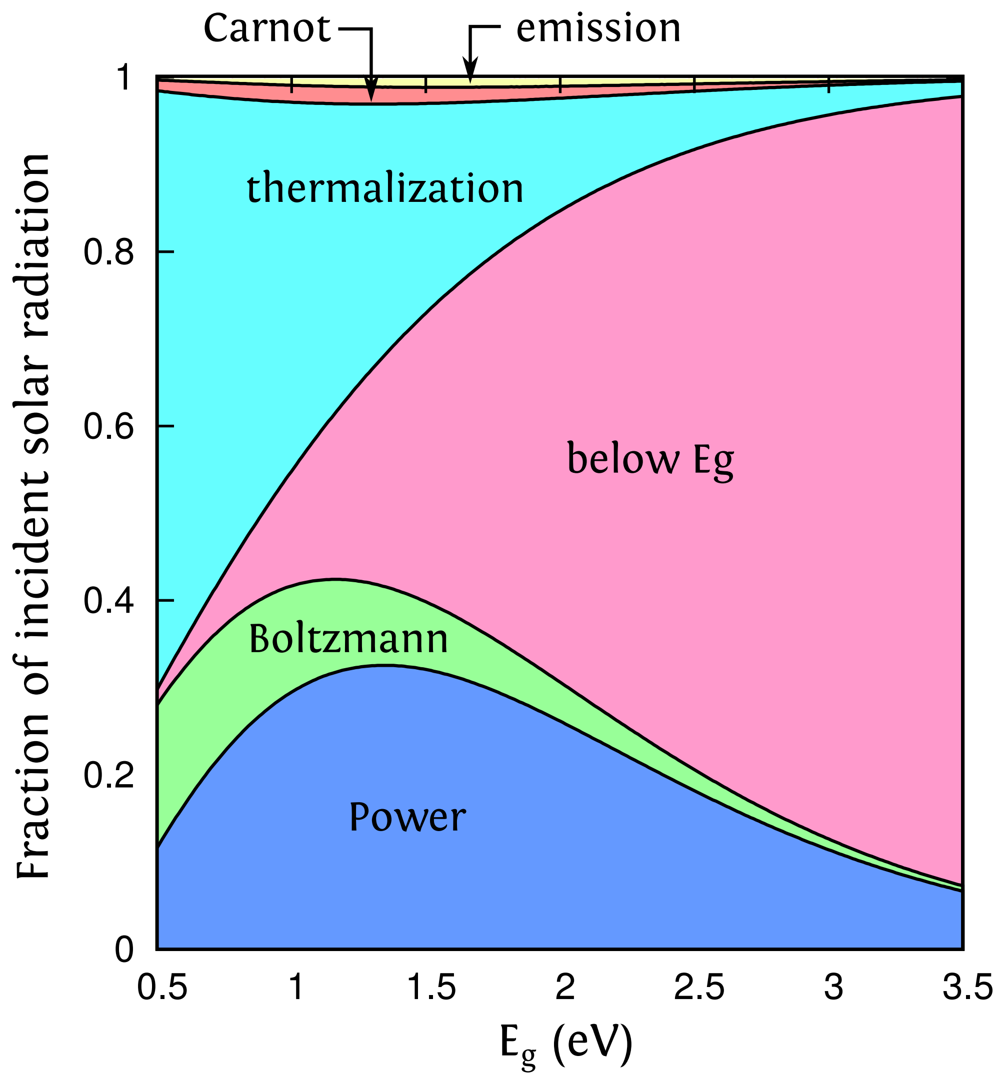
- Multiple absorbers



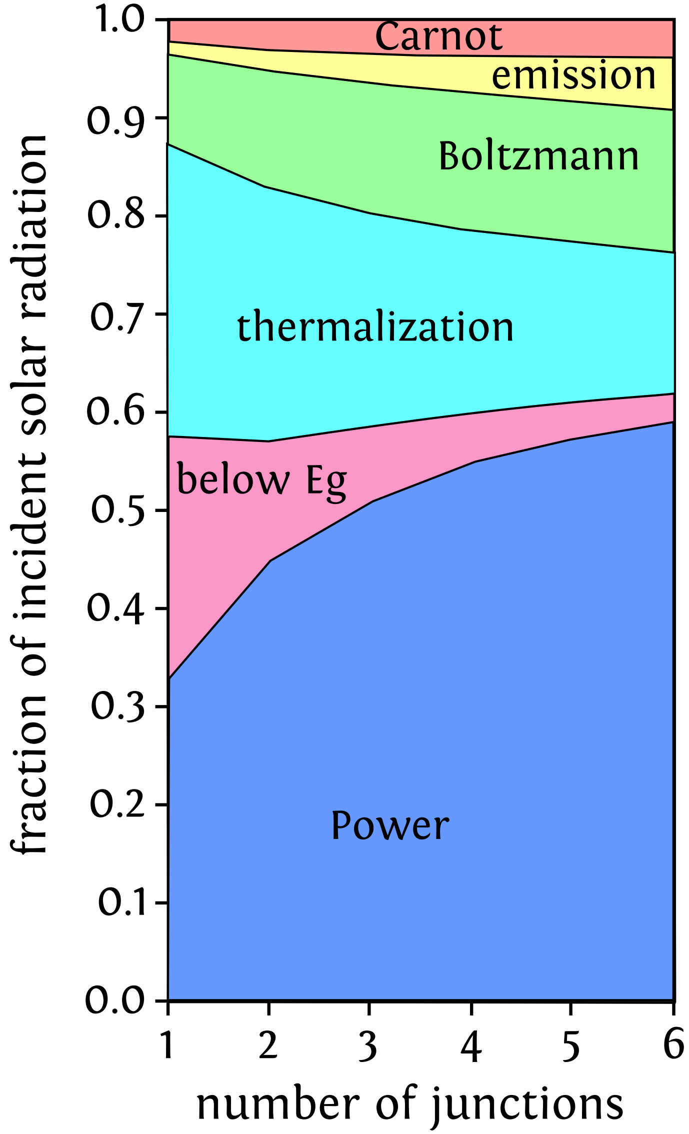
- Hot-carrier solar cells



- Sequential absorption and MEG

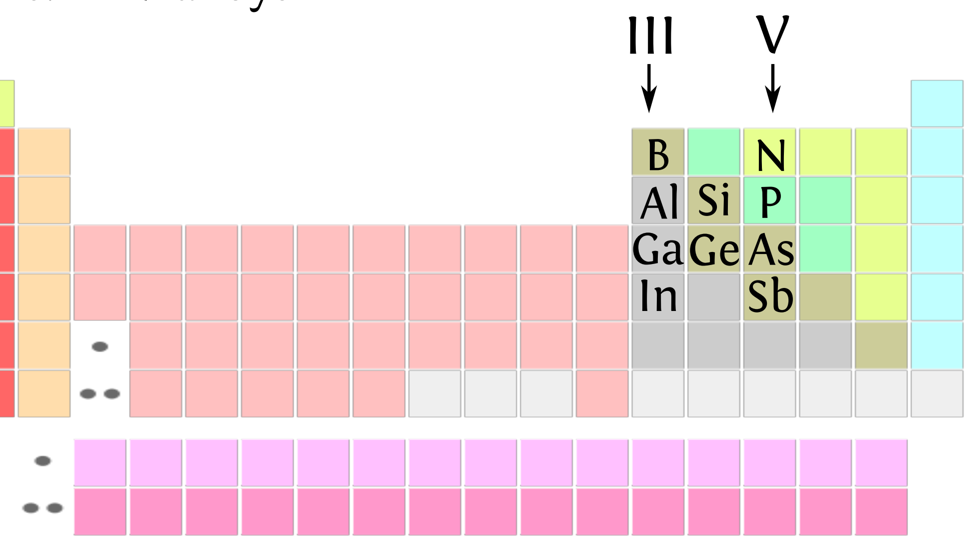


Multi-junction solar cells



- Optimal Eg and separately contacted junctions assumed

- Increasing junction number increases efficiency through a reduction in thermalization and below Eg losses
- Bandgap optimization is a materials engineering challenge
- Conditions:
  - Spectral conditions: terrestrial/space concentrator/flat plate?
  - Stacked cell or monolithic growth?
  - Separately contacted or current matched?
- Solutions: III-V alloys



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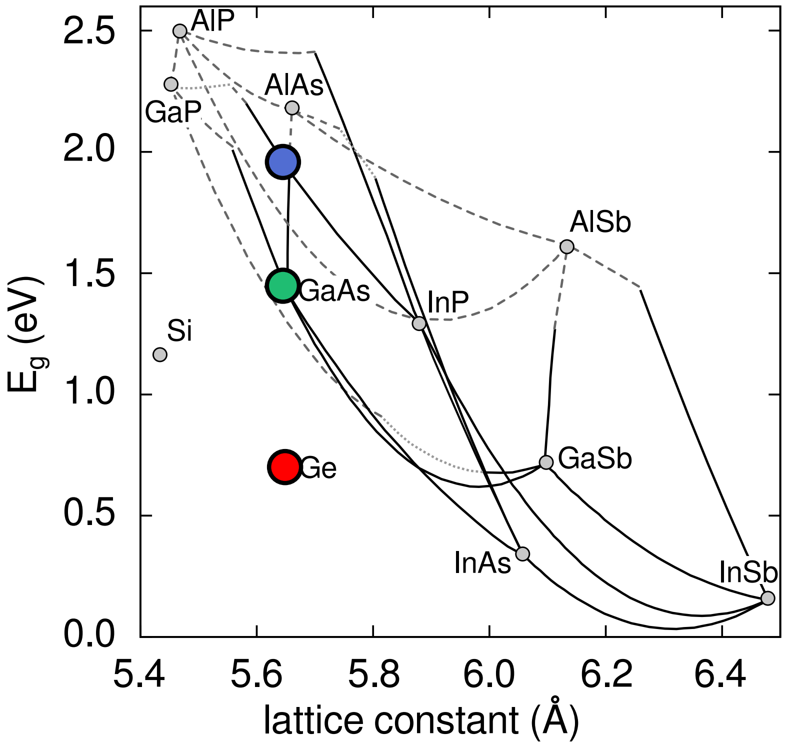


- Industry work horse, space applications:

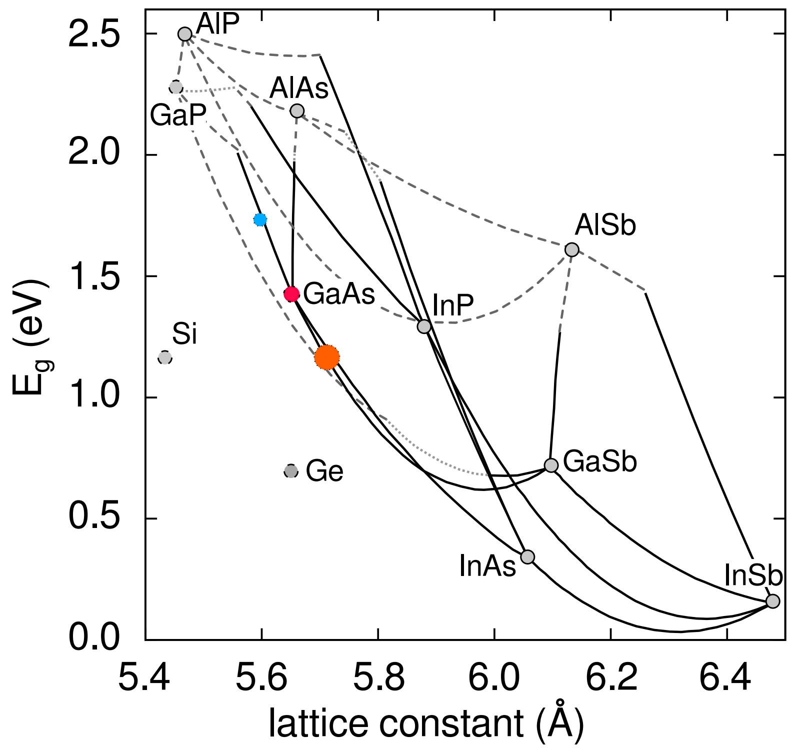
  InGaP/GaAs/Ge

  EMCORE ZTJ - 29.5 %

  - Current matching
  - Eg optimization

- Emerging technologies for high efficiency:

Multi-junction solar cells



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  InGaP/GaAs/Ge
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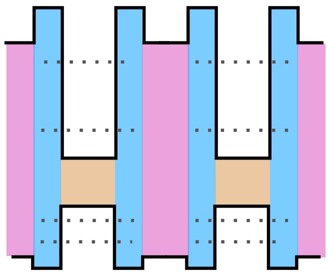
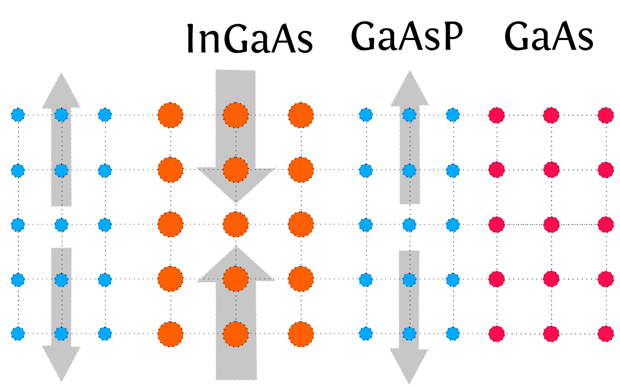
  - Current matching
  - Eg optimization
- Emerging technologies for high efficiency:
- Quantum wells



  - Reduce middle cell Eg for current matching
  - Felixble system for Eg optimization

Ekins-Daukes et al., Appl. Phys. Lett., 75, p. 4195 (1999)



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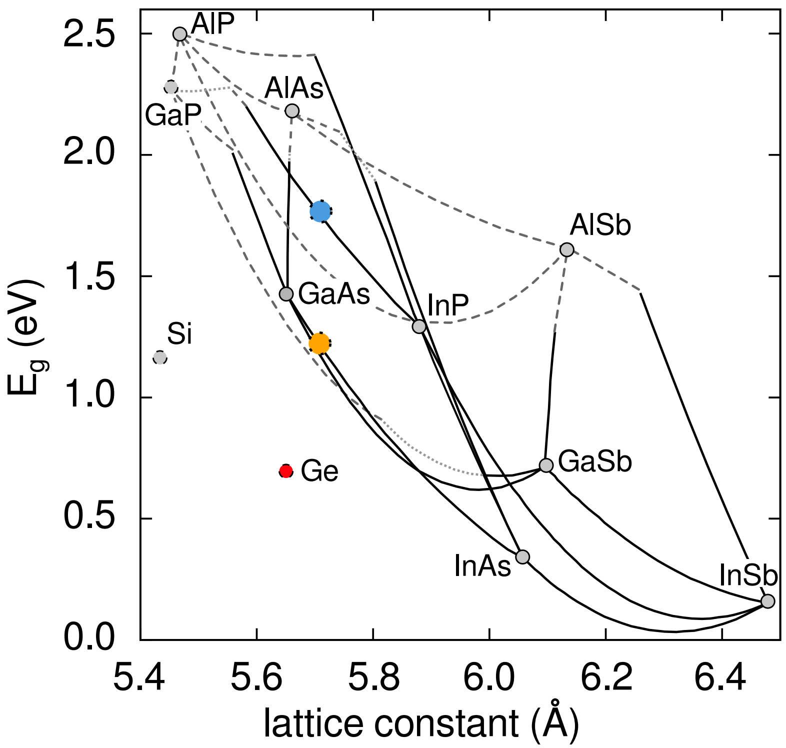

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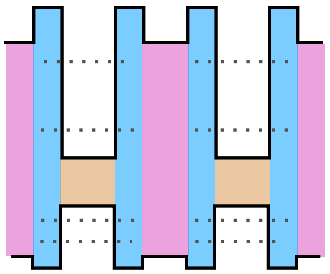
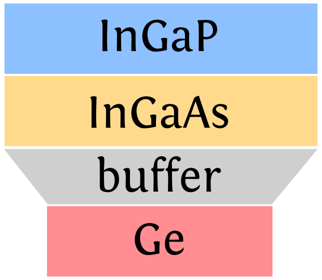


  - Reduce middle cell Eg for current matching
  - Felixble system for Eg optimization
- Metamorphic growth
  - Confine defects to a buffer layer to move lattice constant

MM cell



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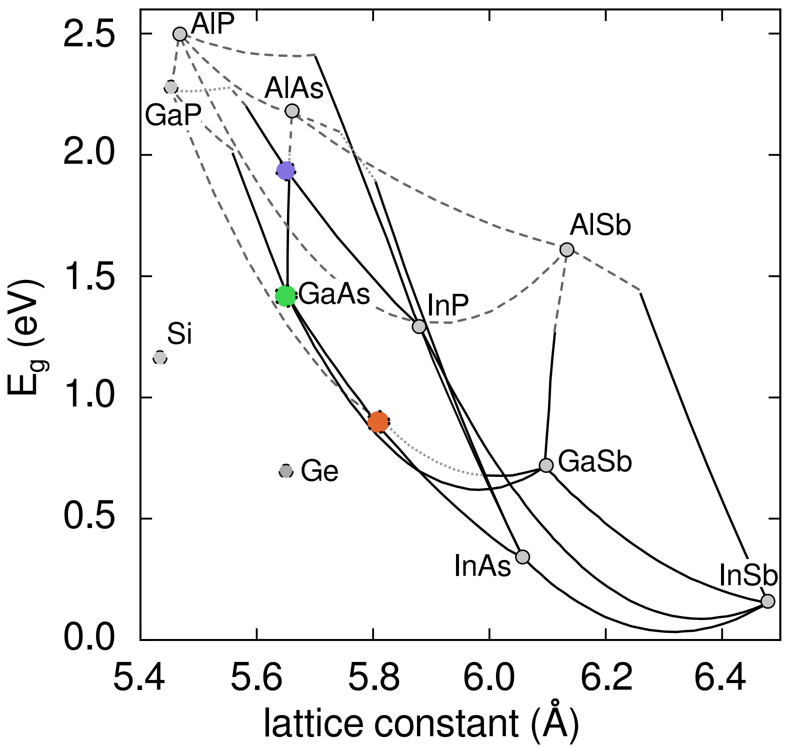

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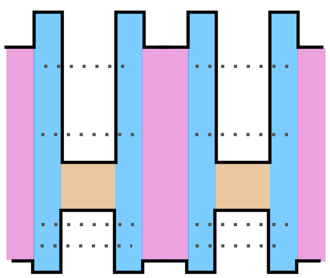

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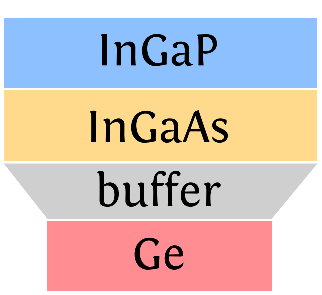
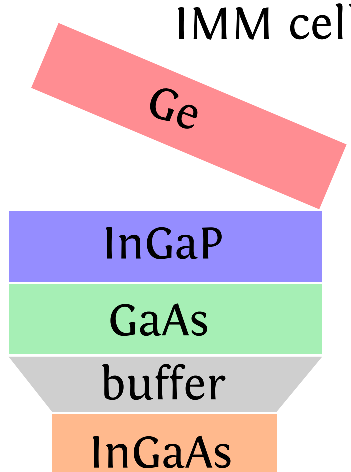


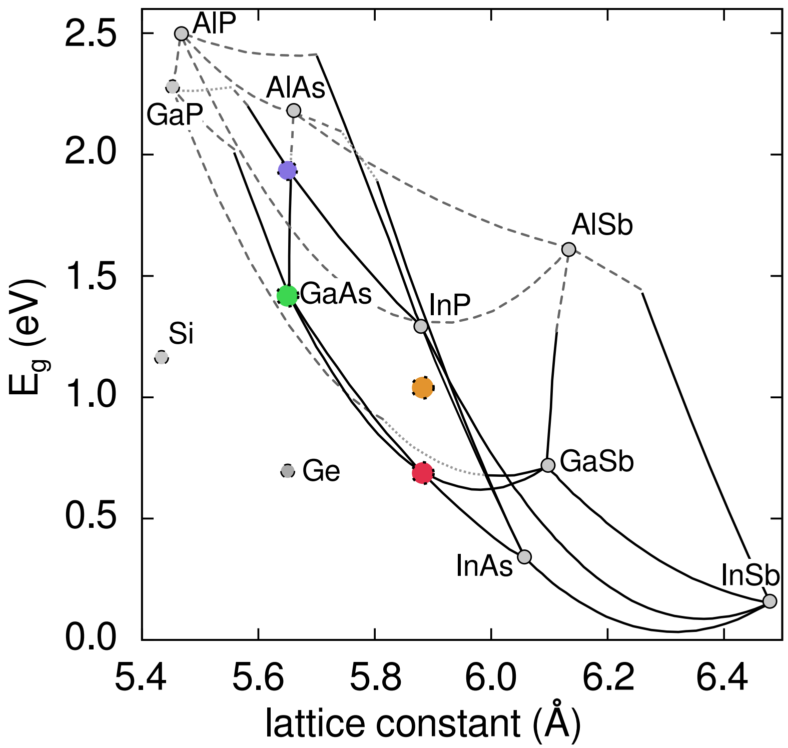
IMM cell



- Metamorphic growth
  - Confine defects to a buffer layer to move lattice constant

Geisz, et al., Appl. Phys. Lett, 93, p. 123505 (2008)

Multi-junction solar cells



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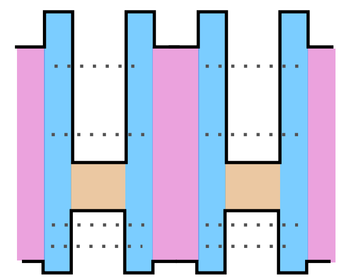
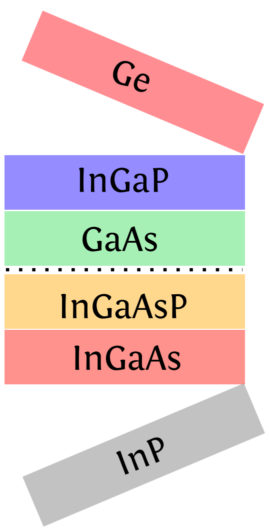
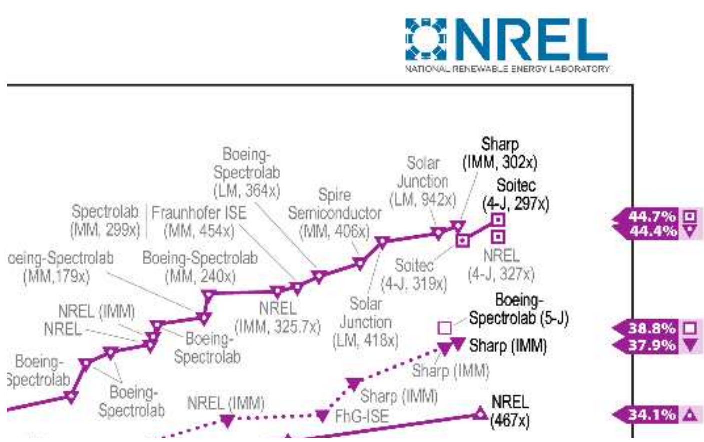


  - Reduce middle cell Eg for current matching
  - Felixble system for Eg optimization





- Metamorphic growth
  - Confine defects to a buffer layer to move lattice constant
- Bonded 4J Soitec - World record (44.7%, 297X)
  - Epitaxial lift-off & mechanical stacking

Dimmroth, et al. Prog. Photovolt., 22, p. 277 (2014)

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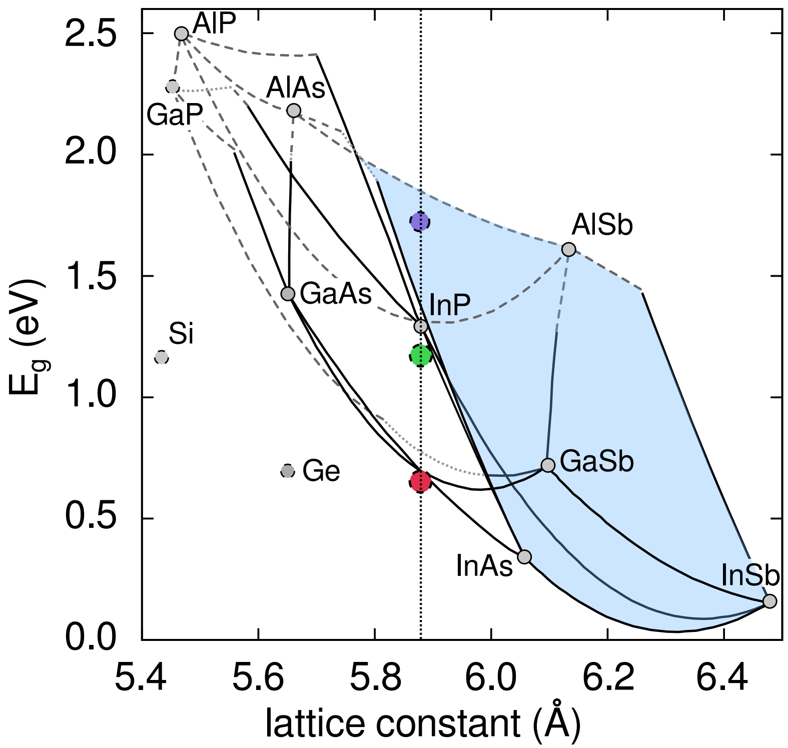
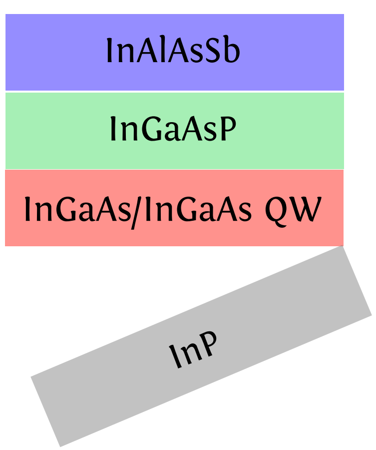
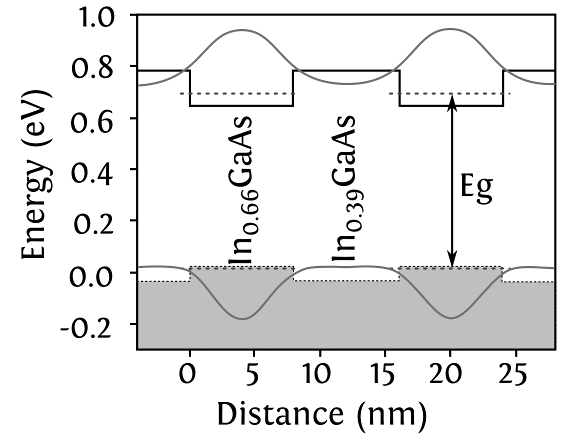
NRL pathway to 50%





- 3J on InP (1.74, 1.17, 0.7 eV)
- AM1.5D, low AOD, 500X



- InGaAs/InGaAs strain compensated QW
- InAlAsSb quaternary - new material
  - Simulate material properties:
    - Ternary end point lattice constants and band alignements from experiment
    - Estimate bowing parameter to interpolate
  - MBE growth for development:
    - Immiscibility - kinetics and thermodynamics
    - Temperature - Growth and anneal
  - Characterization:
    - Emission : PL
    - Device: QE and DLTS
    - Absorption: PLE and transmission

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Broader perspective

Still significant issues with MJ devices other than laboratory efficiency:

- ✗ Cost - extremely expensive materials and fabrication methods
  - ✓ Implement in highly focusing solar concentrator systems
    - ✓ Improved efficiency through Boltzmann loss reduction
    - ✗ Severly limits applications options - only suitable for desert power stations
    - ✗ $/W values - difficult to compete with flate plate Si
    - ✗ Industrial, commercial, transport & portable applications
      - low power density (W/m^2)
      - low specific power (W/kg)

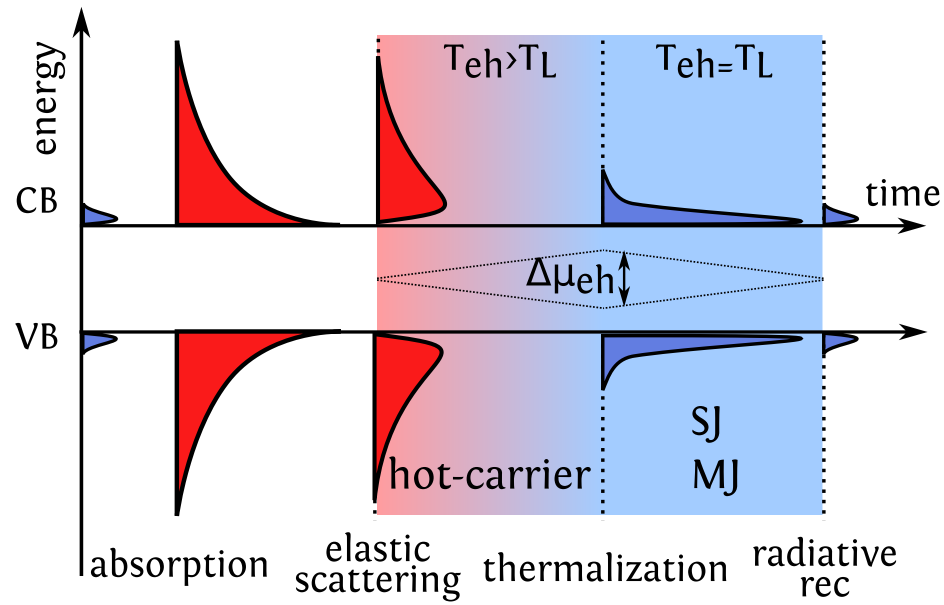
- ✗ Materials abundance
  - ✓ Substrate removal and reuse
  - ✓ Recycling

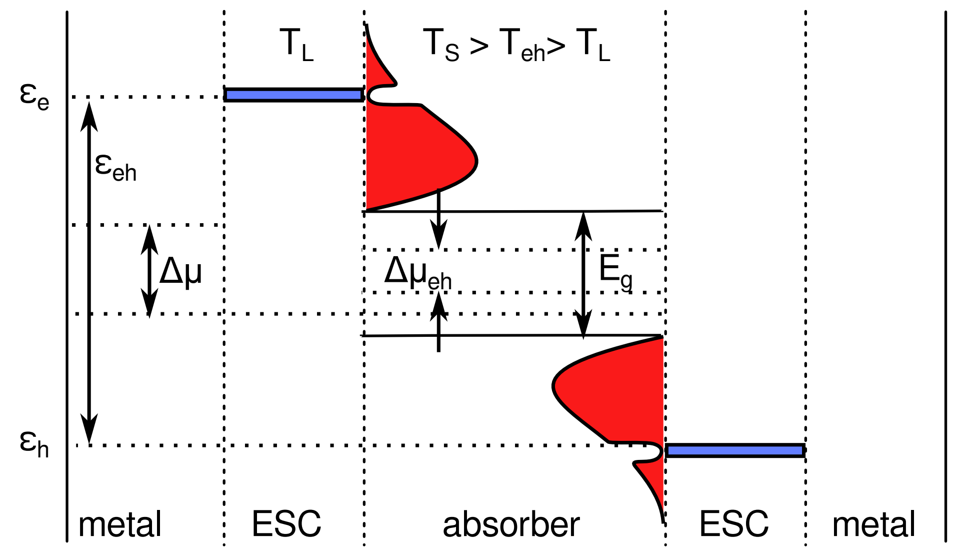
- ✗ Spectral sensivity - limits annual energy yields

- ✗ Ultimately limited by junction number - complexity is not free and only offers incremental improvement in efficiency

The hot-carrier solar cell

- Fundamentally different heat engine
- Carriers do not fully thermalization
- Change the rate balance between absorption and thermalization
  - Steady-state hot-carrier population
- Contact to the hot-carrier population via an energy selective contact
  - Cooling confined within an ∞ narrow energy range is isoentropic
  - Carrier population thermally equilibrates without dissipating excess heat energy
- Most like the Carnot engine





Making an HCSC

Requirements

Hot-carrier absorber

- Broadband absorber
- Restricted carrier-phonon interaction
  - Steady-state non-equilbrium hot carrier population
  - Achievable levels of solar illumination

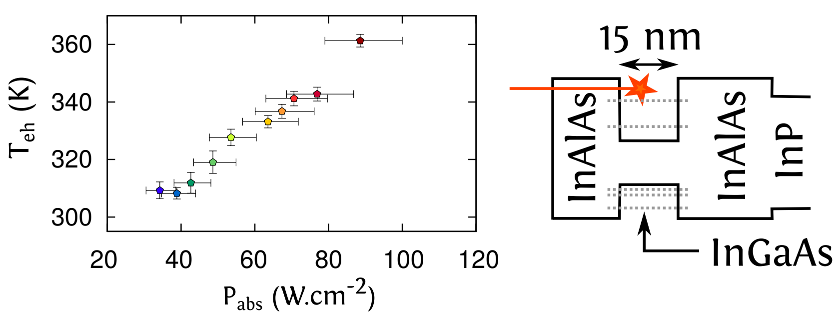
Energy selective extraction

- Energy selective contact
  - Reduced range of energy states relative to absorber
- Carrier transmission
  - High current, concentrator devices

Device solutions

- Slow carrier cooling in QWs
  - Record low thermalization coefficient in InAlAs/InGaAs wells

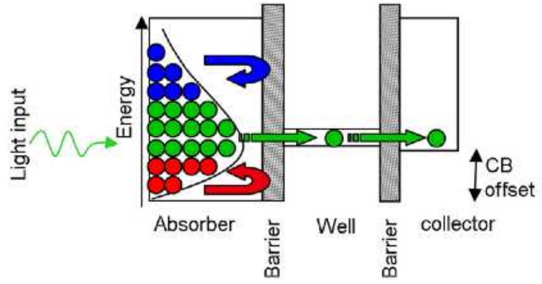
    in press IEEE J. Photovolt., 2014



- E-field enhancement nanostructures
  - Absorption in ultra-thin device
  - High carrier density -> hotter carriers

- Recent progress
  - Resonant tunneling

    Dimmock et al., Prog. Photovolt, 22, p. 151, 2014

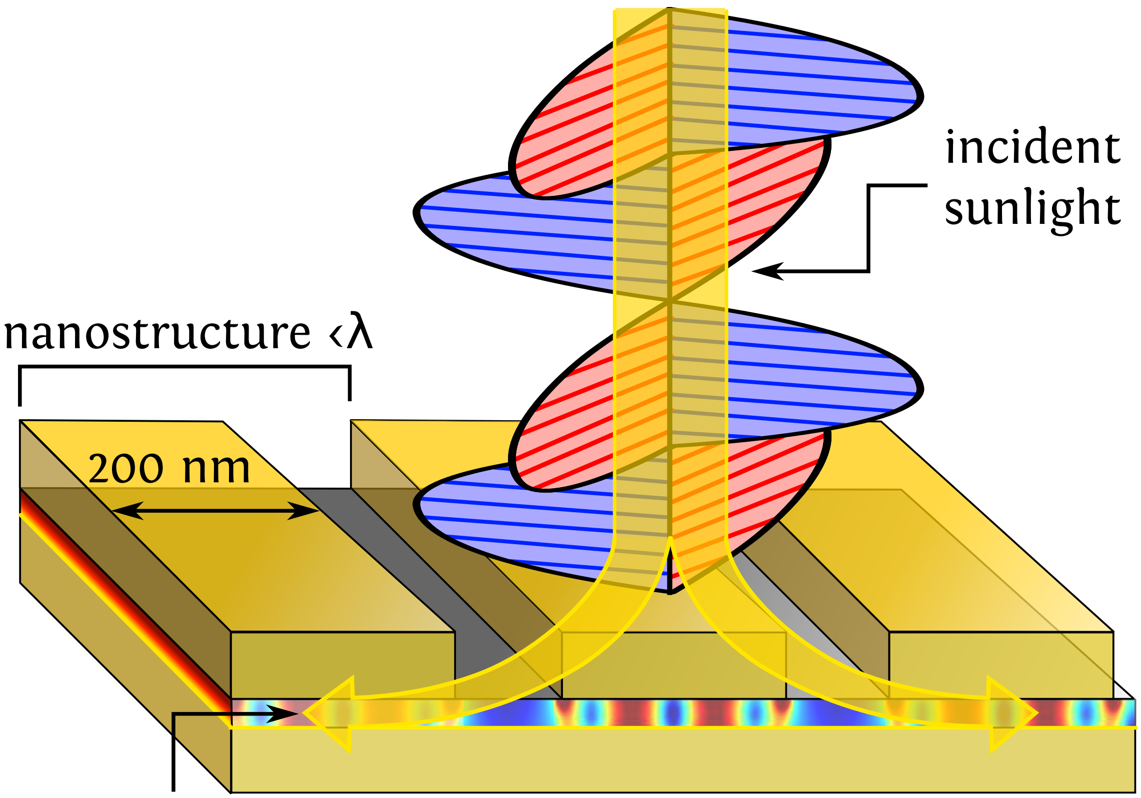


  - Semi-selective energy barrier

    Hirst et al., Appl. Phys. Lett., 2014

- Quaternary superlattice structures on InP for miniband formation

NRL hot-carrier solar cell design



- Ultra-thin (active region ‹ 100 nm)
- Reduction thermalization quantum well hot-carrier absorber
- Superlattice energy selective contact
- Plamonic waveguiding nanostrucutre

✓ Cost

✓ Material abundance

✓ Spectral sensivity

✓ No complexity limit

- CMP tomorrow 2:30pm in room 103 Nielsen Hall

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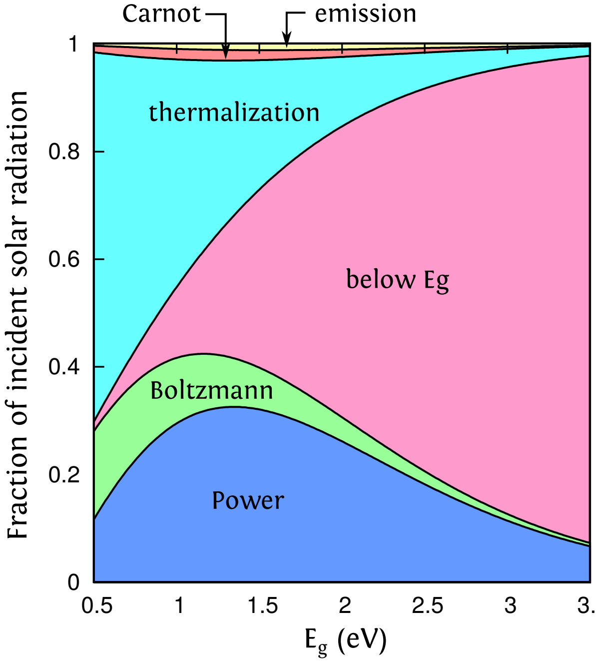
The finish line

- Multi-crystalline Si - 55% of total production
- Extremely cheap - cells produced \$0.2/W
- Key issue with multi-crystalline Si:
    - low power density (W/m^2)
    - low specific power (W/kg)



Pathways to high efficiency

- MJ - Leading high efficiency PV technology
- Race to 50%
    - Metamorphic buffers
    - Quantum wells
    - ELO and bonding
- Ultimately limited by junction number
- What's there at the finish line?