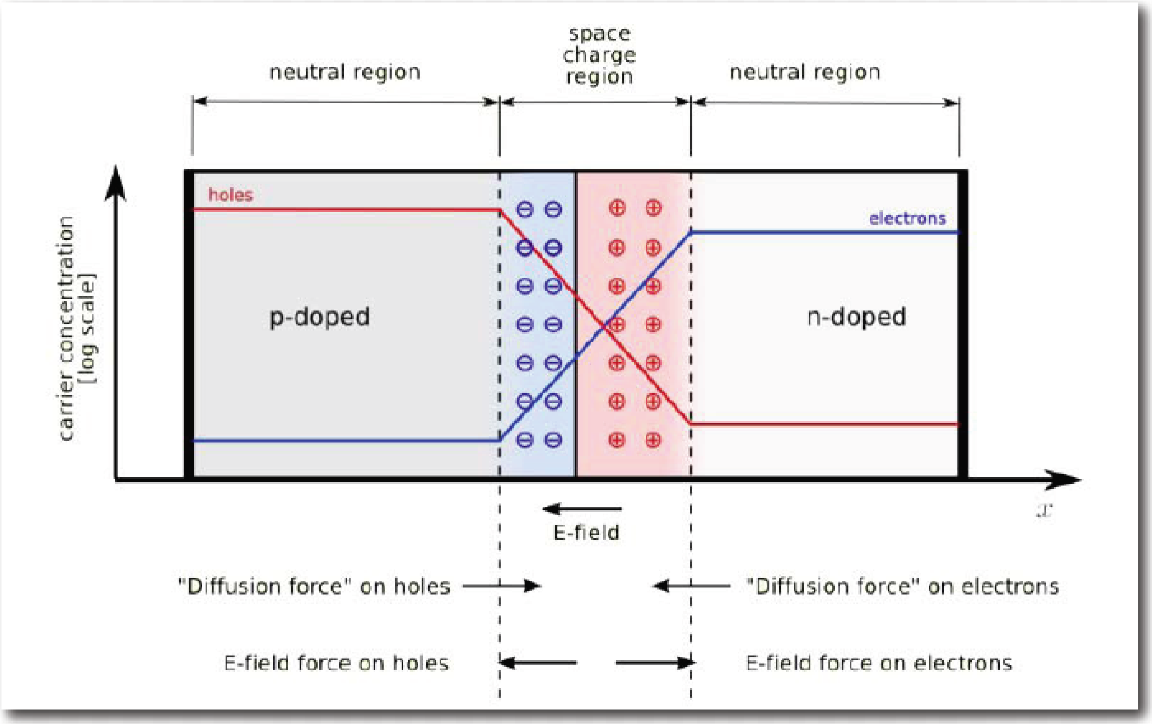
Strategies to Improve Solar Technology

- Lower Cost
- Increase Power Efficiency

Introduction

- 1839: Photovoltaic effect was first recognized by French physicist Alexandre-Edmond Becquerel.
- 1883: First solar cell was built by Charles Fritts, who coated the semiconductor selenium with an extremely thin layer of gold to form the junctions (1% efficient).
- 1946: Russell Ohl patented the modern solar cell
- 1954: Modern age of solar power technology arrives - Bell Laboratories, experimenting with semiconductors, accidentally found that silicon doped with certain impurities was very sensitive to light.
- The solar cell or photovoltaic cell fulfills two fundamental functions:
  - Photogeneration of charge carriers (electrons and holes) in a light-absorbing material
  - Separation of the charge carriers to a conductive contact to transmit electricity

Electricity Generation



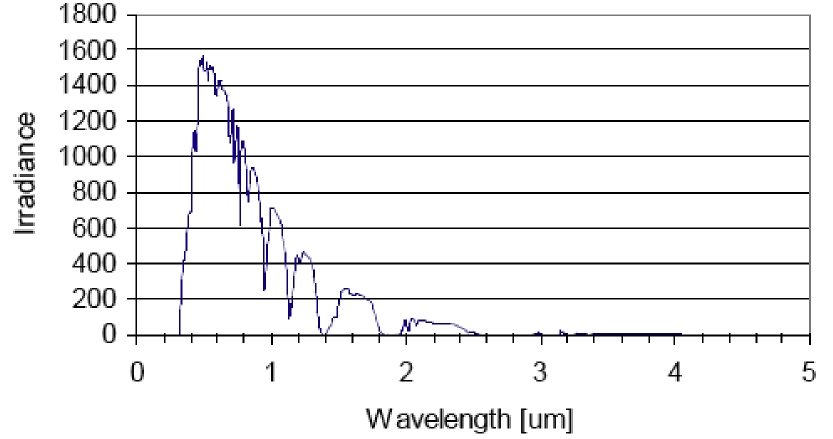
Basic Types:
p-n homojunction
p-n heterojunction
Schottky Junction
Donor-Acceptor

- p-n junction in thermal equilibrium w/ zero bias voltage applied.
- Electrons and holes concentration are reported respectively with blue and red lines.
- Gray regions are charge neutral.
- Light red zone is positively charged; light blue zone is negatively charged.
- Electric field shown on the bottom, the electrostatic force on electrons and holes and the direction in which the diffusion tends to move electrons and holes.

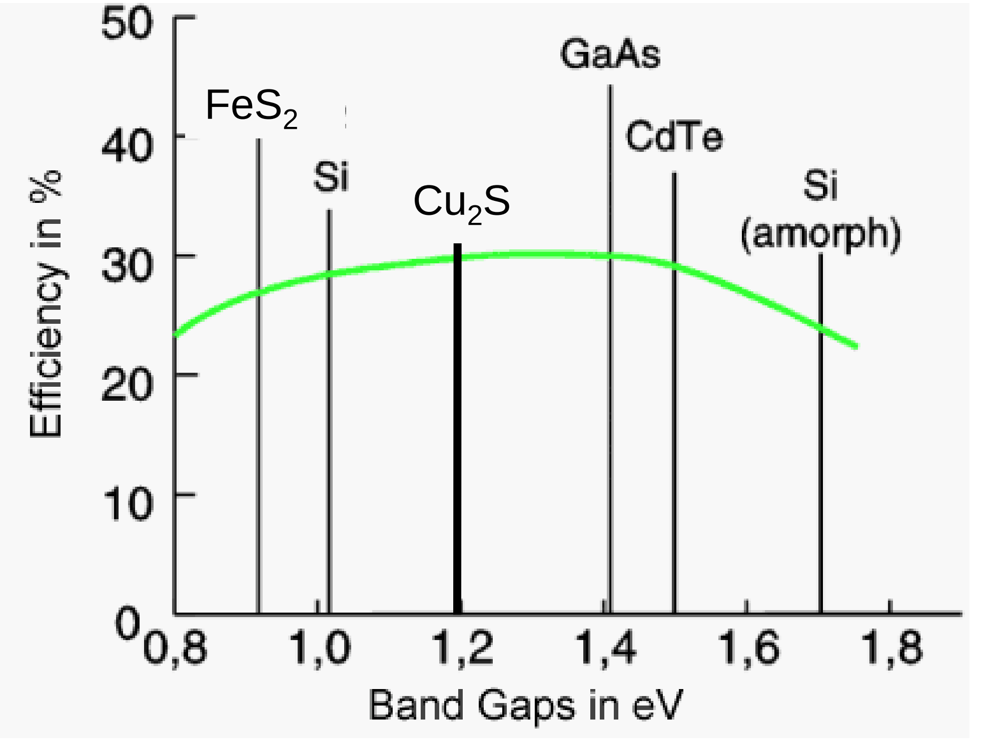
- Sunlight consists of a large number of photons distributed across a large wavelength range.
- The photon energy depends on the photon wavelength in the following manner:

$$E_{phot} = hc/\lambda$$

- The variation in photon energy makes efficient utilization of the entire solar spectrum in one solar cell difficult.



Single-cell Theoretical Maximum Efficiency



First Generation:

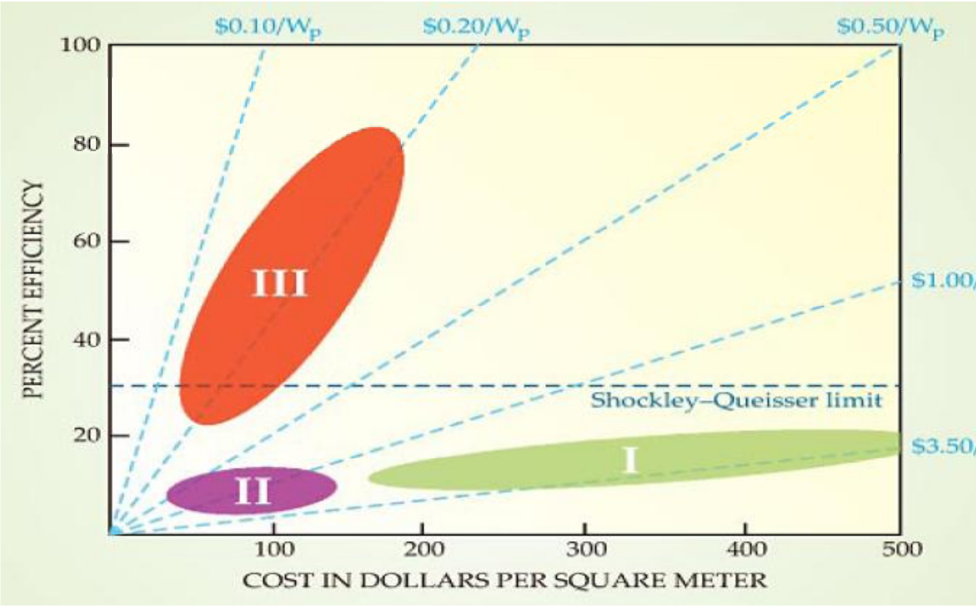
- Single crystal silicon (c-Si)

Second Generation: Lower Cost

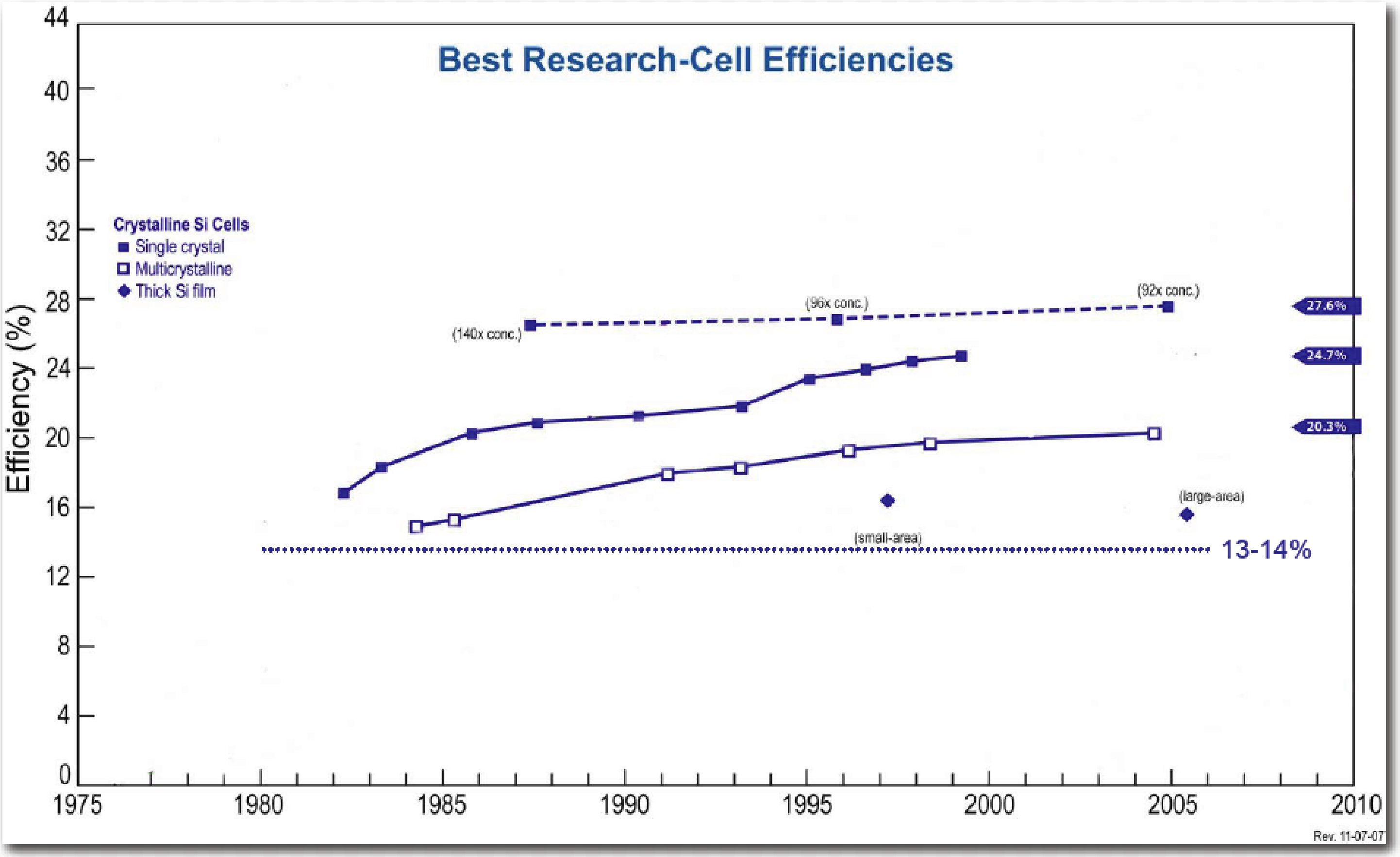
- Amorphous and Polycrystalline Si
- Cadmium Telluride
- Copper Indium Gallium DiSelenide (CIGS)
- Photoelectrochemical Cells
- Organic Solar Cells
- Dye Sensitized Cells

Third Generation: Higher Efficiency

- Quantum Dot Solar Cells
- Tandem Solar Cells
- Thermophotovoltaics



First Generation: Research Cells



Source: National Renewable Laboratory

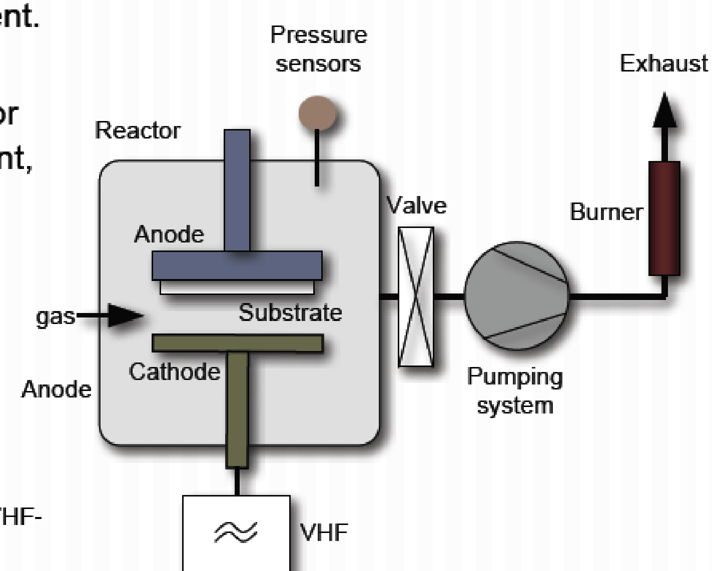
First Generation: Evaluation

- Advantages
  - Broad spectral absorption range
  - High carrier mobilities
- Disadvantages
  - Requires expensive manufacturing technologies
  - Growing and sawing of ingots is a highly energy intensive process
  - Fairly easy for an electron generated in another molecule to hit a hole left behind in a previous photoexcitation.
  - Much of the energy of higher energy photons, at the blue and violet end of the spectrum, is wasted as heat

Second Generation: PECVD

Plasma **E**nhanced **C**hemical **V**apor **D**eposition

- Thin-film deposition
  - Technique for depositing a thin film of material onto a substrate.
  - Layer thickness can be controlled to within a few tens of nanometers
  - Single layers of atoms can be deposited
- Chemical vapor deposition (CVD)
  - Chemical process using a gas-phase precursor.
  - Often a halide or hydride of the deposited element.
- PECVD - Plasma Enhanced CVD
  - Uses an ionized vapor, or plasma, as a precursor
  - Relies on electromagnetic means (electric current, microwave excitation) to produce plasma.



Schematic of a single-chamber VHF-GD deposition system

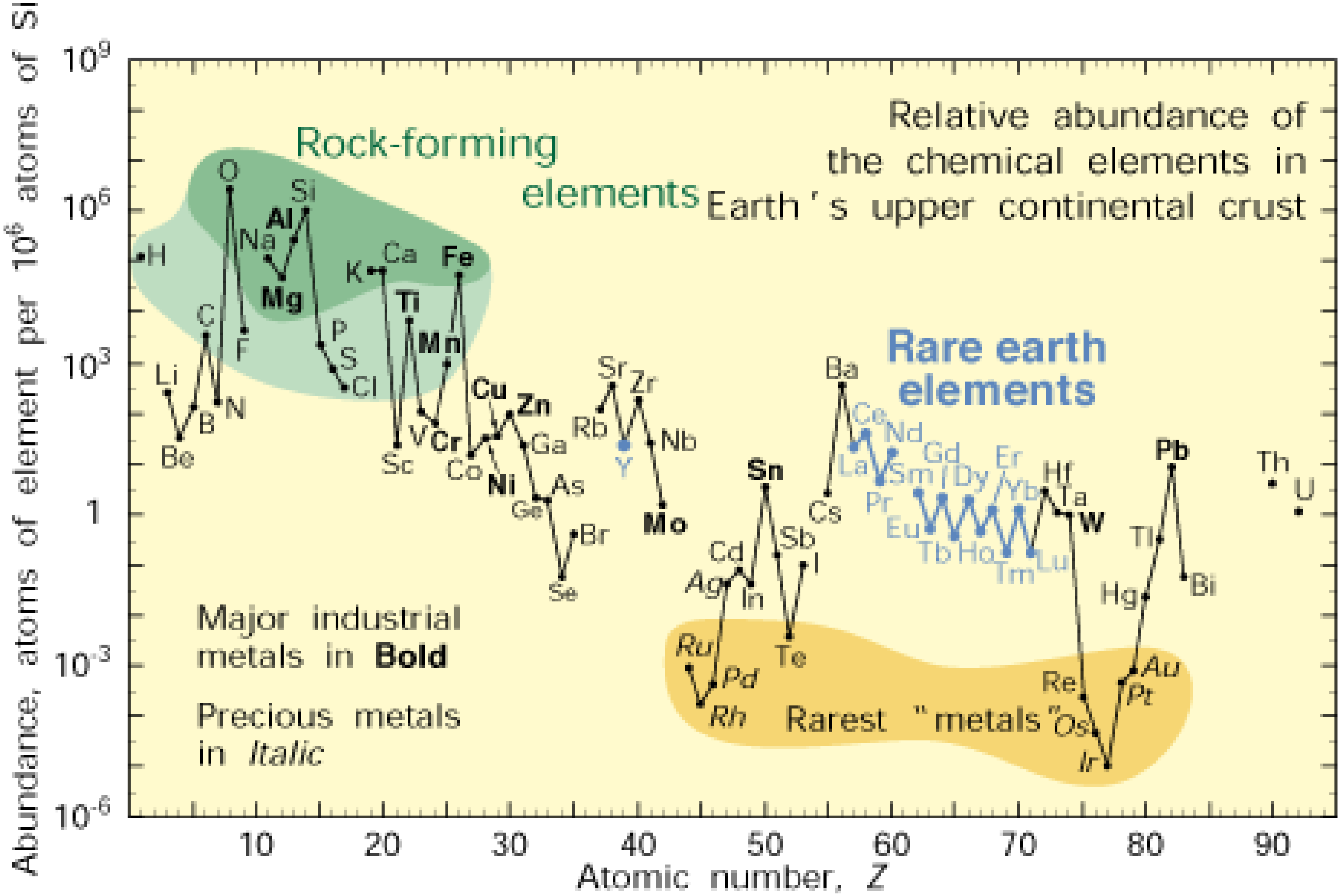
Second Generation: Types

- Amorphous silicon cells deposited on stainless-steel ribbon
  - Can be deposited over large areas by plasma-enhanced chemical vapor deposition
  - Can be doped in a fashion similar to c-Si, to form p- or n-type layers
  - Used to produce large-area photovoltaic solar cells
  - Band gap ~ 1.7 eV
- Polycrystalline silicon
  - Consists solely of crystalline silicon grains (1mm), separated by grain boundaries
  - Main advantage over amorphous Si: mobility of the charge carriers can be orders of magnitude larger
  - Material shows greater stability under electric field and light-induced stress.
  - Band gap ~ 1.1 eV
- Cadmium telluride (CdTe) cells deposited on glass
  - Crystalline compound formed from cadmium and tellurium with a zinc blende (cubic) crystal structure (space group F43m)
  - Usually sandwiched with cadmium sulfide (CdS) to form a p-n junction photovoltaic solar cell.
  - Cheaper than silicon, especially in thin-film solar cell technology - not as efficient
  - Band gap ~ 1.58 eV
- Copper indium gallium diselenide (CIGS) alloy cells
  - Deposited on either glass or stainless steel substrates
  - More complex heterojunction model
  - Band gap ~ 1.38 eV

Second Generation: Evaluation

- Advantages
  - Lower manufacturing costs
  - Lower cost per watt can be achieved
  - Reduced mass
  - Less support is needed when placing panels on rooftops
  - Allows fitting panels on light or flexible materials, even textiles.
- Disadvantages
  - Typically, the efficiencies of thin-film solar cells are lower compared with silicon (wafer-based) solar cells
  - Amorphous silicon is not stable
  - Increased toxicity

Material Availability

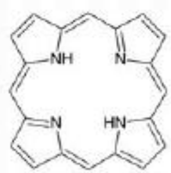


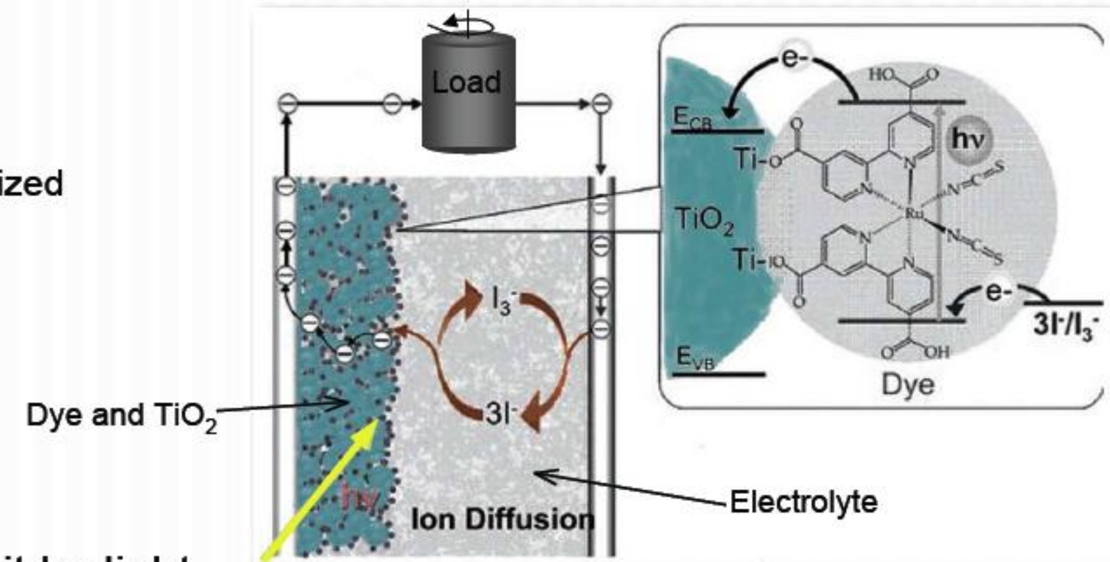
Photoelectrochemical (PEC) cells

- Separate the two functions provided by silicon in a traditional cell design
- Consists of a semiconducting photoanode and a metal cathode immersed in an electrolyte.
  - K_3 $Fe(CN)_6/K_4$ $Fe(CN)_6$
  - Iodide/Triiodide
  - $Fe(CN)_6^{4-}/Fe(CN)_6^{3-}$
  - Sulphide salt/sulphur
- Charge separation not solely provided by the semiconductor, but works in concert with the electrolyte.
- Gräetzel cells
  - Dye-sensitized PEC cells
  - Semiconductor solely used for charge separation,
  - Photoelectrons provided from separate photosensitive dye
  - Overall peak power production represents a conversion efficiency of about 11%

Dyes

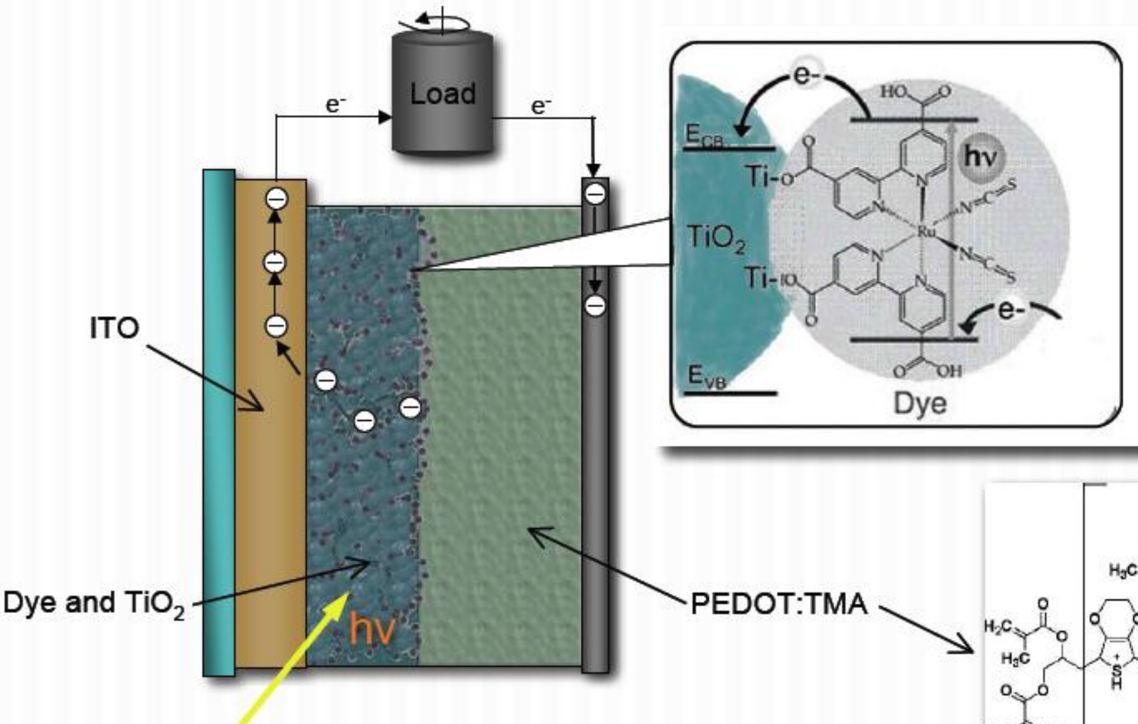
- ruthenium metal organic complex
- carboxylic acid functionalized porphyrin arrays

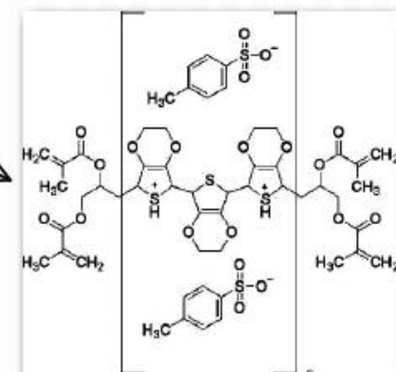




- Dye molecules are hit by light
- Electrons in the dye are transmitted to TiO_2.
- The electrons are collected by front electrode and supplied to external load.
- Dye molecules are electrically reduced to their initial states by electrons transferred from redox couple in the electrolyte.
- The oxidized ions in the electrolyte, diffuse to the back electrode to receive electrons

Dye-sensitized, hole-conducting polymer cell



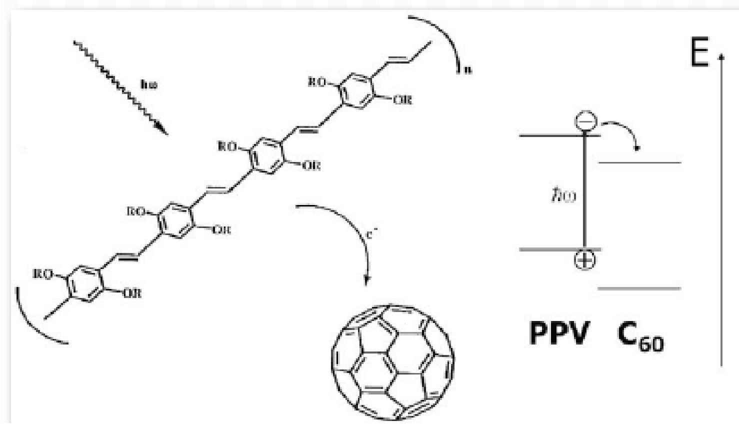


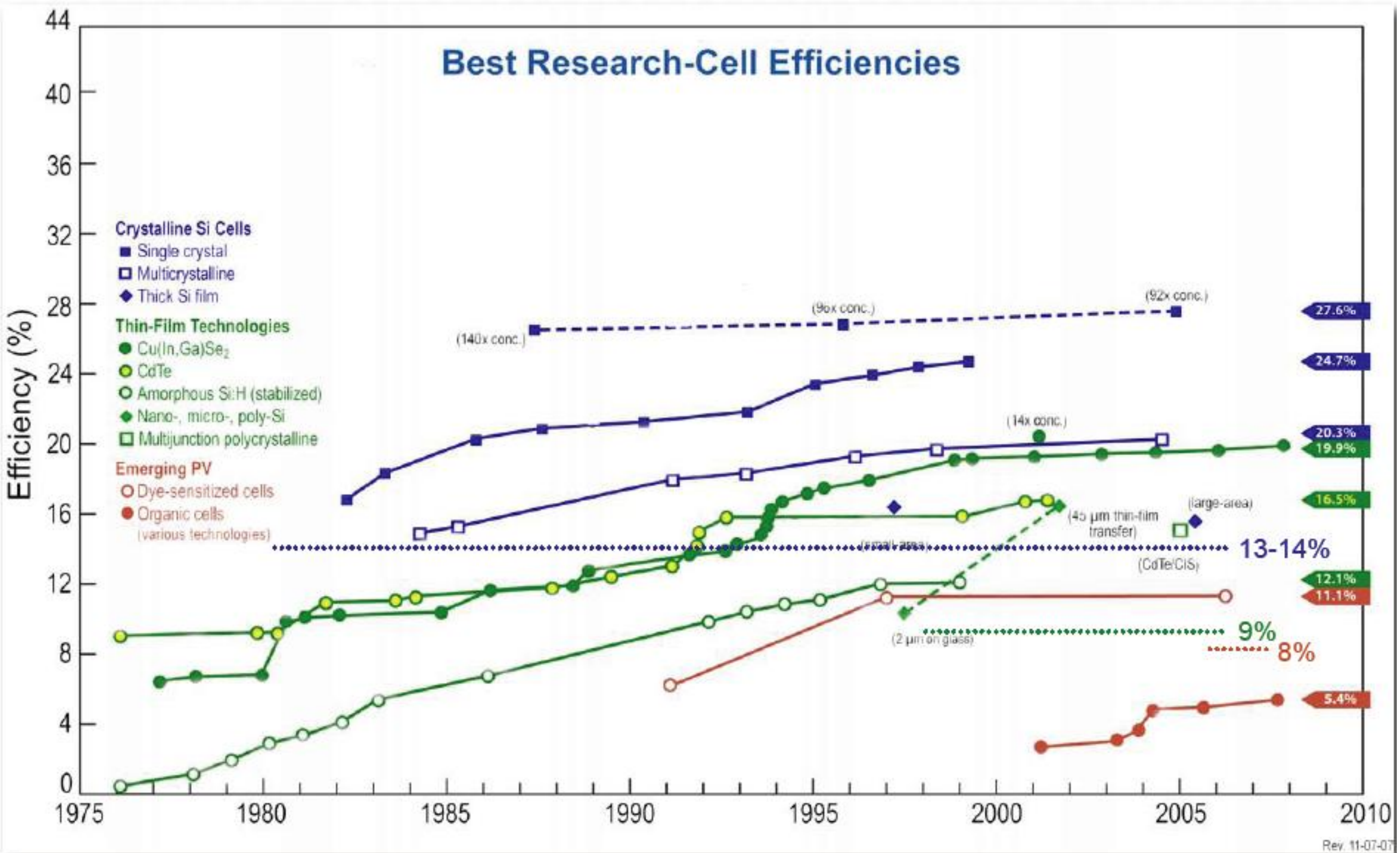
The scheme of DSSC.

- PET - Polyethylene Terephtalate
- ITO - Indium Tin Oxide
- PEDOT:TMA - Poly(3,4-ethylenedioxythiophene)-tetramethacrylate

Polymer solar cells

- 'Bulk heterojunctions' between an organic polymer and organic molecule as electron acceptor.
- Fullerene embedded into conjugated polymer conductor
- Lightweight, disposable, inexpensive to fabricate, flexible, designable on the molecular level, and have little potential for negative environmental impact.
- Present best efficiency of polymer solar cells lies near 5 percent
- Cost is roughly one-third of that of traditional silicon solar cell technology
- Band gaps ≥ 2eV

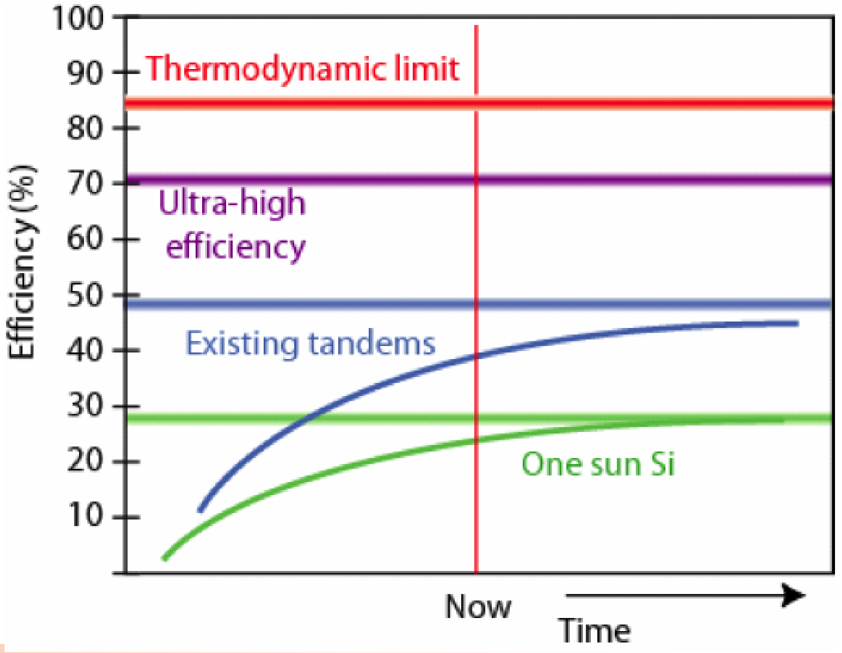




Best Research-Cell Efficiencies
Efficiency (%)
Crystalline Si Cells
Single crystal
Multicrystalline
Thick Si film
Thin-Film Technologies
Cu(In,Ga)Se2
CdTe
Amorphous Si:H (stabilized)
Nano-, micro-, poly-Si
Multijunction polycrystalline
Emerging PV
Dye-sensitized cells
Organic cells
(various technologies)
(140x conc.)
(96x conc.)
(92x conc.)
(14x conc.)
(45 μm thin-film transfer)
(large-area)
(CdTe/CIS)
(small-area)
(2 μm on glass)
27.6%
24.7%
20.3%
19.9%
16.5%
13-14%
12.1%
11.1%
9%
8%
5.4%
44
40
36
32
28
24
20
16
12
8
4
0
1975
1980
1985
1990
1995
2000
2005
2010
Rev. 11-07-07

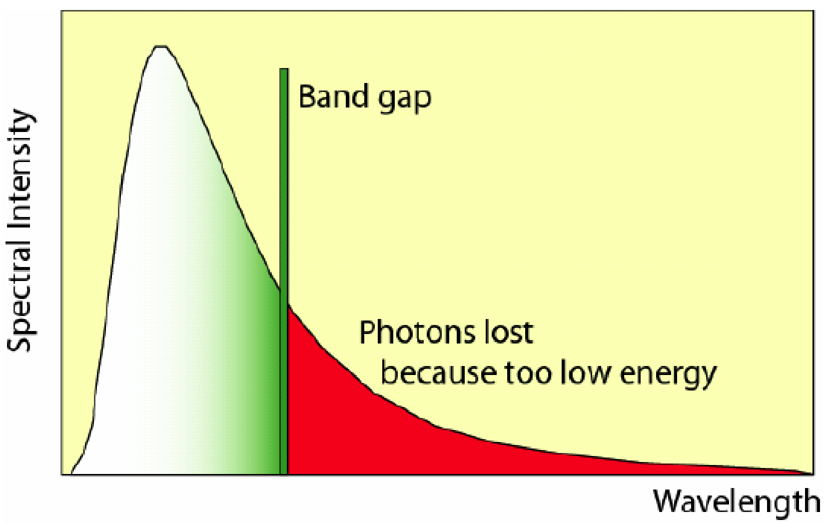
Towards Higher Efficiency Photovoltaics

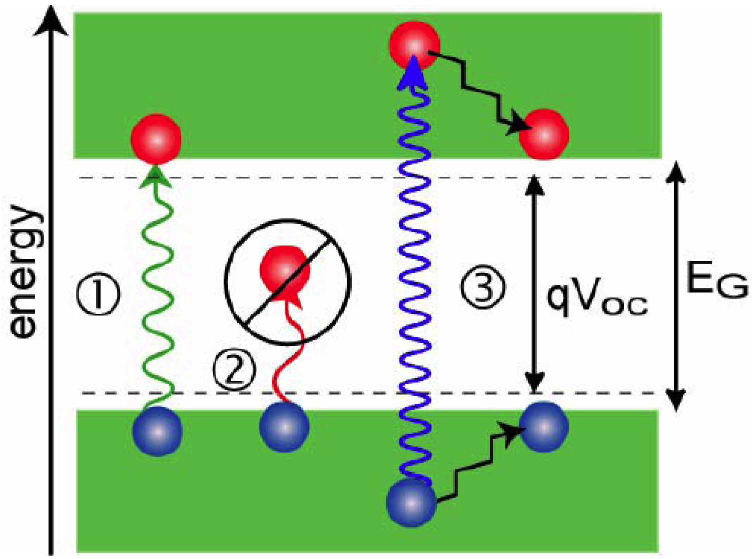
- Solar cells efficiencies have developed from relatively low values to approaching their efficiency limits.
- Single junction solar cells: ~25% in silicon and GaAs
- Multiple junction tandem: ~37% for three-stack tandem under concentration.
- Corresponds to ~85% of the theoretical limit for single junction solar cells
- Concentrators and tandems have reached ~70% of their material-imposed limits.

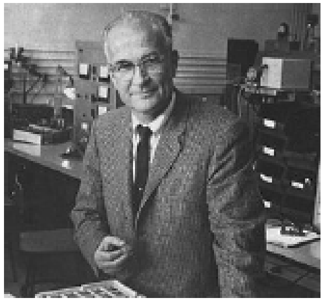


Limits to to Detailed Balance (the Shockley-Queisser Limit)

- Solar cell losses primarily arise from large range of photon energies in incident spectrum and ability to only utilize energy = band gap.
- Detailed balance calculations quantify these losses, giving single junction efficiency = 30.8% under one sun and 40.8% under max concentration.
- Ultra-high efficiency (sometimes called 3rd Generation) approaches are solar cells which can exceed the single-junction efficiency limit.







The Shockley-Queisser limit

- The Shockley-Queisser limit is a measure of the upper obtainable efficiency of a perfect solar cell based on only one solar cell material with only one electronic band gap.

  - Main assumptions:
    - All photons incident on cell captured
    - Complete absorption of all photons with $E > E_g$
    - Complete thermalization occurs
    - Lossless transport and collection of charge carriers
    - Ideal materials: Only Auger or radiative recombination

- The very best homo-junctions can in principle reach ~33%
- The efficiency limit of a perfect Si homo-junction solar cell is ~ 30%

The Shockley-Queisser limit

- Upper limit for homo-junction efficiency: **33%**
- Where do the remaining **67%** go?

Thermalization ($E > E_g$)	47%
Transmission ($E < E_g$)	18.5%
Recombination	1.5%
Remaining efficiency	33%
Total	100%

Multiple Junction Approaches to High Efficiency

- Multiple junction (tandems) are first class of approaches to exceed single junction efficiency.
- To reach >50% efficiency, need ideal Eg 5-stack tandem or equivalent (assuming can reach ~80% of detailed balance limit).
- Tandem approach limited by existence of materials with suitable band gaps and which can be feasibly incorporated into a solar cell or system.

# 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%

Detailed balance calculations for concentration ratio = 500X

n	*Values of Band Gap (eV)*	*η %*
4	0.60, 1.11, 1.69, 2.48	62.0
5	0.53, 0.95, 1.40, 1.93, 2.68	65.0
6	0.47, 0.84, 1.24, 1.66, 2.18, 2.93	67.3
7	0.47, 0.82, 1.19, 1.56, 2.0, 2.5, 3.21	68.9
8	0.44, 0.78, 1.09, 1.4, 1.74, 2.14, 2.65, 3.35	70.2

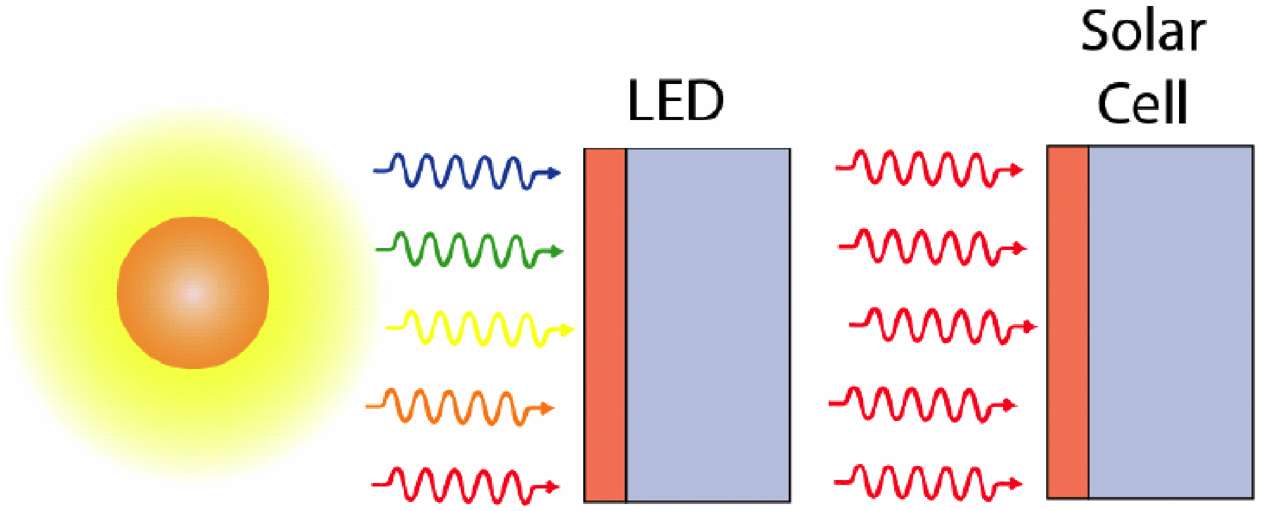
Other Approaches to High Efficiency

- Approaches other than tandems determined by examining assumptions in conventional detailed balance and calculating efficiencies by generalized detailed balance.
- Assumptions in conventional detailed balance:
  2. Solar spectrum at a given concentration ratio
  3. One photon = one electron-hole pair
  4. One constant quasi-Fermi level separation
  5. Constant temperature

Efficiency can be increased to thermodynamic limits by tandems using approaches that circumvent the above assumptions.

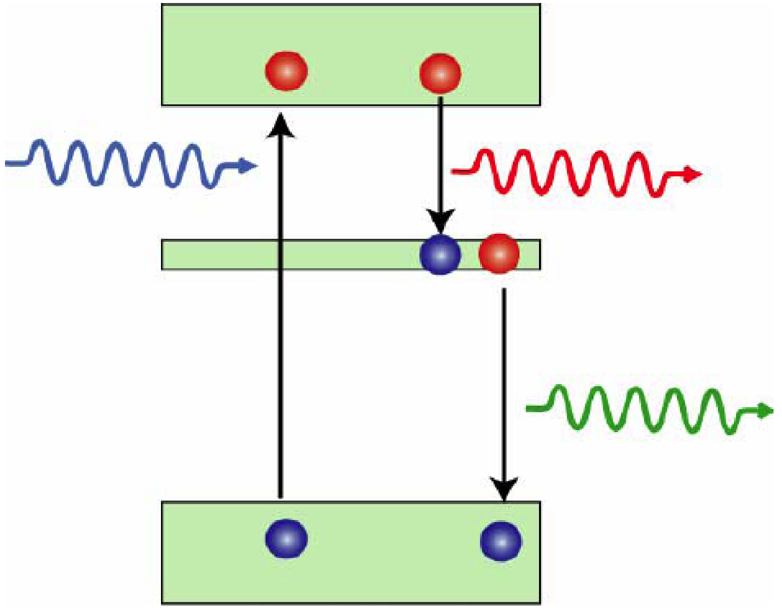
Multiple Spectrum Solar Cell Devices

- Multiple spectrum devices: take the input solar spectrum, and change it to a new spectrum with the same power density
  - Does not need to be incorporated into solar cell – can use existing solar cells, and add additional optical coatings
  - Approaches for multiple spectrum solar cells.
    - Thermophotonics: Use thermally-excited LED to generate a narrow solar spectrum



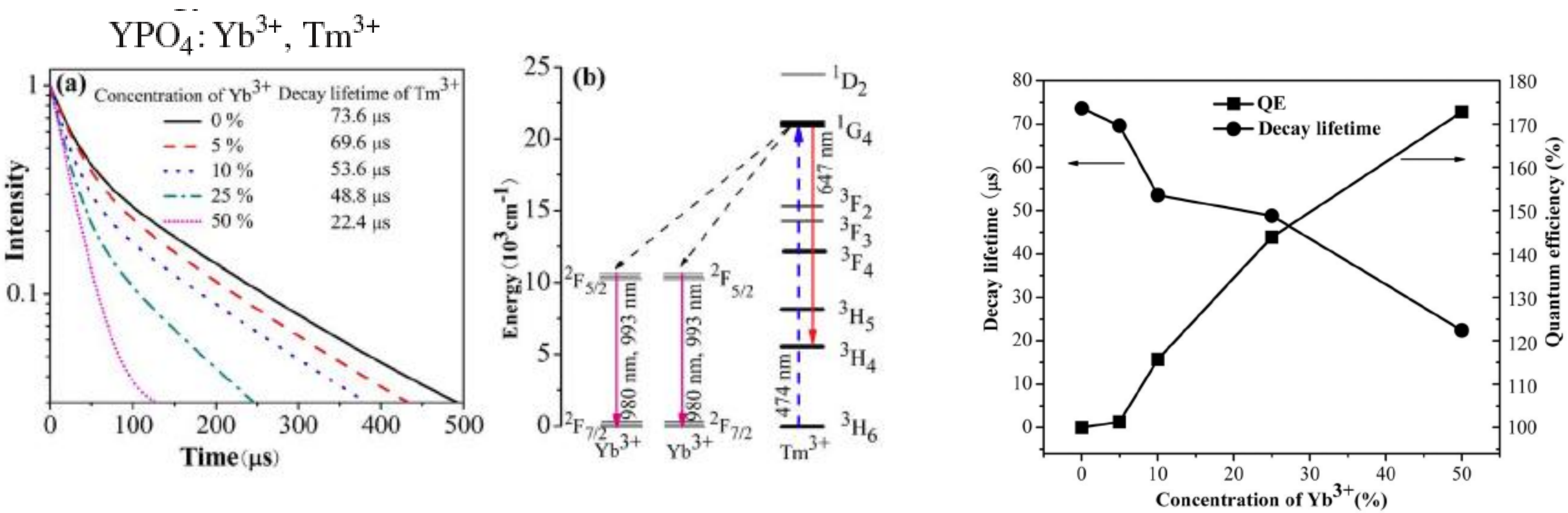
Multiple Spectrum Solar Cell Devices

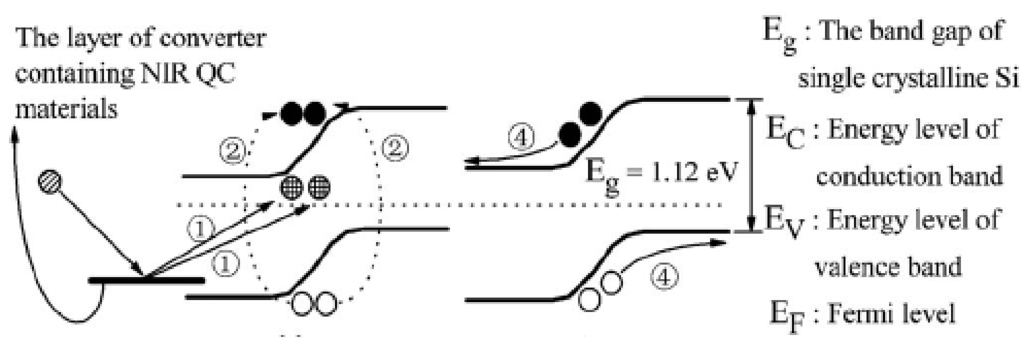
- Up/down conversion
  - Involves transformation of narrow regions of solar spectrum to higher or lower energies.
  - Substantial effort in developing efficient down conversion for other applications, eg phosphors.
  - Up/down conversion can be implemented by either material systems or by using approaches such as quantum wells and quantum dots.



Energy Down Conversion: Quantum Cutting

High energy photons create multiple lower energy photons





Other Approaches to High Efficiency

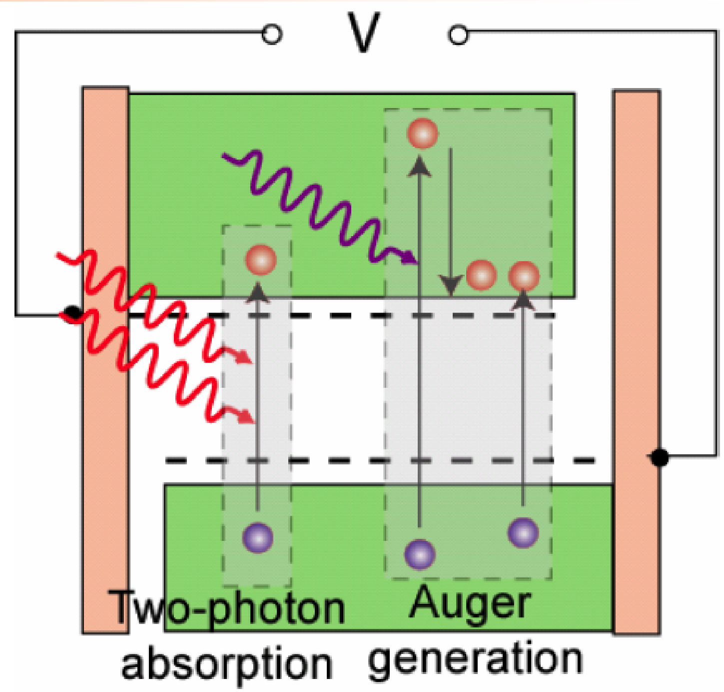
- Approaches other than tandems determined by examining assumptions in conventional detailed balance and calculating efficiencies by generalized detailed balance.
- Assumptions in conventional detailed balance:

2. Solar spectrum at a given concentration ratio
3. One photon = one electron-hole pair
4. One constant quasi-Fermi level separation
5. Constant temperature

Efficiency can be increased to thermodynamic limits by tandems using approaches that circumvent the above assumptions.

Multiple Exciton Generation and/or Two-Photon Absorption

- Change absorption mechanisms such that one photon ≠ one electron-hole pair
- Mechanisms include:
  - Two-photon absorption
  - Impact ionization/Auger generation
- Issues:
  - Effects low in bulk materials
  - Both effects can be made larger in quantum-confined structures
  - Energy threshold for impact ionization affects potential efficiency.
  - For E_{th} = 3Eg (experimentally demonstrated from nanocrystal quantum dots), detailed balance efficiency = 48%, similar to a two junction tandem.



Other Approaches to High Efficiency

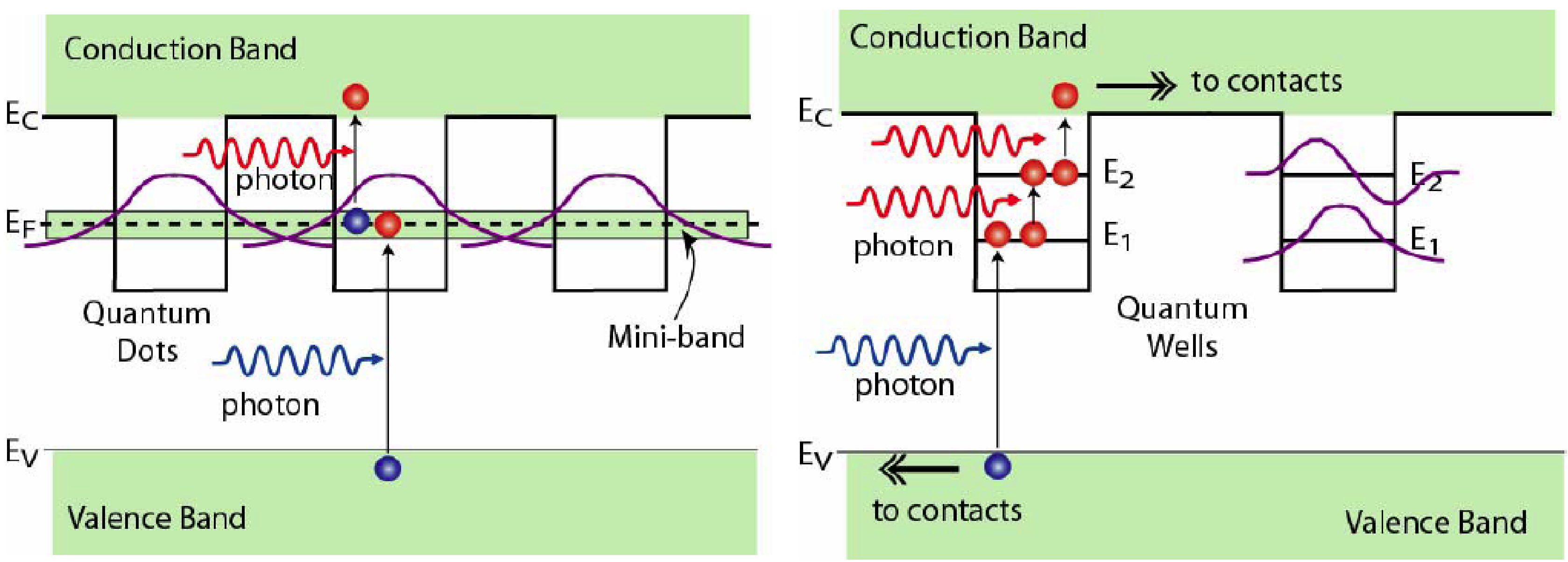
- Approaches other than tandems determined by examining assumptions in conventional detailed balance and calculating efficiencies by generalized detailed balance.
- Assumptions in conventional detailed balance:

2. Solar spectrum at a given concentration ratio
3. One photon = one electron-hole pair
4. One constant quasi-Fermi level separation
5. Constant temperature

Efficiency can be increased to thermodynamic limits by tandems using approaches that circumvent the above assumptions.

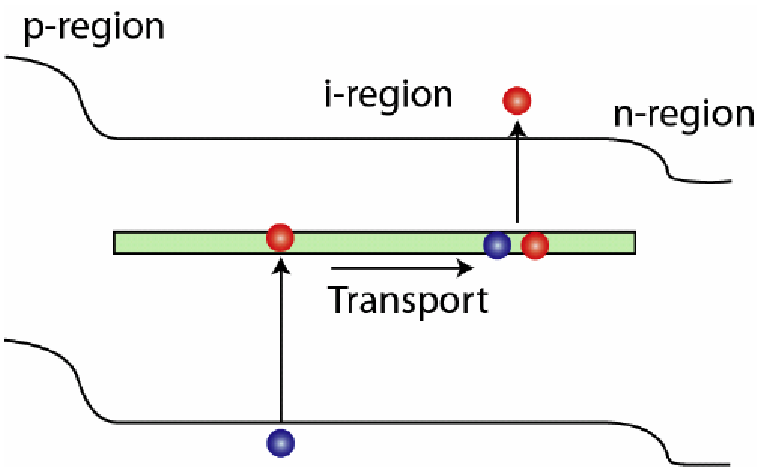
Extracting Higher energy electrons

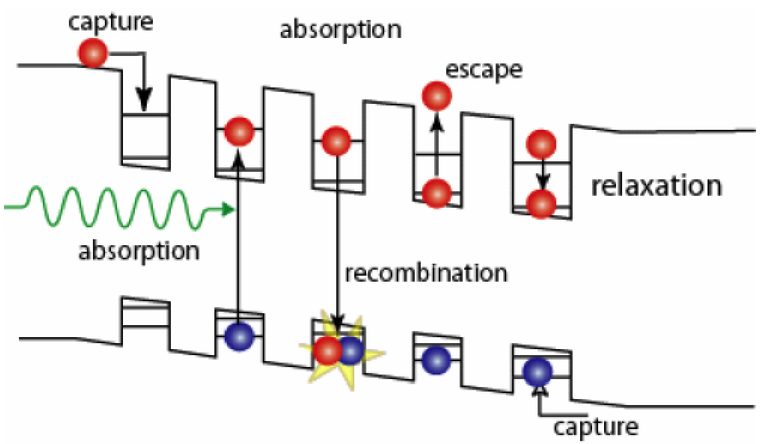
- Introduce more than a single quasi-Fermi level separation by introducing additional energy levels or bands, such that extracted energy of photon ≠ energy of band gap
- Energy levels can be spatially localized (energy levels) or interacting to form mini-bands.



Extracting Higher energy electrons

- Difference between two is transport of carriers.
  - In mini-bands, carriers must not thermalize from one band to another – must use quantum dot approaches.
  - Localized energy levels: transport requires that collection or escape time less than recombination time.





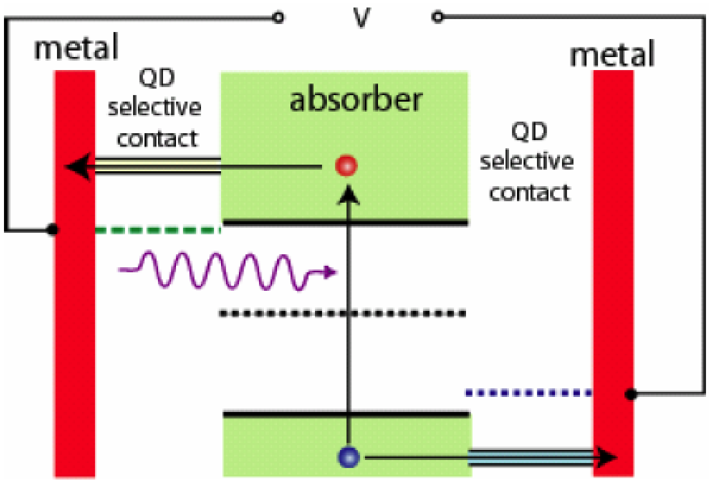
Other Approaches to High Efficiency

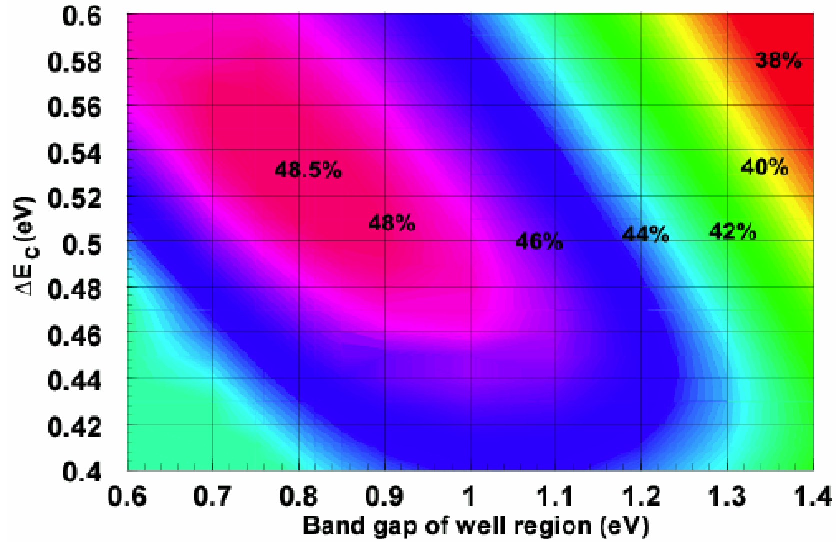
- Approaches other than tandems determined by examining assumptions in conventional detailed balance and calculating efficiencies by generalized detailed balance.
- Assumptions in conventional detailed balance:

2. Solar spectrum at a given concentration ratio
3. One photon = one electron-hole pair
4. One constant quasi-Fermi level separation
5. Constant temperature

Efficiency can be increased to thermodynamic limits by tandems using approaches that circumvent the above assumptions.

- Multiple temperature solar cells extract energy from temperature differentials in solar cell.
- Possible that temperature differentials are lattice temperature differential, but requires materials with substantially different thermal conductivity than electrical conductivity.
- Easier to maintain a temperature differential in carrier temperature by introducing variations in the band structure.





How to get to > 50%?

- Efficiencies of ultra-high efficiency approaches
  - 1. Tandems: 5-6 junction tandems feasible.
  - 2. Multiple spectrum:
    - Generating narrow spectrum allows high efficiency.
    - Up/down conversion has issues with efficiency, making it suitable for moderate efficiency increase of existing cells.
  - 3. Multiple absorption path:
    - Existing mechanisms can achieve ~ 2 stack tandem assuming it can be transferred to ideal band gaps and other components are completely ideal.
    - Effect demonstrated in potentially low cost approach.

- 4. Multiple energy levels:
  - Mini-band approach can theoretically achieve 3-junction tandem efficiency assuming ideal band gaps.
  - Localized approaches can theoretically approach ∞ junction tandem.
- 5. Multiple temperature solar cells:
  - Get equivalent tandem with high number of junctions.
- What structures can be used?
  - Combine new approaches with tandem – get equivalent of ~ 9 junction tandems
  - Localized multiple energy level, multiple temperature

Physical mechanisms for new approaches

Approach	Match single junction efficiency	Ultra-high efficiency
Multiple Junction	N/A	New materials
Multiple Spectrum	No degradation in solar cell efficiency	Efficient, full spectrum conversion
Multiple Absorption Path	$V_{oc} \approx V_{oc}$ of solar cell without absorption	QE > 1 over substantial range of energy
Multiple Energy Level	No degradation in QE for high Eg	Extended QE and multiple quasi-Fermi level
Multiple Temperature	N/A	Demonstration of basic effect

- Several fundamental physical processes to be demonstrated, including improved impact ionization, identification of materials for all approaches, multiple quasi-Fermi levels, new thermal conversion processes.
- Implementation of ultra-high efficiency can be accomplished by:
  - New materials
  - Engineering of band structure using quantum-confinement

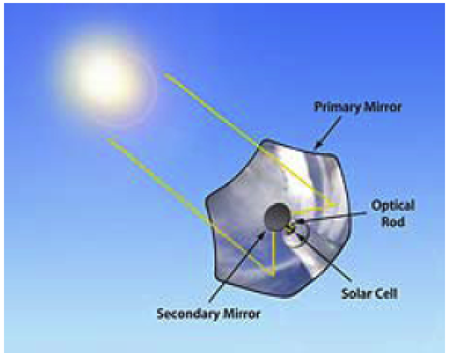
Concentrating photovoltaics (CPV)

- Concentrate direct sunlight onto solar cell.

\+ Less semi-conducting material necessary.

\- Tracking is necessary to keep the focal point upon the cell as the sun moves across the sky.

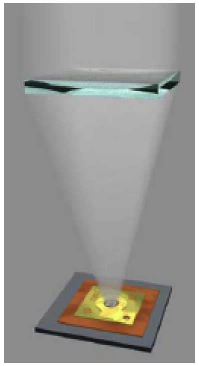
- Two main approaches: Metallic collectors and planar lens structures.



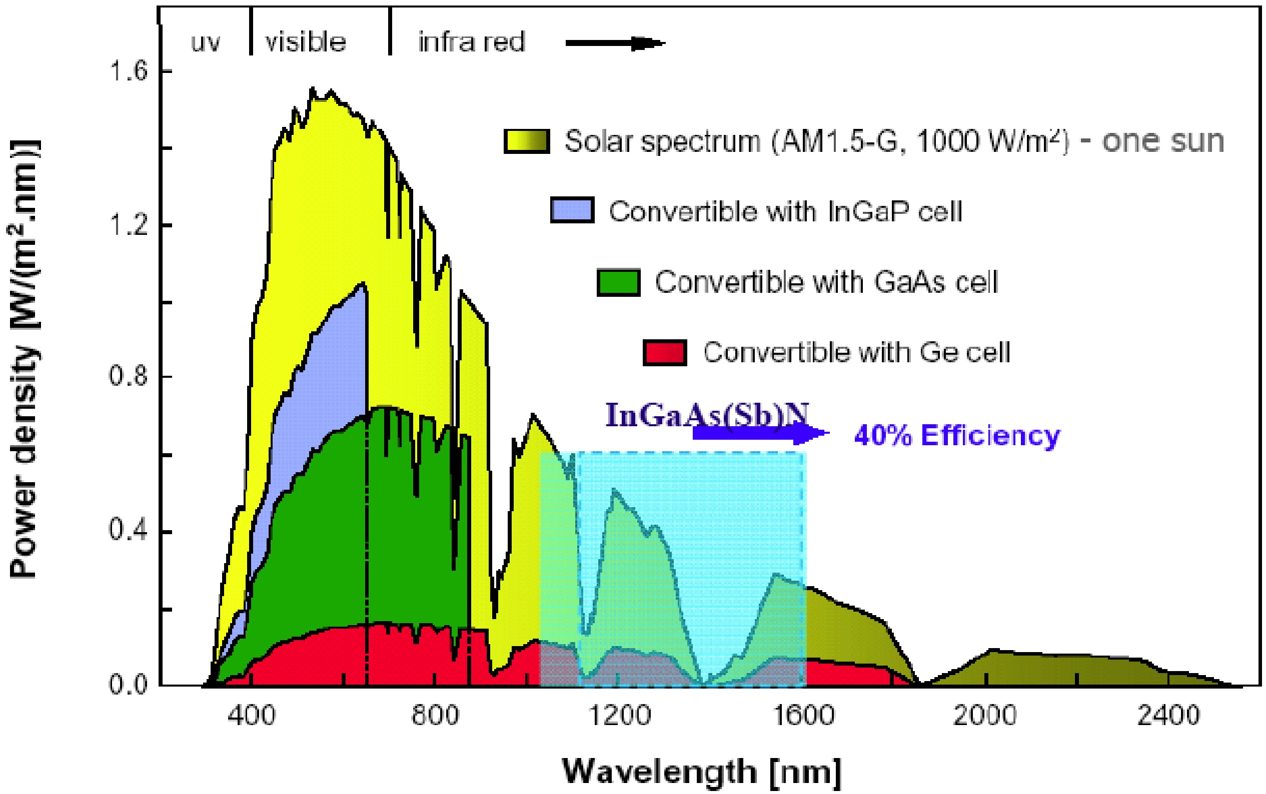
CVP principle


Tracking installation


Metallic solar concentrator


Fresnel concentrator

Fabrication of high efficiency triple-junction cells requires MBE

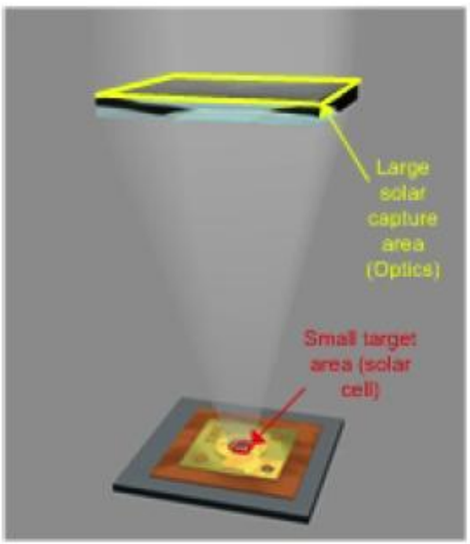


Introduction

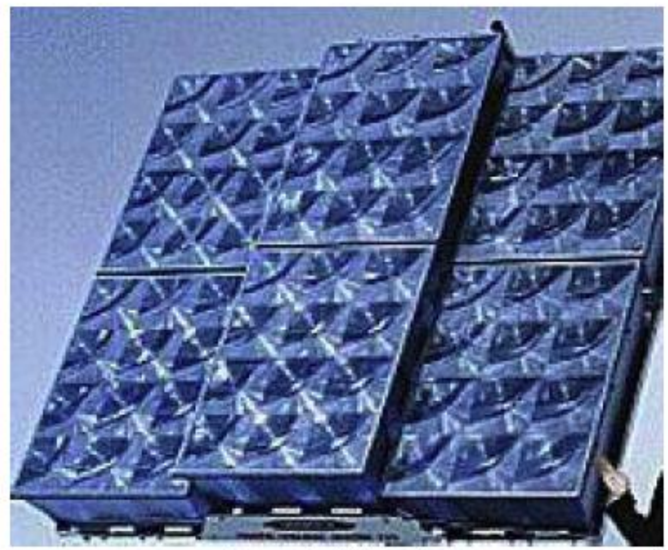
- **SolFocus:**
  - **Manufacturer of *Photovoltaic Concentrators (CPV)***
  - **3 ½ years old Silicon Valley startup**
  - **Combination VC, strategic backing ($100M)**
  - **Now 130 people**
  - **Product in test. 4 field sites (Ca, Hi, Az, Spain)**
  - **Preparing to ramp manufacturing**

What is CPV?

- Devices using optics to concentrate a LARGE area of sunlight on to a SMALL area of solar cell.
- Typical concentration ratios 150X – 500X – 1200X (some in 10x to 30x range)



- Image:Reuk Co



- Image: SunWind Solar

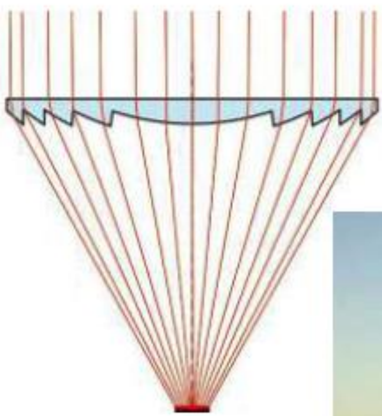
Why CPV?

- Most economical technology in areas of ***High Direct Radiation.***
  - Reduces use of expensive photovoltaic material with inexpensive optics
  - Uses established high volume industries for technology & methods (automotive, electronics)

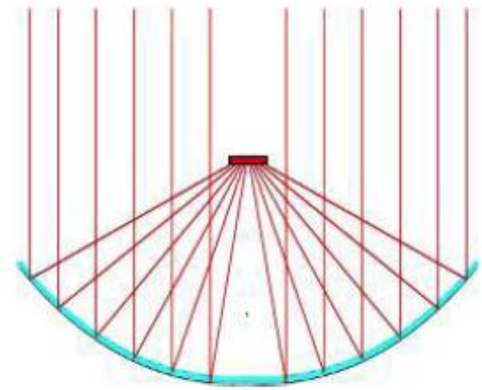
Solar Systems Pty Ltd

Two fundamental approaches

- Refractive: with lenses



- Reflective: with mirrors

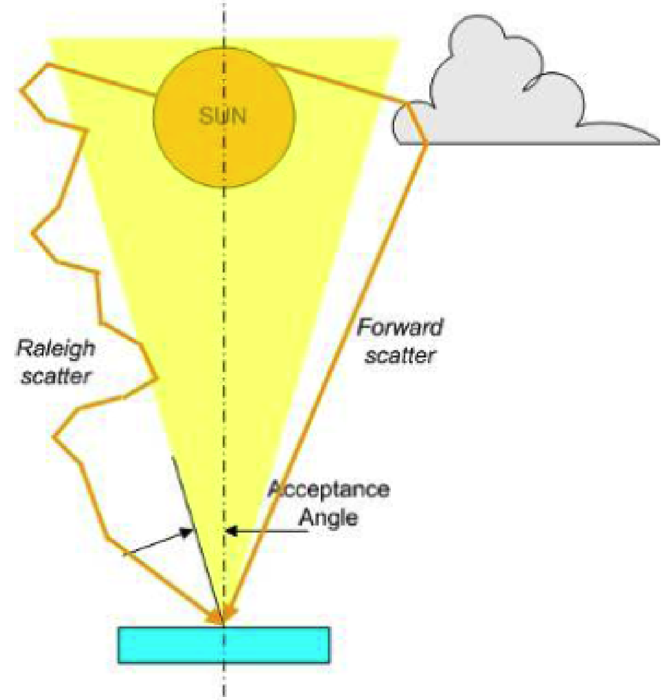


CPV characteristics

- **High power density**
  - Mid 20% efficiency now.
  - Over 33% with new generation cells
- **…but with Narrow Field of View**

- **CPV performs best in areas of high direct radiation, or "DNI"**
  - **Mediterranean climates**

    -close to 40% of the world's population centers



CPV characteristics

- **Scalable from hundreds of kW to GW**
  - CSP feasible in large project sizes only
  - Thin film: low to moderate sizes
  - Silicon: low to medium sizes

Other Concentrator Options:

- Luminescent Solar Concentrators
- Thermophotovoltaics