Multi-Junction High-Performance Solar Cells

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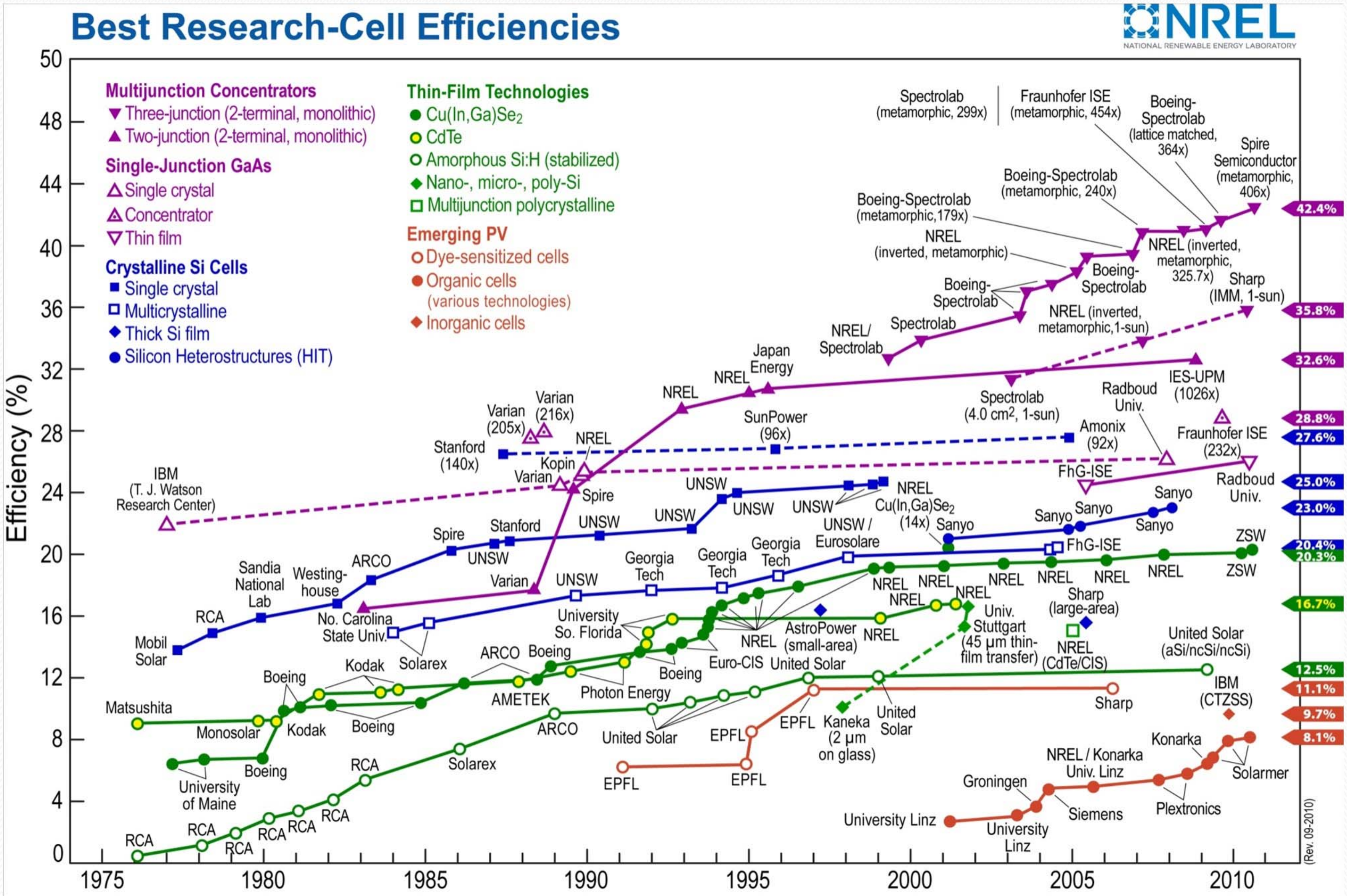
What makes a High-Efficiency Solar Cell?

- Solar cells often measured through their energy conversion efficiency, η
- Efficiency related to power and light irradiance:

$$\eta = \frac{P_M}{E \times A_C} = \frac{I_{SC} V_{OC} FF}{P_{in}}$$

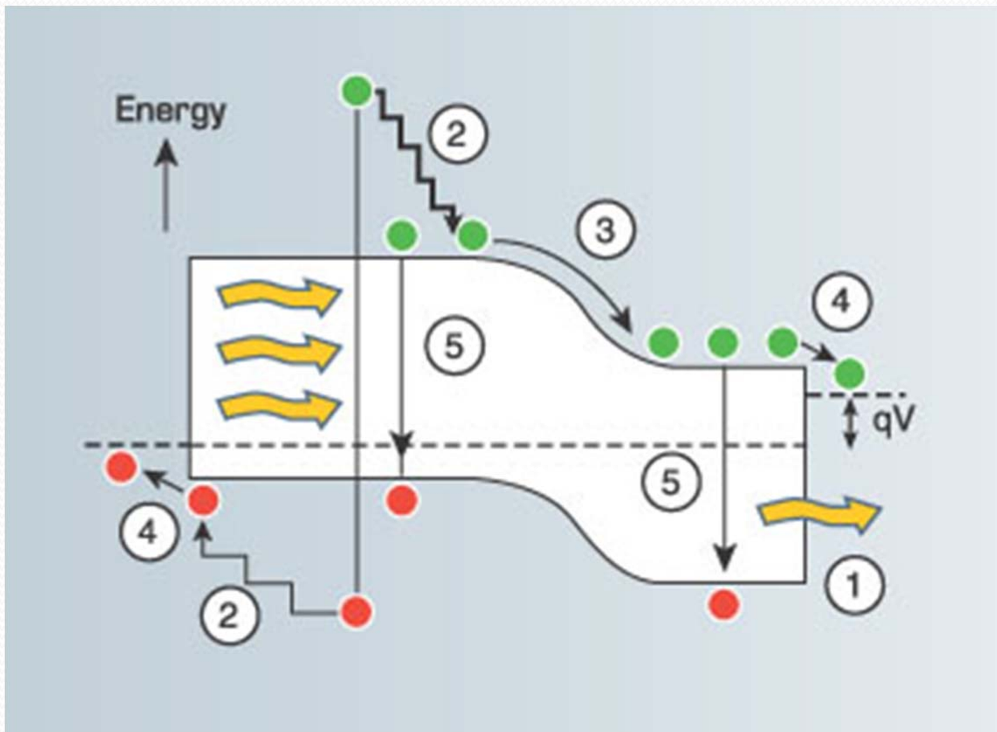
- Maximum theoretical conversion efficiency: 86.8%
- High-efficiency solar cells typically greater than 25% efficiency that can be found in the highest quality commercial solar cells

Cell-Efficiency Overview

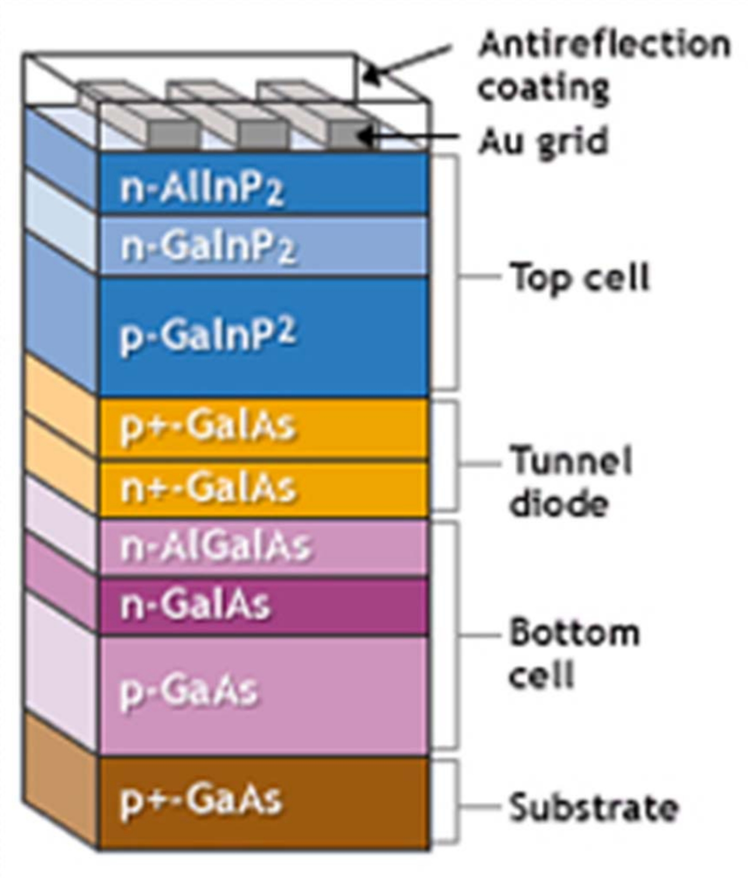


Key Solar Cell Energy Transfers: Where Does All the Energy Go?

- 1) Photons transmitted through solar cell and not absorbed
- 2) Solar energy losses resulting from conversion to heat
- 3) & 4) Junction and contact voltage losses
- 5) EHP recombination losses

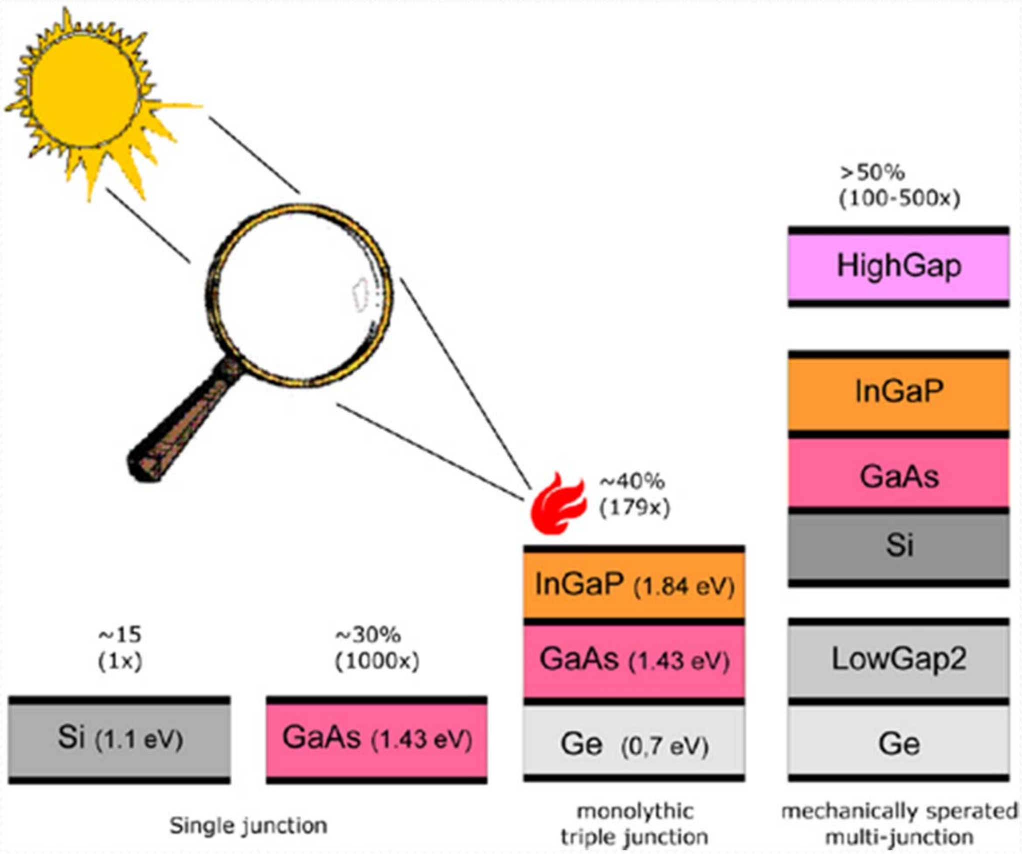


Why Use Multi-Junction Solar Cells?



- Each layer tuned to a different wavelength, shortest on top to longest on bottom.
- Tunnel junction to allow electrons to flow between cells
- Greater likelihood of energy capture
- Efficiency record: University of Delaware (42.8% Conversion), ‘07

Single Junction v. Multi-Junction



- Single junction efficiency losses due to non-absorption
- Multi-junction capability to absorb a larger spectrum of energy values
- Multi-junction solar cells preferred

Single Junction v. Multi-Junction

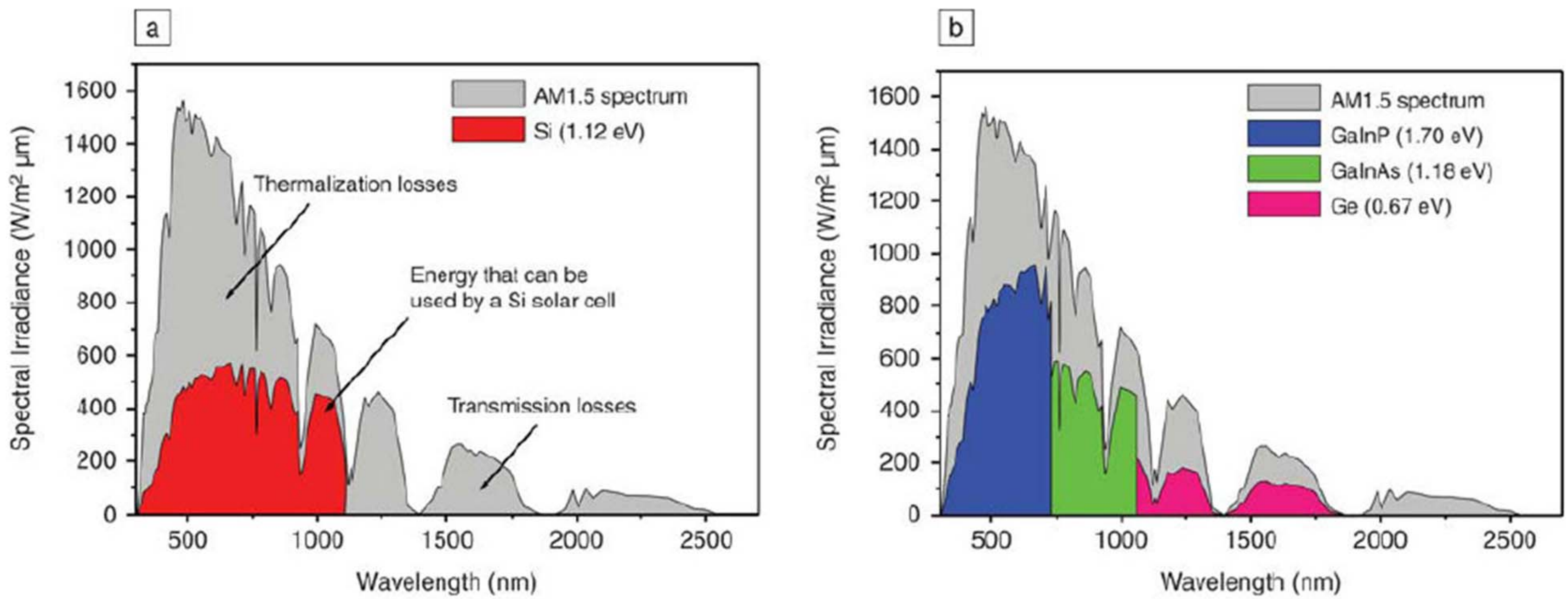


Figure 4: The AM1.5 solar spectrum[1] and the parts of the spectrum that can, in theory, be used by: (a) Si solar cells; (b) $Ga_{0.35}In_{0.65}P/Ga_{0.83}In_{0.17}As/Ge$ solar cells [25].

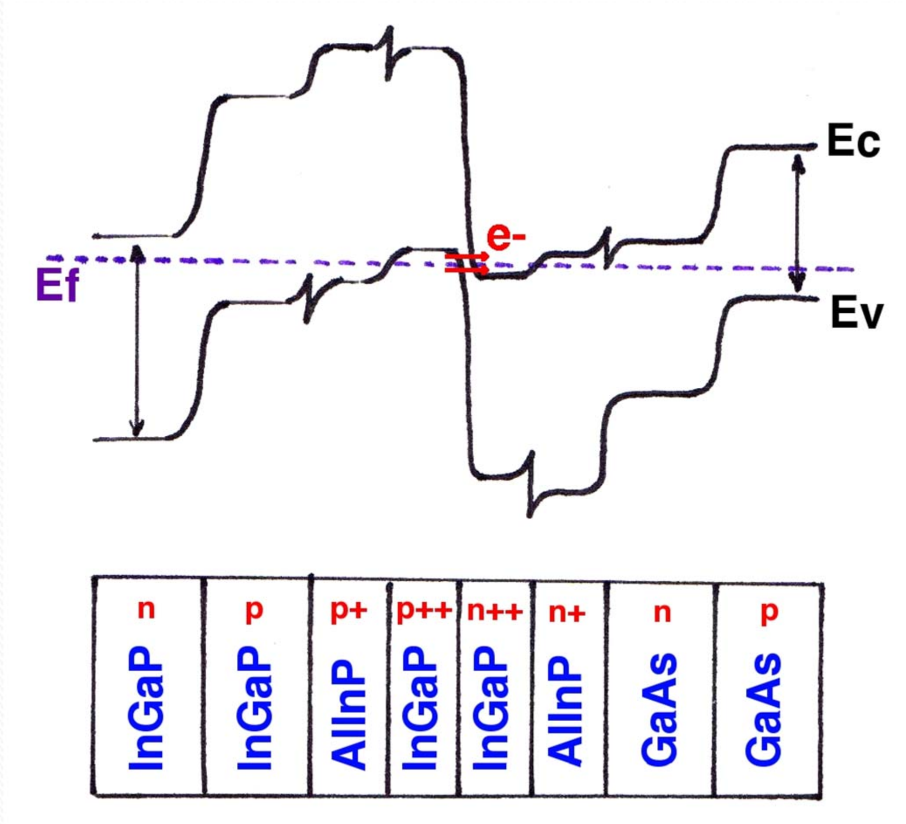
High-Efficiency Multi-Junction Cell Features and Characteristics

- III-V Semiconductors most popular
  - InGaP/InGaAs/p-Ge (Boeing Spectrolab, 40.7%)
  - InGaP/InGaAs/p-GaAs
- Most efficient solar cells to date developed with triple junction separated by tunnel junctions (up to 20 layers)
- Fabrication through MOCVD or MBE
- Strong doping in tunnel junction in order to have thin depletion region and minimal optical losses between cell regions

Band Structure of Tunnel Junction

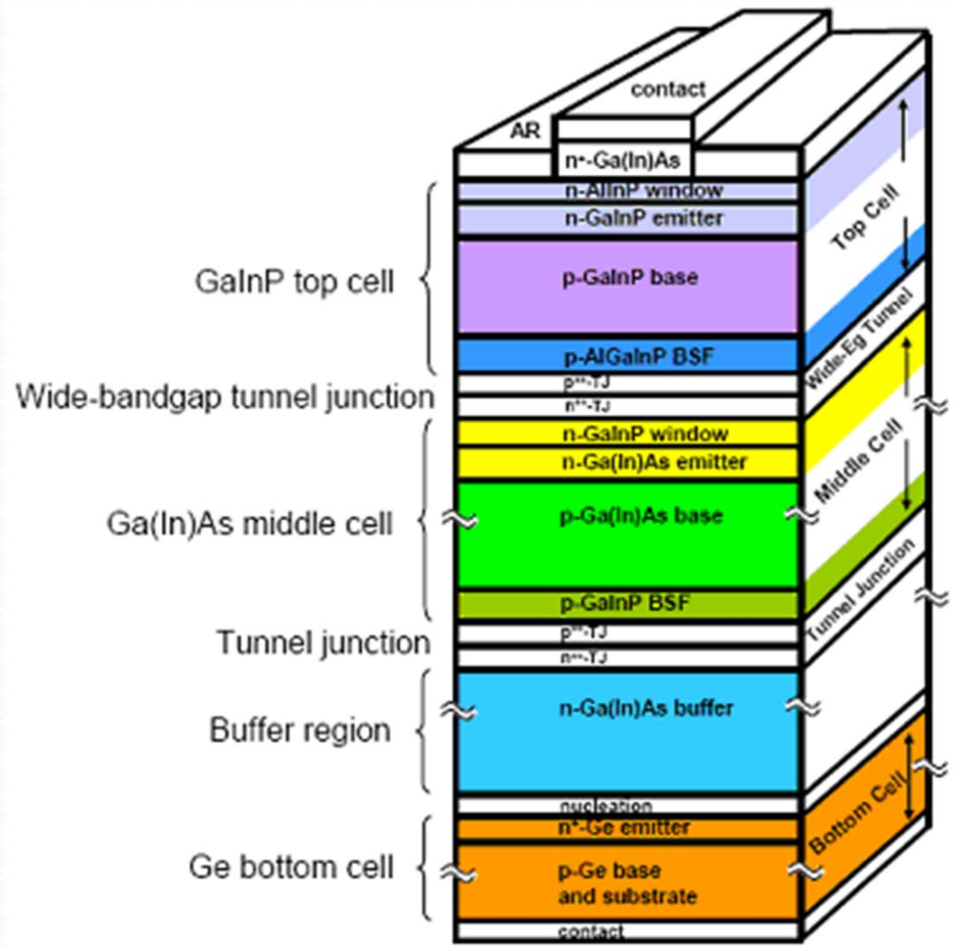
- Small depletion region for minimal resistance due to high doping

$$d_{depl} = \sqrt{\frac{2\varepsilon(\phi_0 - V)}{q}\frac{N_A + N_D}{N_A N_D}}$$



Anatomy of Boeing Spectrolab's 40.7% Efficient Solar Cell

- Specific E_g choices:
  - GaInP (1.85 eV) for blue and UV light
  - GaAs-layer (1.42 eV) for near-infrared light
  - Ge/GaAs (0.67 eV) lower photon energies of IR radiation
- Layer thickness dictated by current-matching
- Configuration used: $Ga_{0.44}In_{0.56}P/Ga_{0.92}In_{0.08}As/Ge$



How to Improve From Here: Research Goals and Initiatives

- DARPA funding for VHESC Cells (2007-present)
  - ~$100 million for three-years of research to manufacture solar cells that will register 50% conversion efficiency
  - Front-runners: University of Delaware, University of New South Wales, Boeing Spectrolab
- Exploring different materials and increasing number of junctions
- Increased study of concentrator photovoltaic systems
- Deeper understanding regarding the feasibility of quantum dots

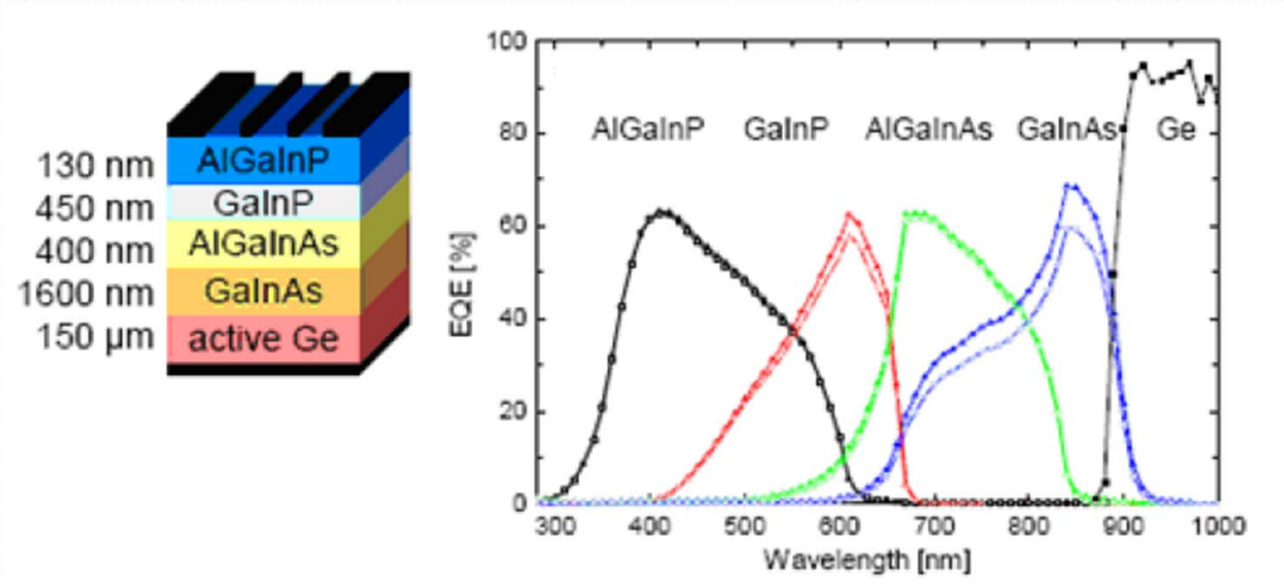
Future Design Improvements

- Optimization of Existing Layers
  - Consider AlGaAs or AlGaInP to replace GaInP for higher bandgap
  - Lower bandgap (~1.25 eV) to replace GaAs layer to increase current and reduce photons transmitted to p-Ge or p-GaAs layer
- Increasing number of junctions imply greater opportunity for absorption, leading to the theoretical 86.8% absorption possibility

# junctions in solar cell	1 sun η	Max con. η
1 junction	30.8%	40.8%
2 junction	42.9%	55.7%
3 junction	49.3%	63.8%
∞ junction	68.2%	86.8%

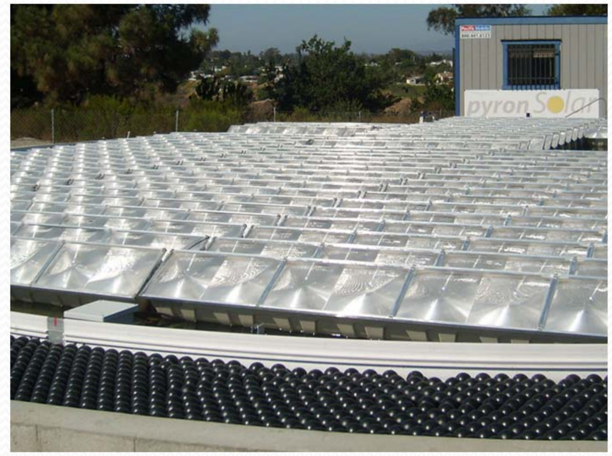
Future Design Improvements

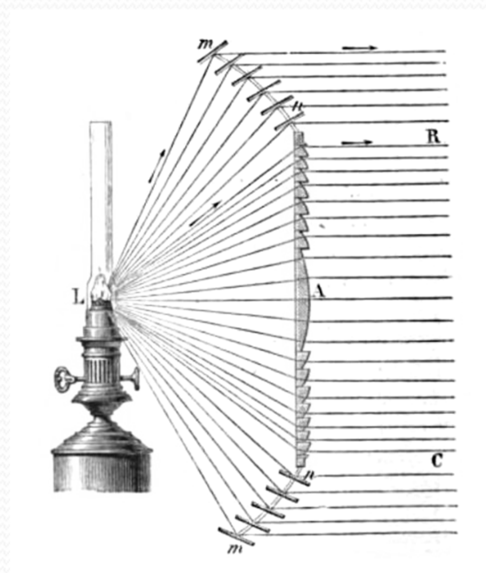
- Example of possible 5-junction design
  - Problems: Doubtful practicality
  - Does not address ways to increase cell surface exposure to the sun



How Can We Minimize Cost?

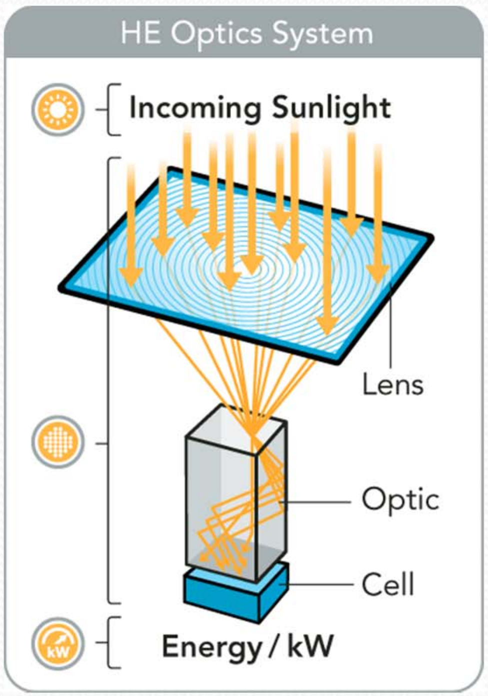
- Current high-efficiency manufacturing cost: $10,000-$70,000 per square meter!
- Maximizing Input Power: Concentrator Photovoltaic Systems (CPVs)
- Example: PyronSolar Fresnel lenses for Spectrolab's high-efficiency solar cells

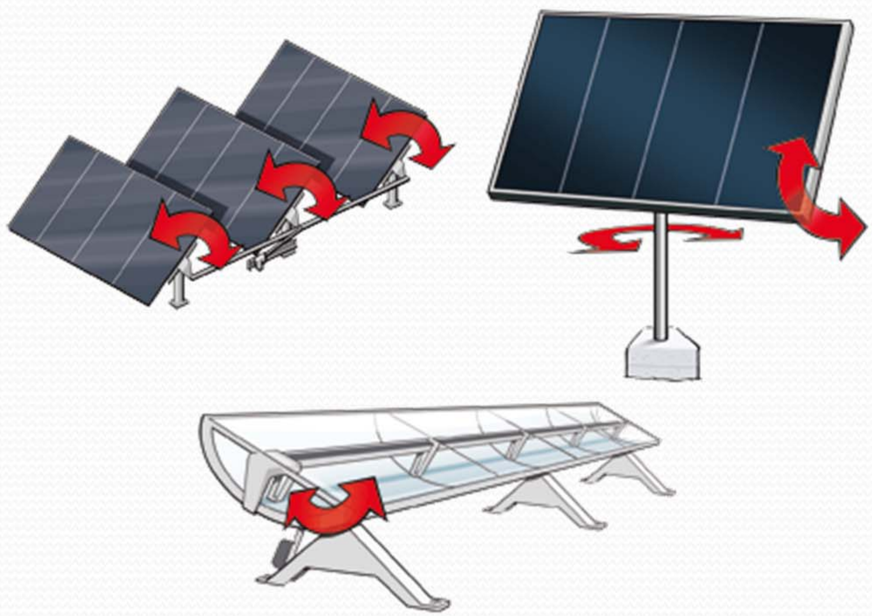


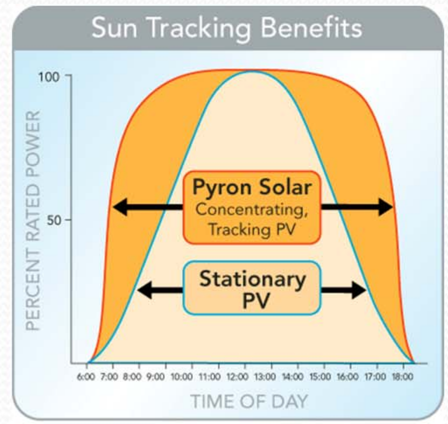


Increasing Maximum Input Power

- HE Optics System
  - Short Focal-length
  - Acrylic Concentrating Lens
  - Can produce up to 800 times more electricity overall
- Solar Tracking
  - Platform with multiple arrays
  - Vertical axis rotation
  - Tilting to match daily azimuthal travel of sun

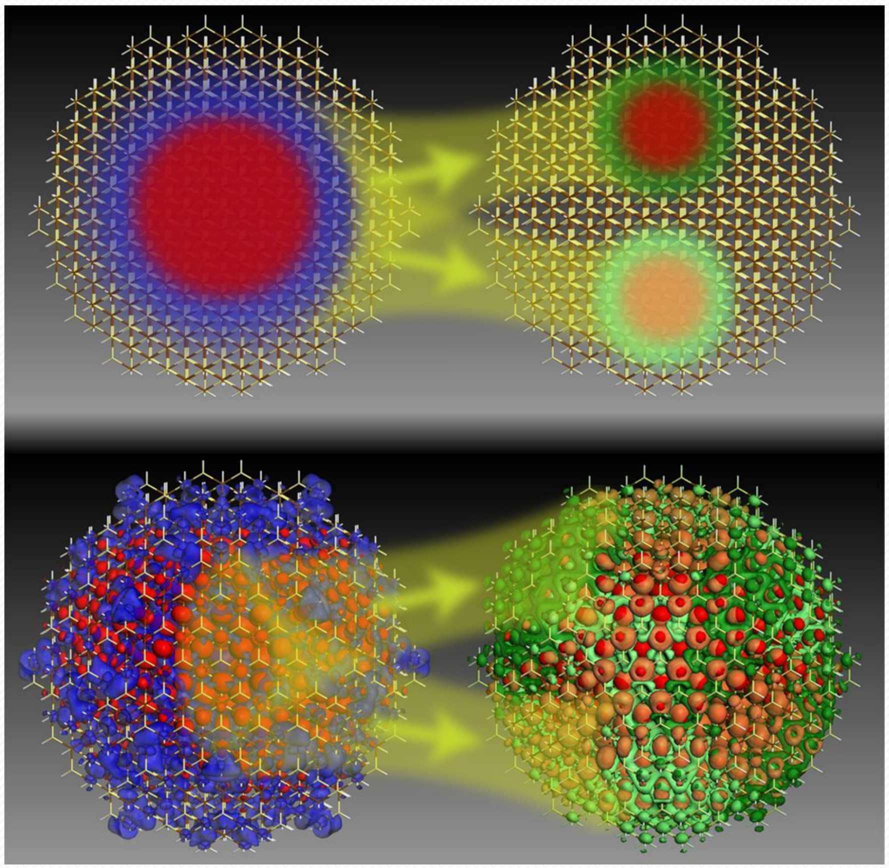






System Specifications	
Name Plate Capacity	90 kWp DC
Cell Efficiency	36.5%
Solar Aperture (Single Lens)	0.1225 m^2
Module Efficiency	20% - 22%
Tracking System	Dual Axis

Controversial Multi-Junction Alternative: Quantum Dots



- Man-made attempt to generate more than one free electron per absorbed photon, i.e. "carrier multiplication" through multiple-exciton generation
- Longstanding debate about any significance in efficiency improvement
- Strong interactions with other electrons potentially counterbalanced by limited energy structure in QDs; requires more research

References

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