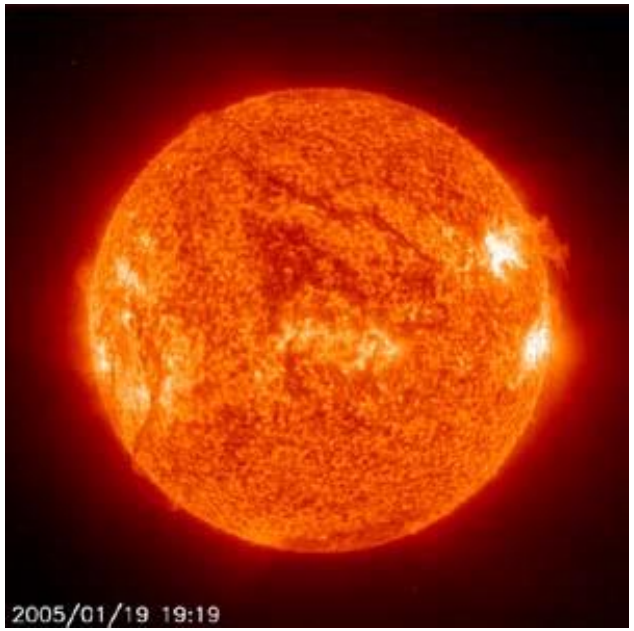
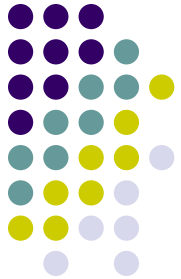
Photovoltaic Energy Conversion

Frank Zimmermann

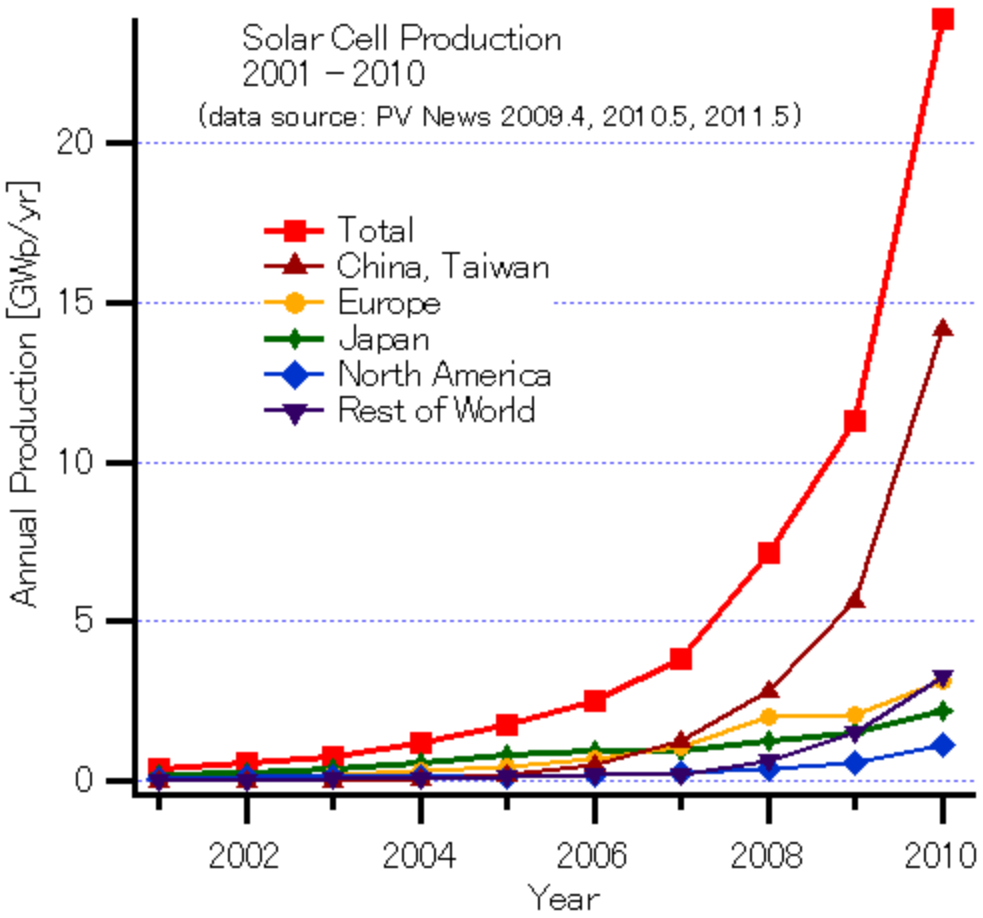


Solar Electricity Generation



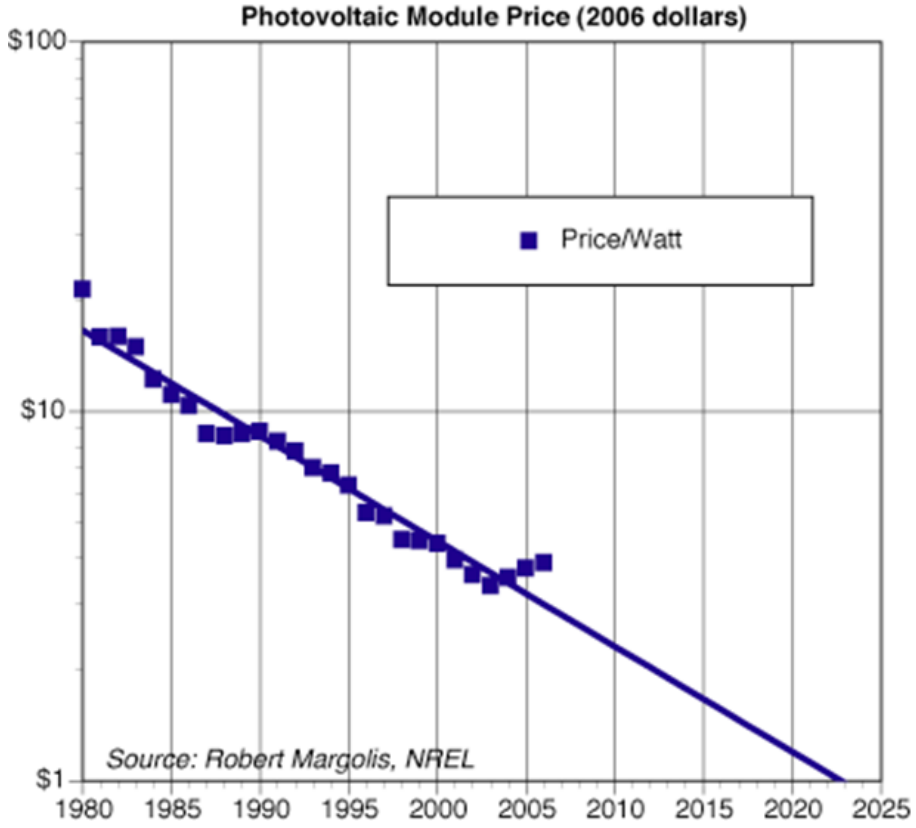
- Consumes no fuel
- No pollution
- No greenhouse gases
- No moving parts, little or no maintenance
- Sunlight is plentiful & inexhaustible
- Cost competitive with fossil fuels/nuclear. Cost coming down every year.
- Considerably cheaper than electricity from coal if cost of carbon capture is factored in
- Great promise for solving global warming ***and*** fossil fuel depletion problems!

Photovoltaics: Explosive Growth

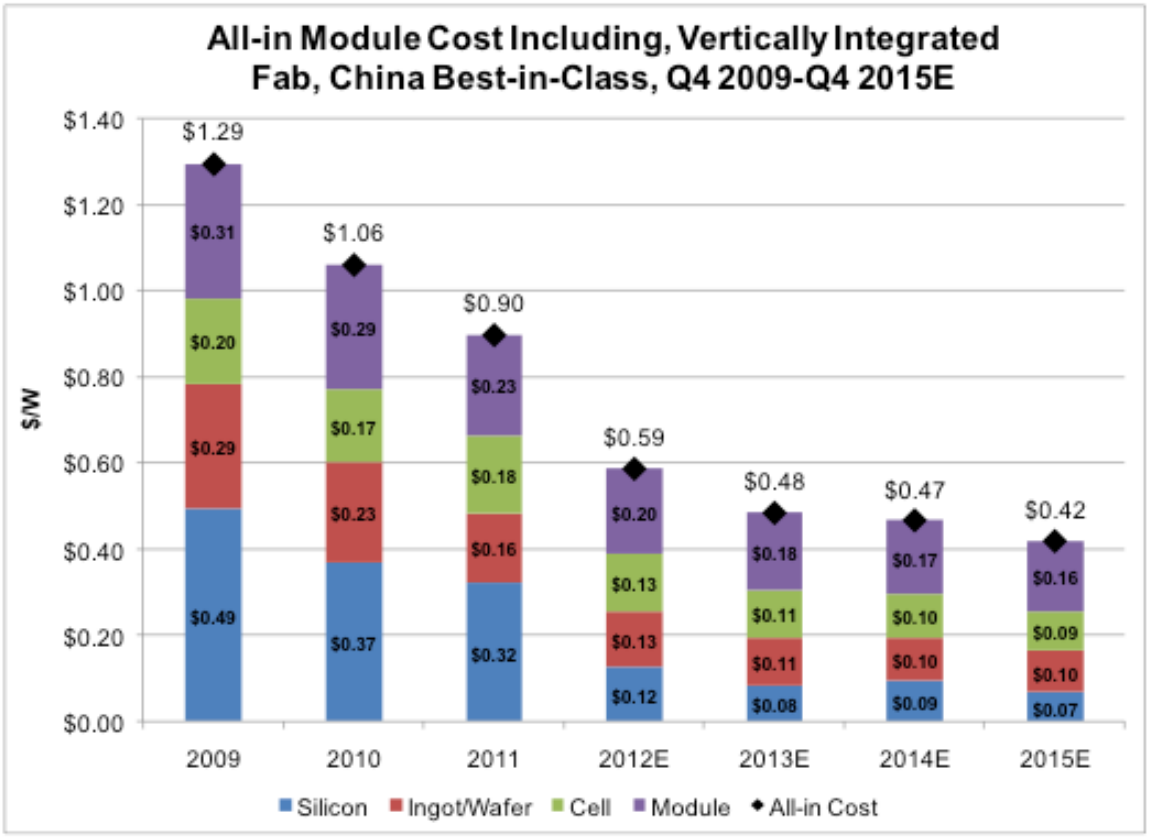


Sustained growth of 30 – 50 % per year

Extrapolation of historical PV module prices



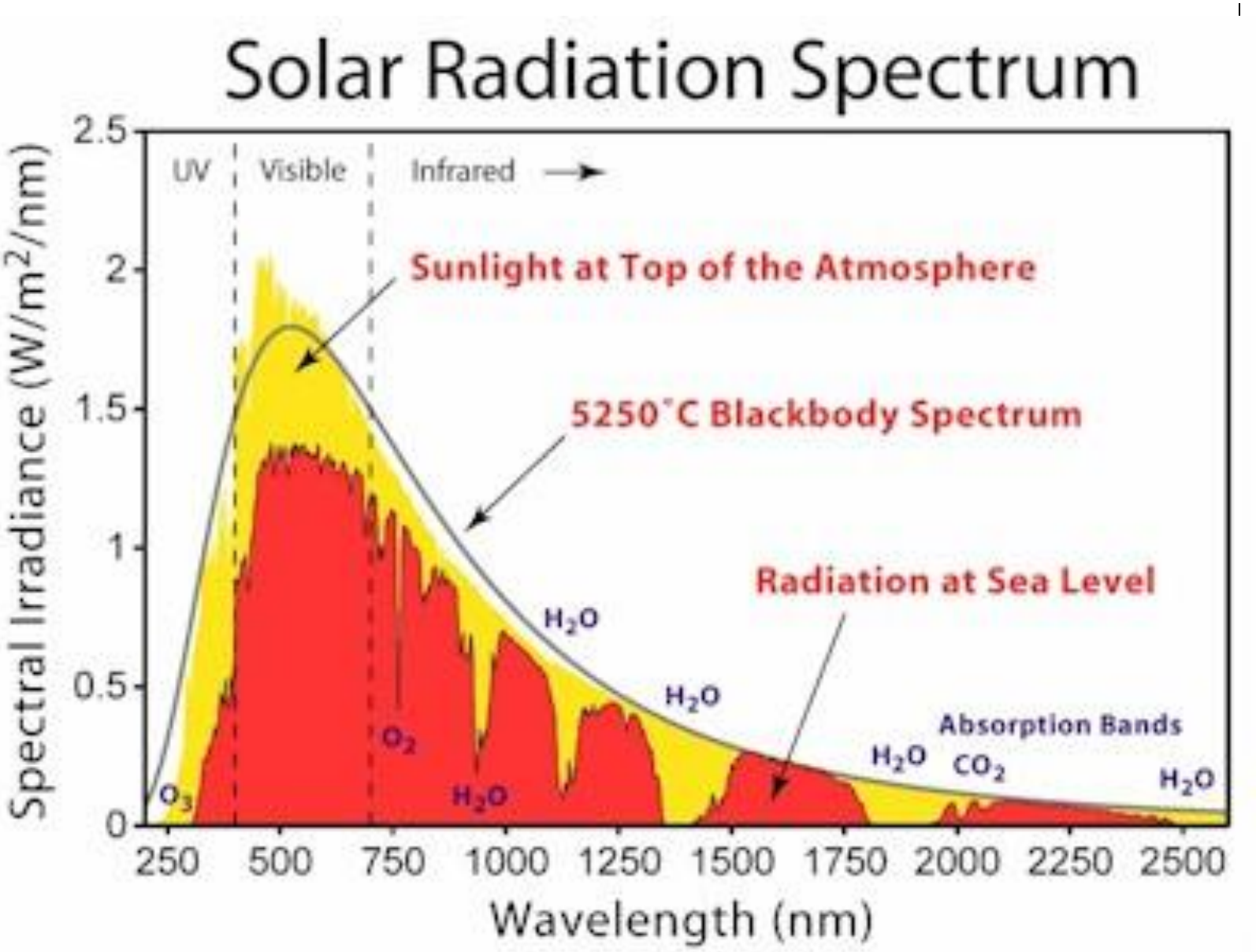
Actual 2013 PV Module Cost: ~ 50 cents/Watt!



“Grid Parity” has been reached in India, Italy, Spain, and other countries

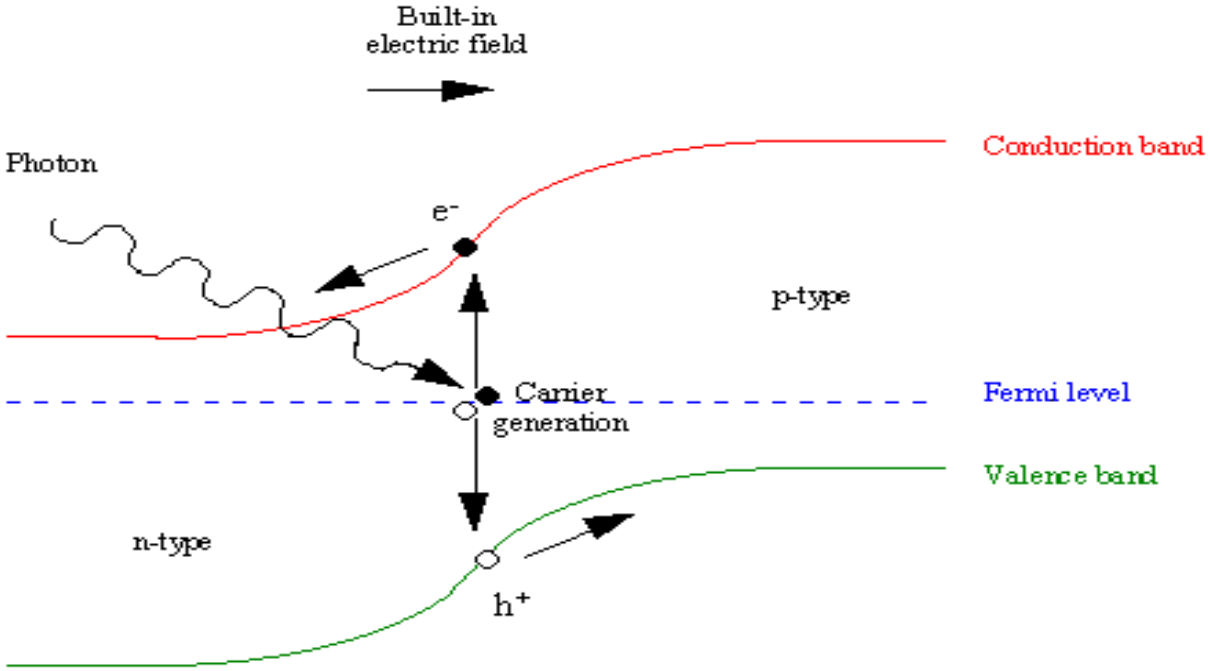
Challenges

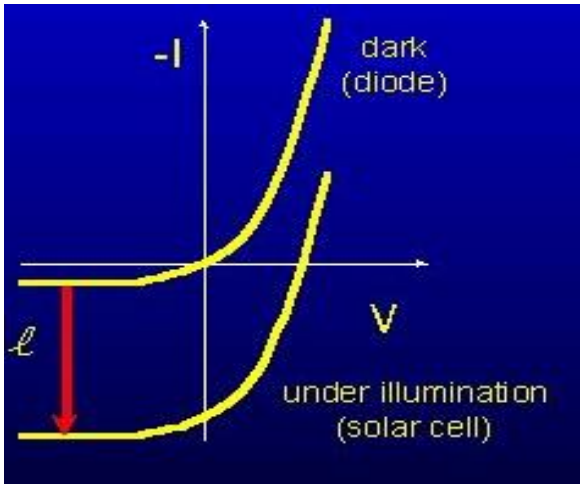
- Make solar cells more efficient
  - Theoretical energy conversion efficiency limit of single junction solar cell is 31%
  - Actual efficiencies are even lower: ≤ ~20%
- Make solar cells cheaper
  - “Grid Parity” has been achieved in some countries, others are soon to follow
- Require high reliability, long service life
- Use only abundant, nontoxic materials



- Power reaching earth 1.37 KW/m^2

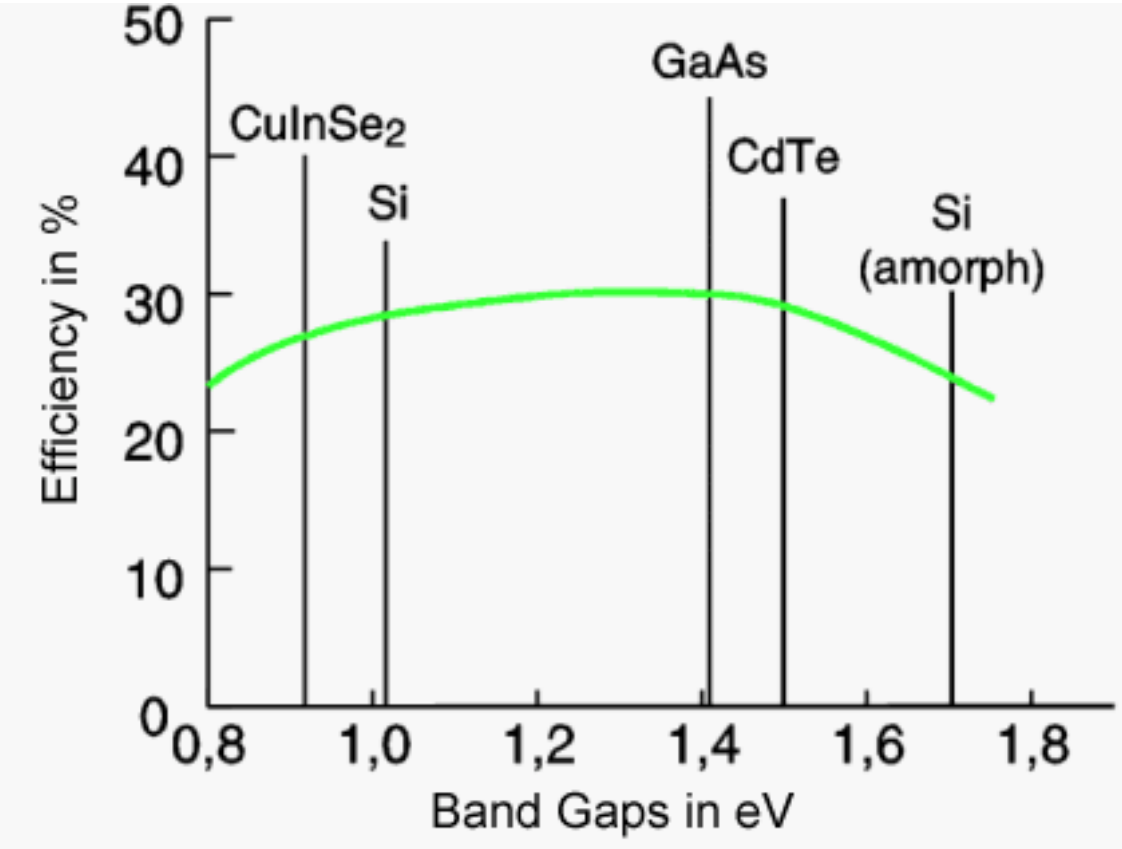
Solar cell – Working Principle





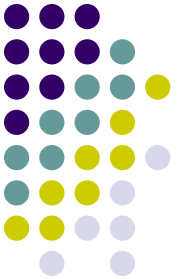
- Operating diode in fourth quadrant generates power

Semiconductor Bandgaps



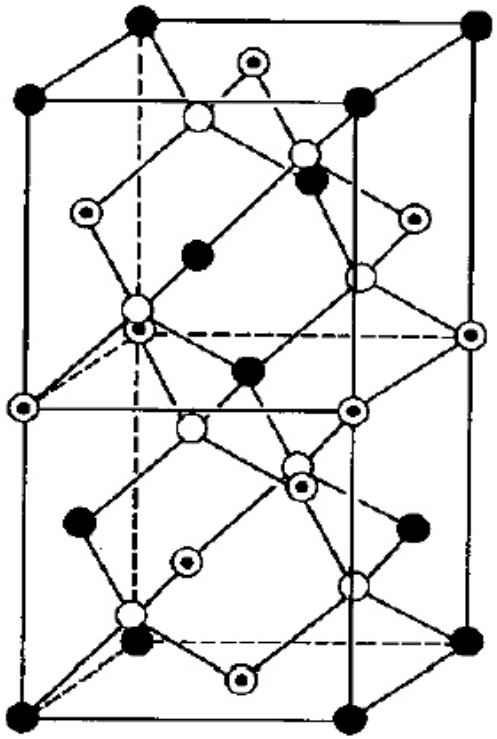
Crystalline silicon is by far the most important PV material.

Thin Film Solar Cells



- Produced from polycrystalline thin films
- Cheaper than single crystal silicon
- High optical absorption coefficients
- Bandgap suited to solar spectrum
- Poly-Si
- CdTe
- CIGS (Copper-Indium-Gallium-Selenide)
- Organic and Dye-Sensitized Solar Cells

$CuInSe_2$ (with Ga: "CIGS")



Chalcopyrite Structure

Direct Band Gap : 1 eV

High absorption coefficients (10^4 -10^5 cm^{-1})

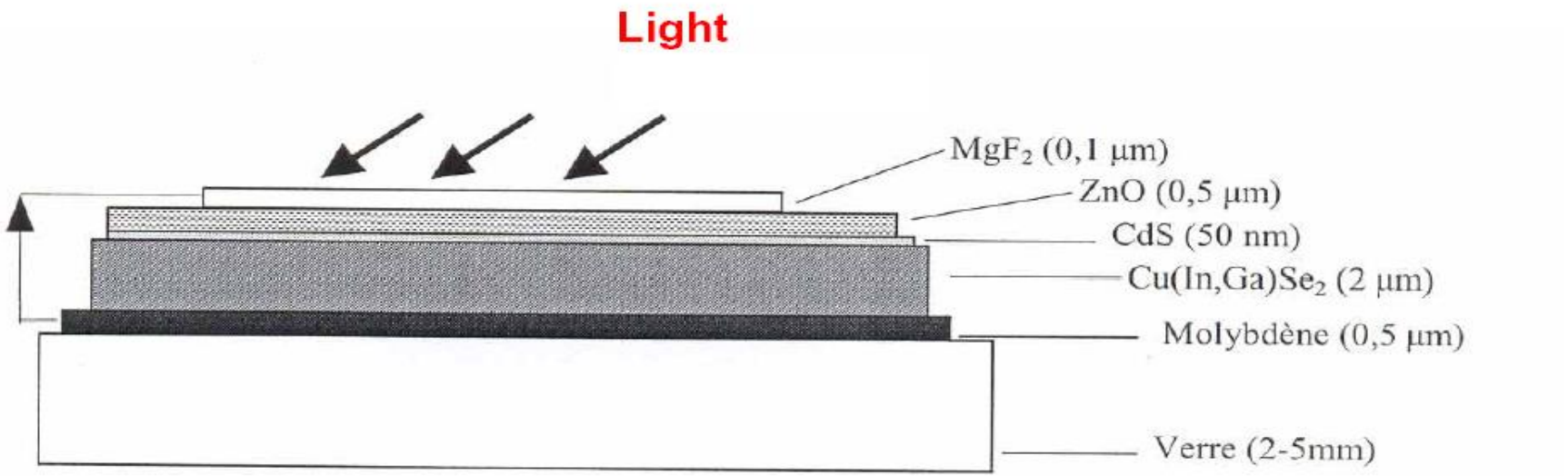
Thin film absorbers (1 -2 micron)

P type – n type

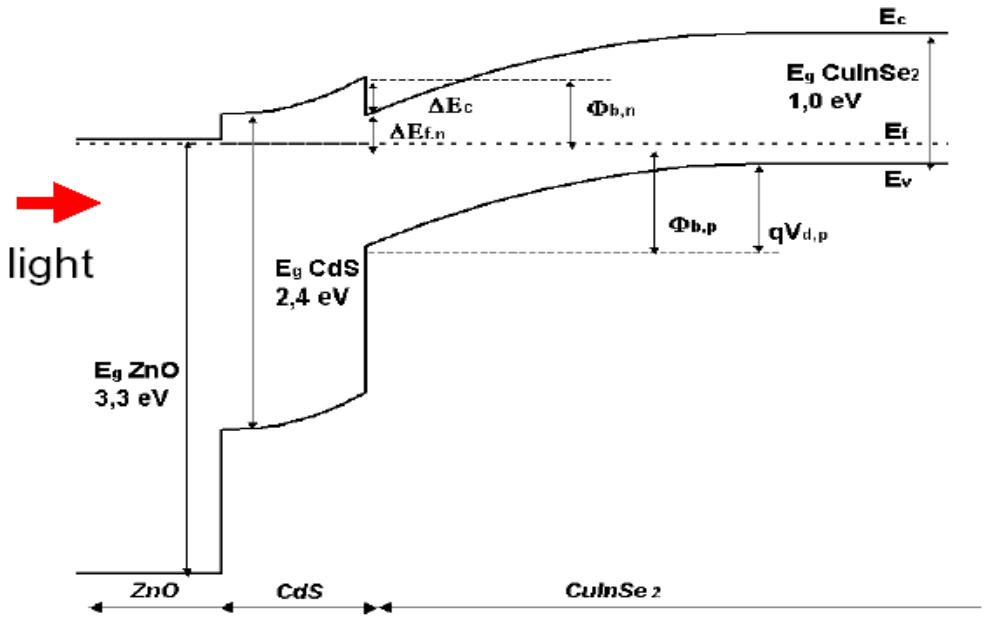
Tolerant to defects and grain boundaries

CIGS Solar Cell

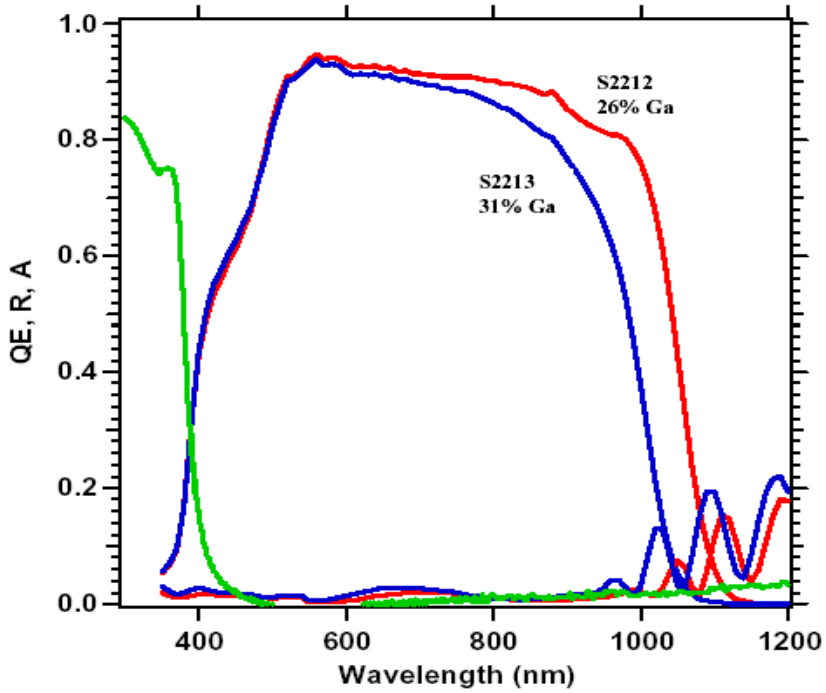
Structure of CIGS Thin Film Solar Cells



Band Diagram CIGS Solar Cell



Spectral response

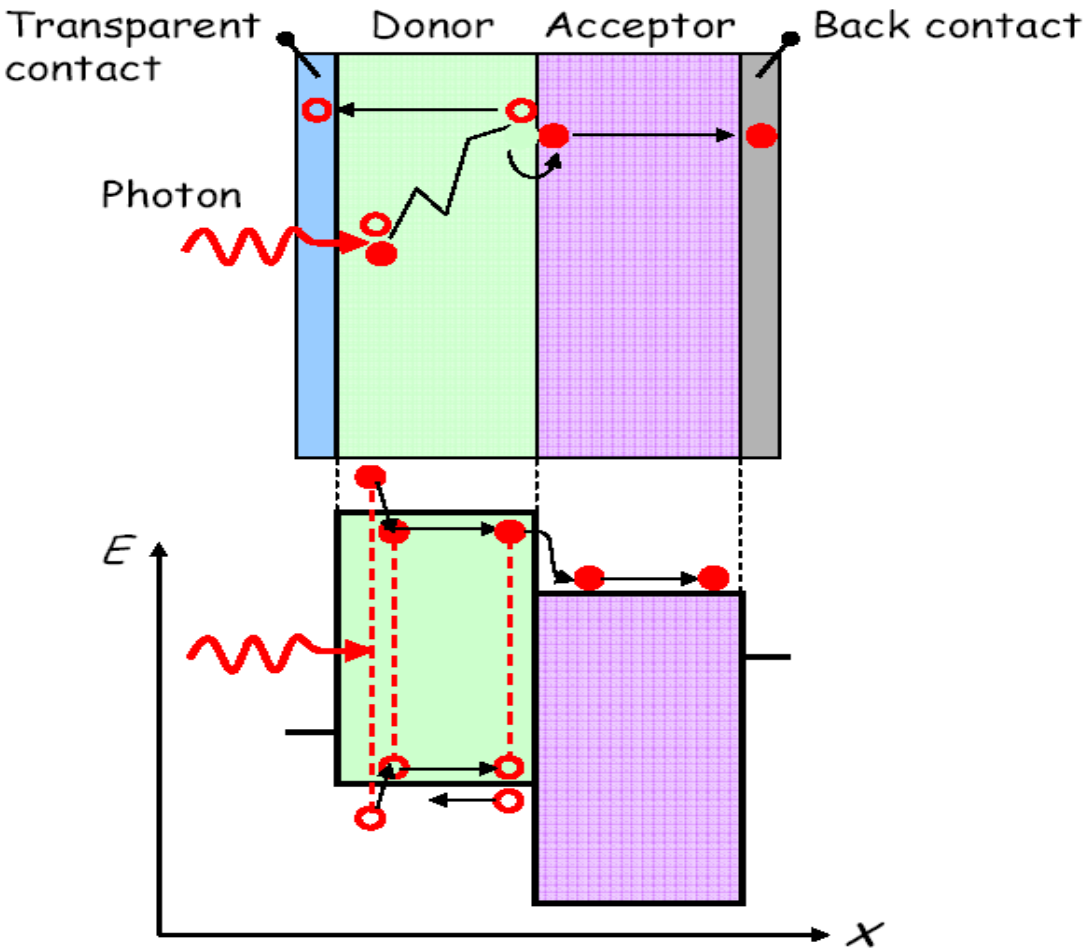


By Courtesy of Dr. K. Ramanathan et al., NREL, EMRS 2004

Organic Solar Cells

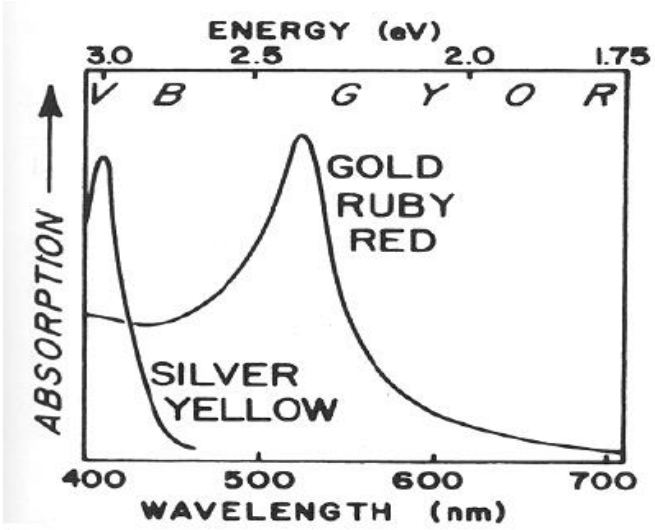
- A typical cell operation
  1. Photon absorption
  2. Exciton diffusion
  3. Charge transfer
  4. Charge separation
  5. Carrier collection

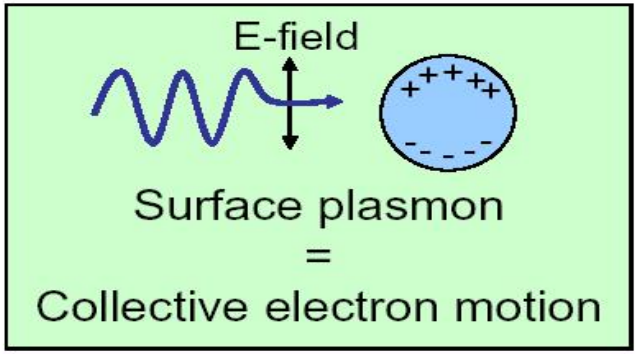
- Band diagram



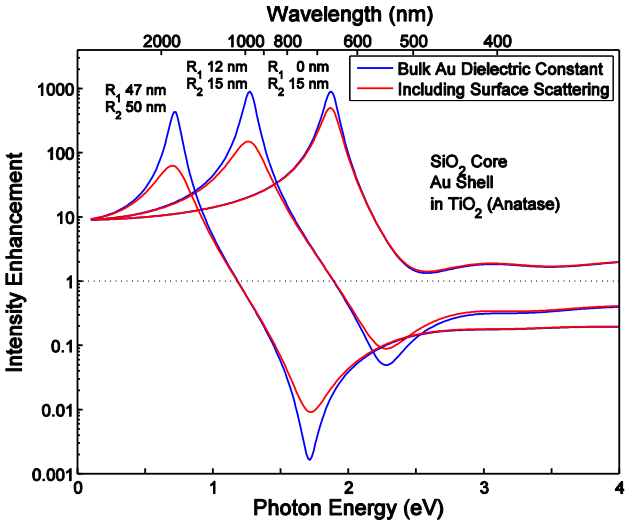
Plasmon Resonances of Metal Nanoparticles

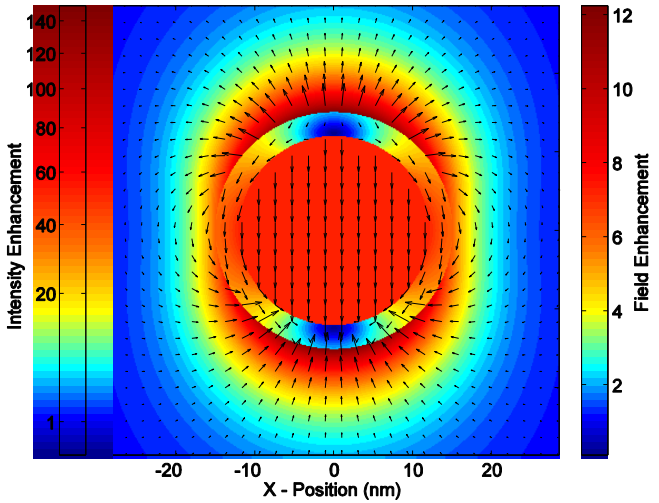
- Colorful Czech glass vase
- Ag nanoparticles cause yellow coloration
- Au nanoparticles cause red coloration

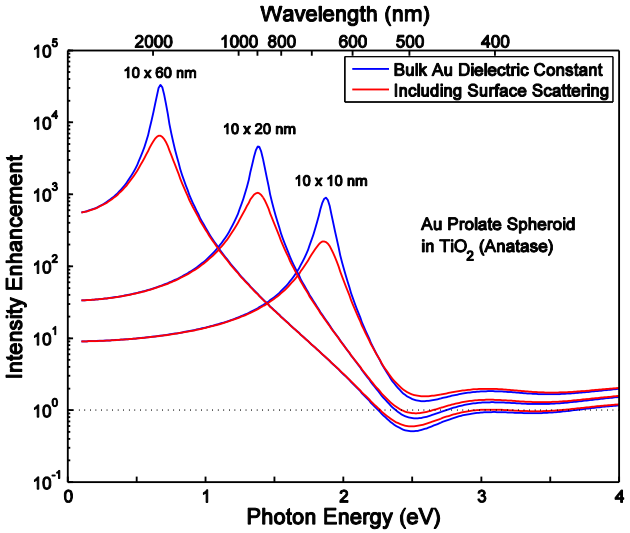


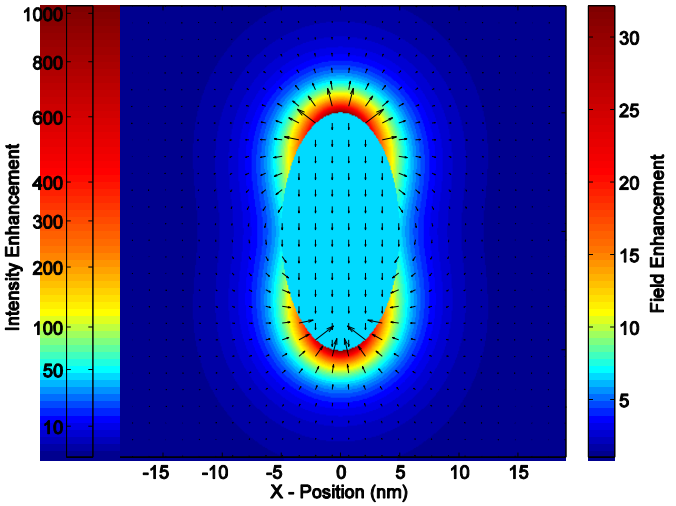


Plasmon Resonances of Metal Nanoparticles





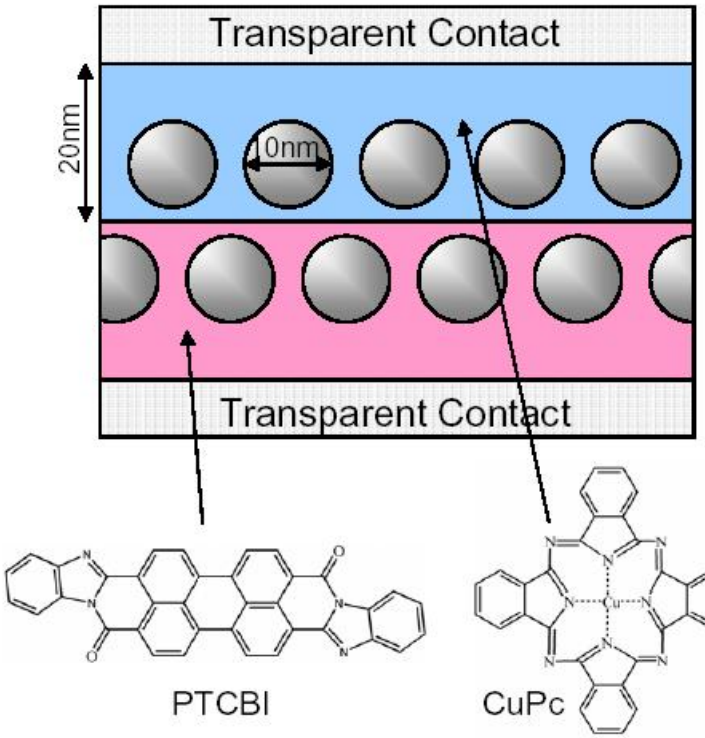




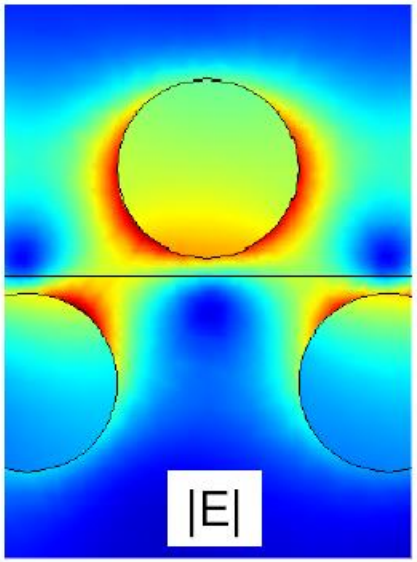
Light Concentration using Nanoparticle Plasmon Resonances

- Zig-zag configuration concentrates electromagnetic power at active junction

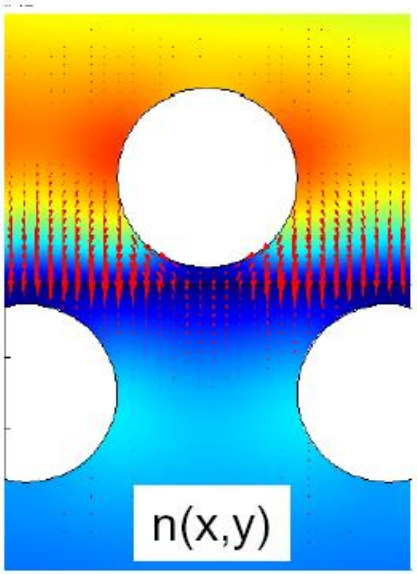
Geometry



Absorbed Power Density

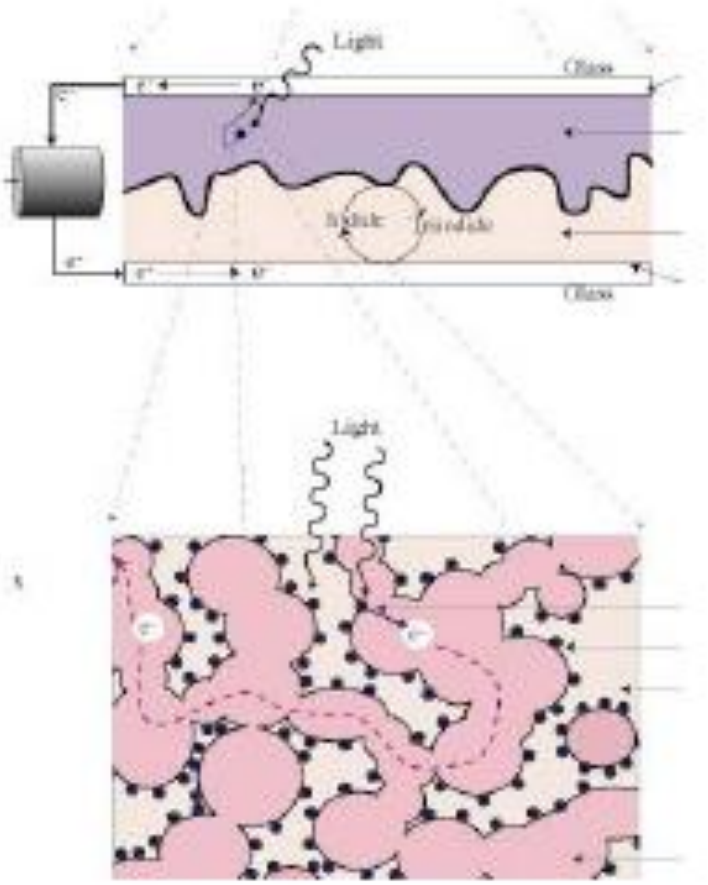


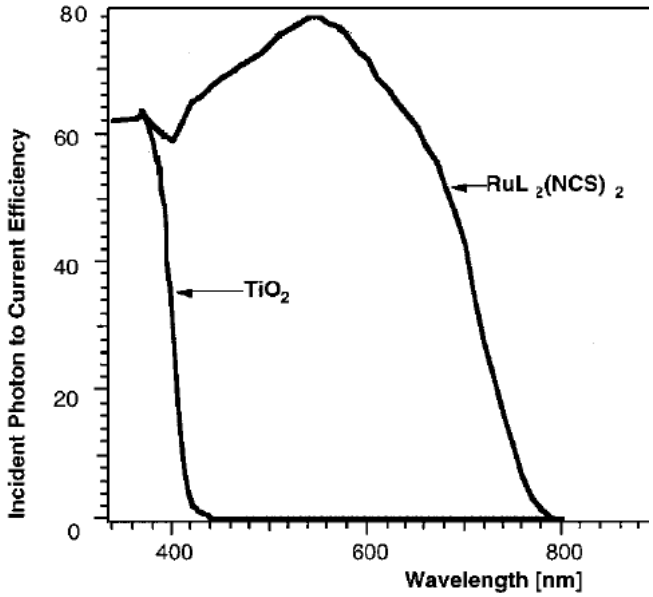
Exciton Density



Peumans group

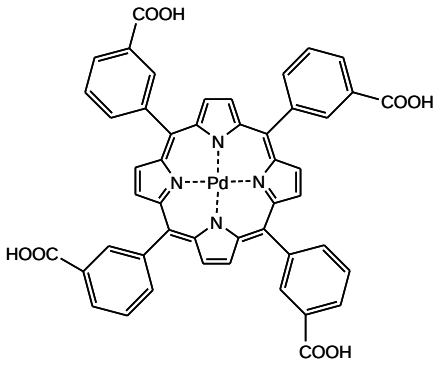
Dye Sensitized Solar Cells

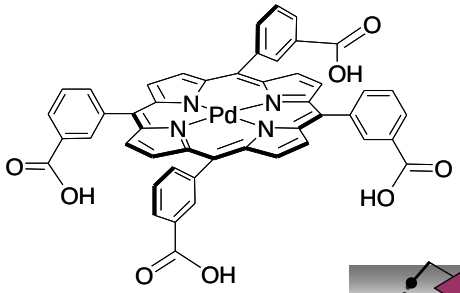


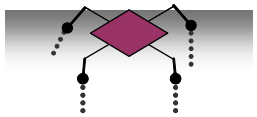


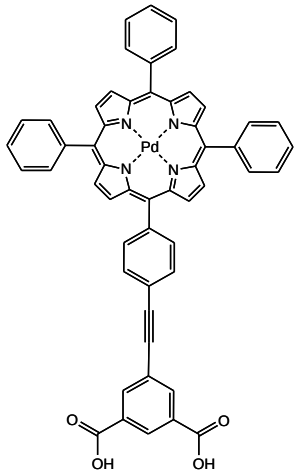
L = 4,4'-COOH-2,2'-bipyridine

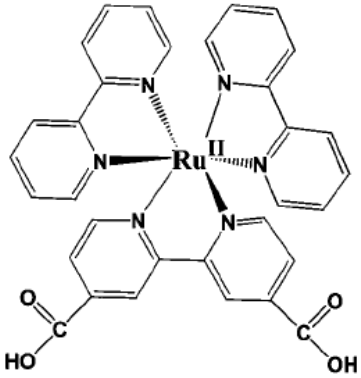
Dye Sensitizer Molecules

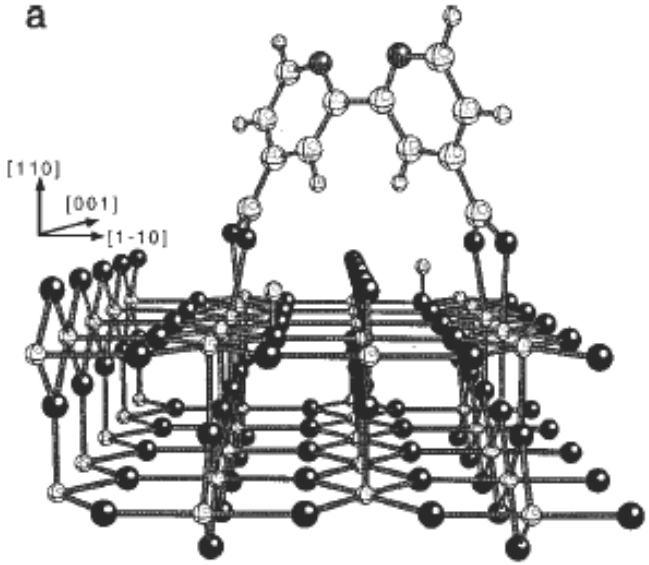






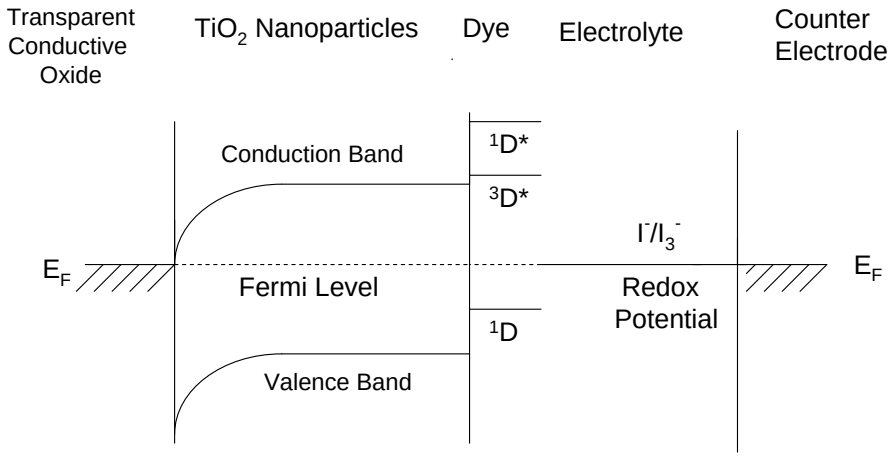




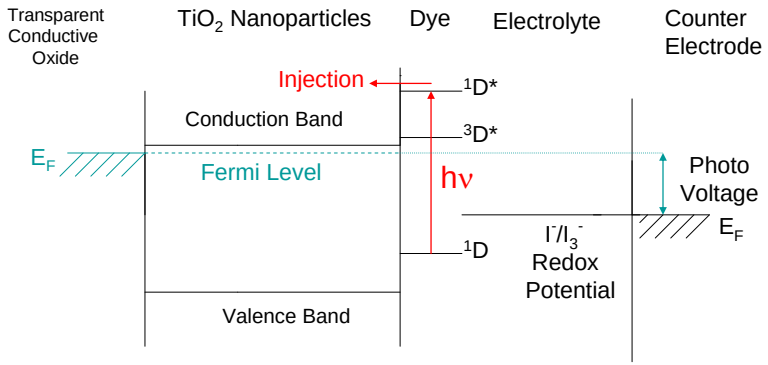


Dye Sensitized Solar Cells

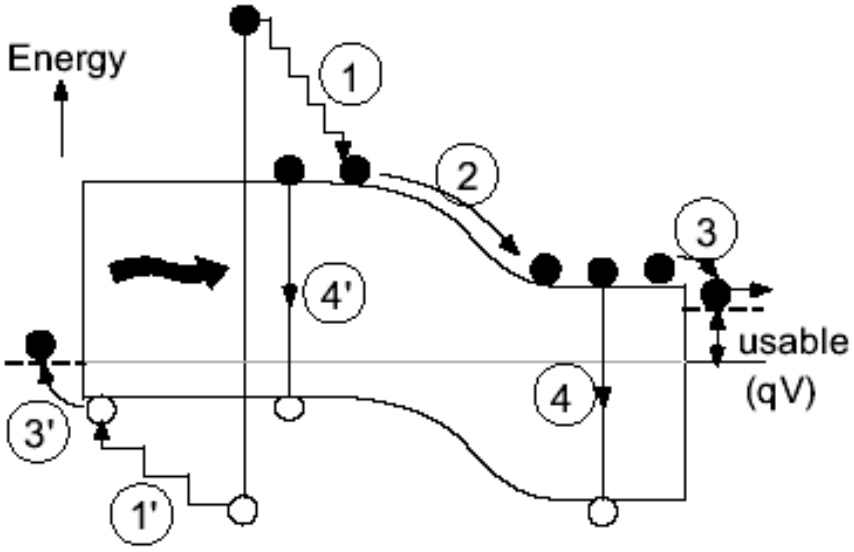
Energy Levels (Dark)

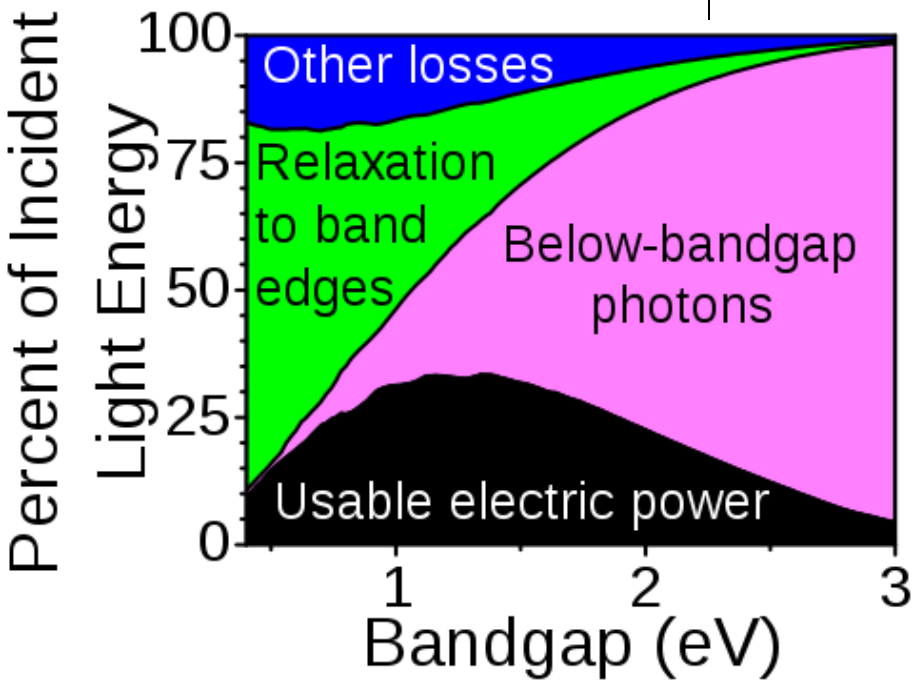


Energy Levels (Illuminated)



Efficiency Losses in Solar Cell





1 = Thermalization loss

2 and 3 = Junction and contact voltage loss

4 = Recombination loss

Conversion Efficiency Limits

- Thermodynamic limit:

  Carnot efficiency: $1 - \frac{T_c}{T_s} = 1 - \frac{300K}{6000K} = 0.95$

- Ultimate efficiency (T = 0) for single junction: 45%
- Detailed balance limit for single junction:

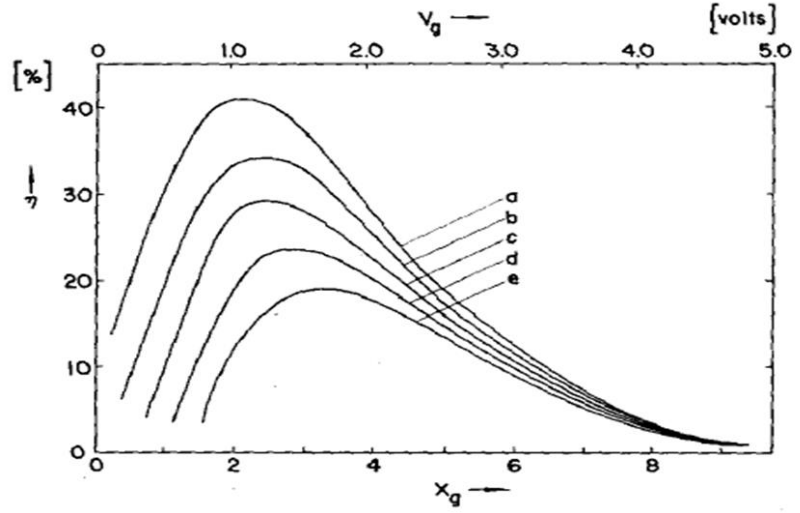
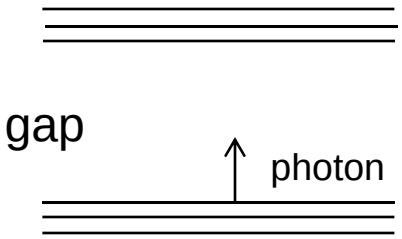


FIG. 5. Efficiency η for a blackbody solar cell at $T_c = 300°K$, with sun at $T_s = 6000°C$, as a function of energy gap for different values of the parameter f: curve (a) $f = 1$; (b) $f = 10^{-3}$; (c) $f = 10^{-6}$; (d) $f = 10^{-9}$; (e) $f = 10^{-12}$.

Shockley and Queisser (1961)

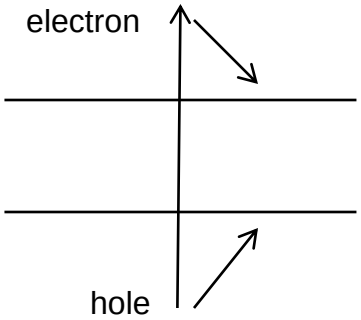
Ultimate Efficiency

- Sub-bandgap photons are not absorbed:



- Carrier relaxation to band edges:

  Photon energy exceeding bandgap is lost



Ultimate Efficiency

Let Q(T) be the photon flux in blackbody radiation of temperature T with photon energy $h\nu > E_g$:

$$Q(T) = \frac{2\pi}{c^2} \int_{E_g/h}^{\infty} \frac{\nu^2 d\nu}{e^{h\nu/kT} - 1}$$

photon flux = number of photons / (unit area unit time)

The total energy flux in the blackbody radiation is:

$$I_s = \frac{2\pi h}{c^2} \int_{0}^{\infty} \frac{\nu^3 d\nu}{e^{h\nu/kT} - 1}$$

Energy flux = energy / (unit area unit time)

Ultimate Efficiency

Incident solar power: $P_{\text{in}} = A\, I_{\text{s}}$

Electrical output power: $P_{\text{out}} = A\, E_{\text{g}} Q(T_{\text{s}})$

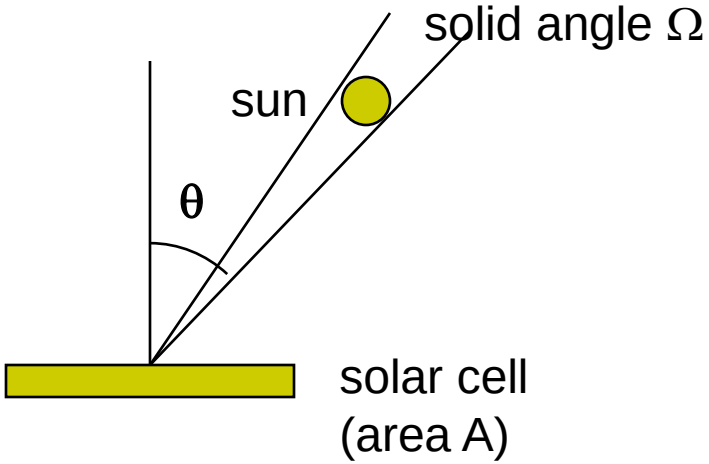
Ultimate efficiency: $\eta_{\text{ult}} = \dfrac{P_{\text{out}}}{P_{\text{in}}} = \dfrac{E_{\text{g}} Q(T_{\text{s}})}{I_{\text{s}}}$

- For $T_{\text{s}} = 6000$ K, the ultimate efficiency is maximized for a band gap of $E_{\text{g}} = 1.1$ eV, reaching $\eta_{\text{ult}} \approx 45\%$.
- Ultimate efficiency can only be achieved if there is perfect absorption of blackbody radiation at $T = T_{\text{s}}$ and the cell temperature $T_{\text{c}} = 0$.
- It does not take into account carrier recombination, which must occur at $T_{\text{c}} > 0$.

Detailed Balance Limit

- For finite cell temperature, need to take into account carrier recombination.
- Use the principle of detailed balance (Shockley and Queisser, 1961).

First consider solid angle of sun, as seen from earth:



- $\Omega = 6.85 \times 10^{-5}$ steradians (no concentration)
- Ω may be greatly enhanced using solar concentrators (lenses, parabolic reflectors).
- Set $\theta = 0$ from here on (normal incidence).

Detailed Balance Limit

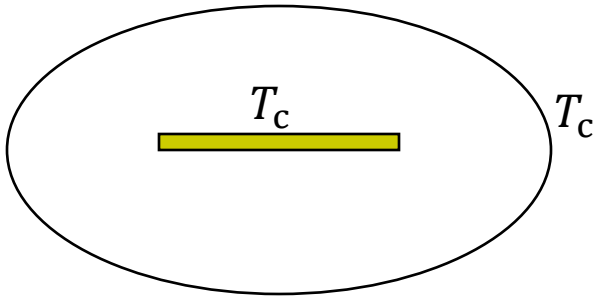
- Incident solar power (= absorbed power)

$$P_s = A\, I_s\, \frac{\Omega}{\pi}$$

- # of e-h pairs created (given by # of absorbed photons):

$$F_s = A\, Q(T_s)\, \frac{\Omega}{\pi}$$

- Now consider solar cell in thermal equilibrium, i.e., surrounded by a box at $T = T_c$:



e-h pair creation rate =

$F_c = 2\, A\, Q(T_c)$ = recombination rate

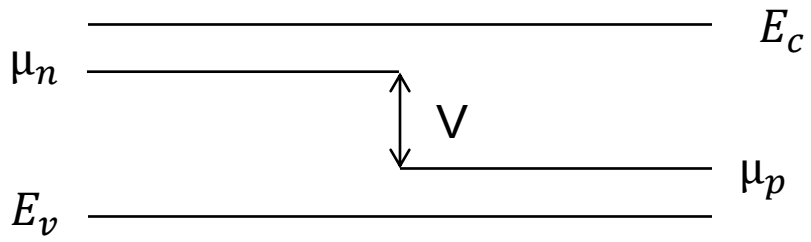
↑ both sides

"detailed balance"

$F_c = F_c(0)$ (zero voltage)

Detailed Balance Limit

Apply a voltage V across the junction:



recombination rate:

$$F_c(V) \propto n\,p$$

hole density

electron density

From the Fermi distribution: $\left(\beta = \frac{1}{k_B T}\right)$

$$n = \frac{1}{e^{\beta(E_c - \mu_n)} + 1} \approx e^{-\beta(E_c - \mu_n)} \qquad p = 1 - \frac{1}{e^{\beta(E_v - \mu_p)} + 1} \approx e^{\beta(E_v - \mu_p)}$$

thus $n\,p = e^{-\beta E_g}\, e^{\beta q V}$ $\quad (qV = \mu_n - \mu_p)$

and $F_c(V) = F_c(0)\, e^{\beta q V}$

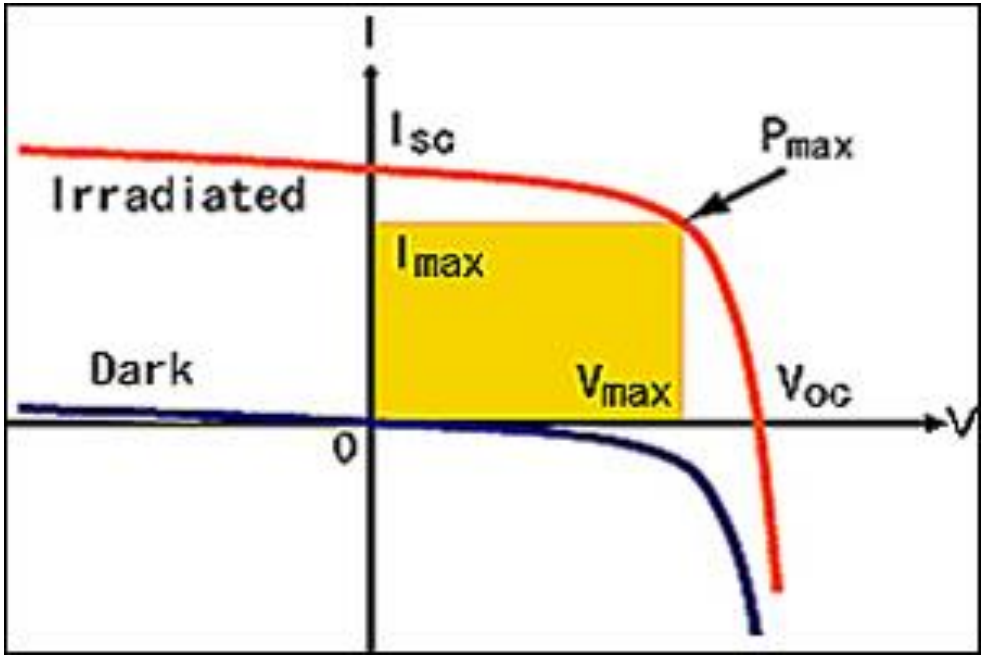
Detailed Balance Limit

- Photocurrent:

$$i = q[F_s - F_c(V)] = q\left[F_s - F_c(0)e^{\beta qV}\right]$$

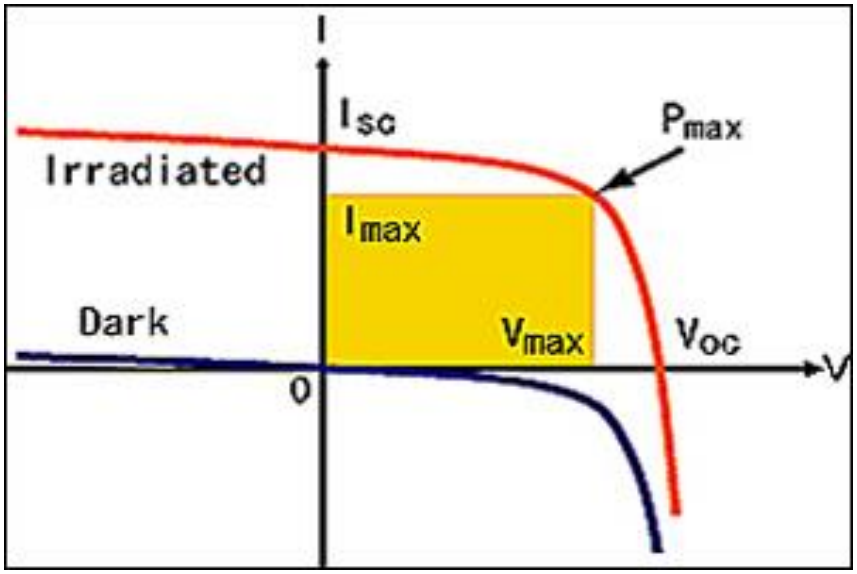
recombination rate

number of e-h pairs created



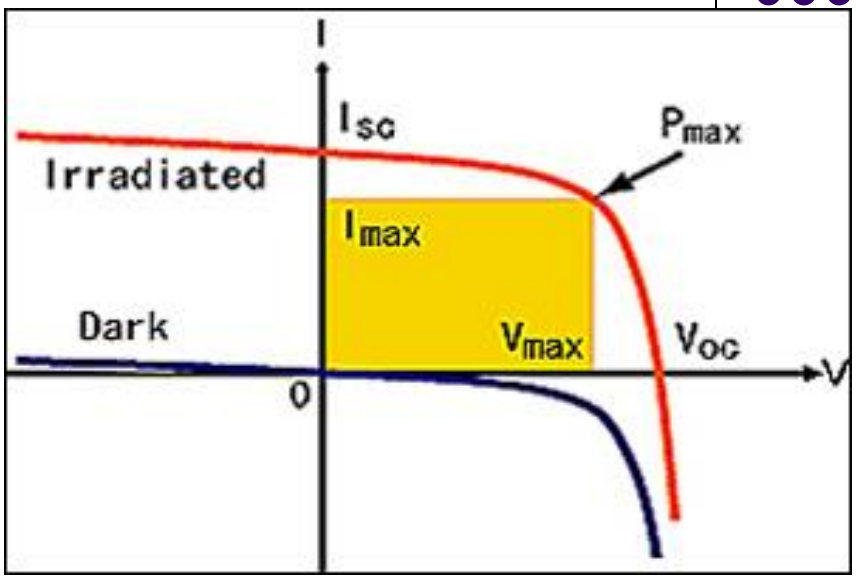
Detailed Balance Limit

- Output power: $P_{\text{out}} = iV = q\left[F_s - F_c(0)e^{\beta qV}\right]V$



- Maximize output power: set $\frac{d(iV)}{dV} = 0$, solve for V_{max}
- $i_{\text{max}} = i(V_{\text{max}})$
- Maximum output power: $P_{\text{max}} = i_{\text{max}} V_{\text{max}}$

Detailed Balance Limit



- maximum efficiency:

$$\eta_{\max} = \frac{P_{\max}}{P_s} = \frac{i_{\max} V_{\max}}{A I_s \Omega/\pi}$$

- re-write in terms of ultimate efficiency $\eta_{\text{ult}} = \frac{E_g F_s}{P_s}$ and short-circuit current $i_{\text{sh}} = i(0) = q[F_s - F_c(0)] \approx q F_s$:

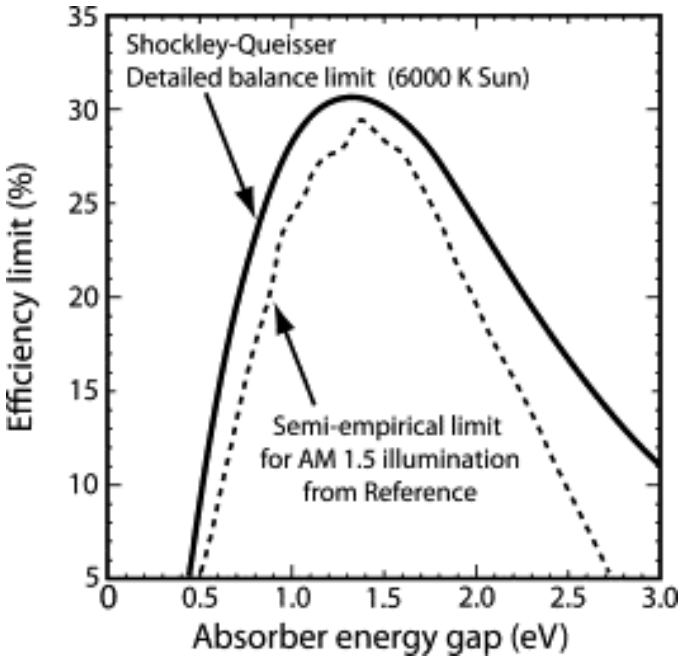
$$\eta_{\max} = \eta_{\text{ult}} \frac{q\,V_{\text{oc}}}{E_g} \frac{V_{\max}}{V_{\text{oc}}} \frac{i_{\max}}{i_{\text{sh}}}$$

"fill factor"

reduction of V_{oc} from zero-temperature value $\frac{E_g}{q}$

Detailed Balance Limit

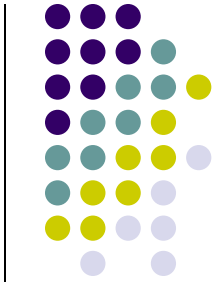
- In the limit $T_c \rightarrow 0$, the efficiency $\eta_{\max} \rightarrow \eta_{\text{ult}}$



$\eta_{\text{ult}} \approx 31\%$ for 6000 K blackbody (no concentration)

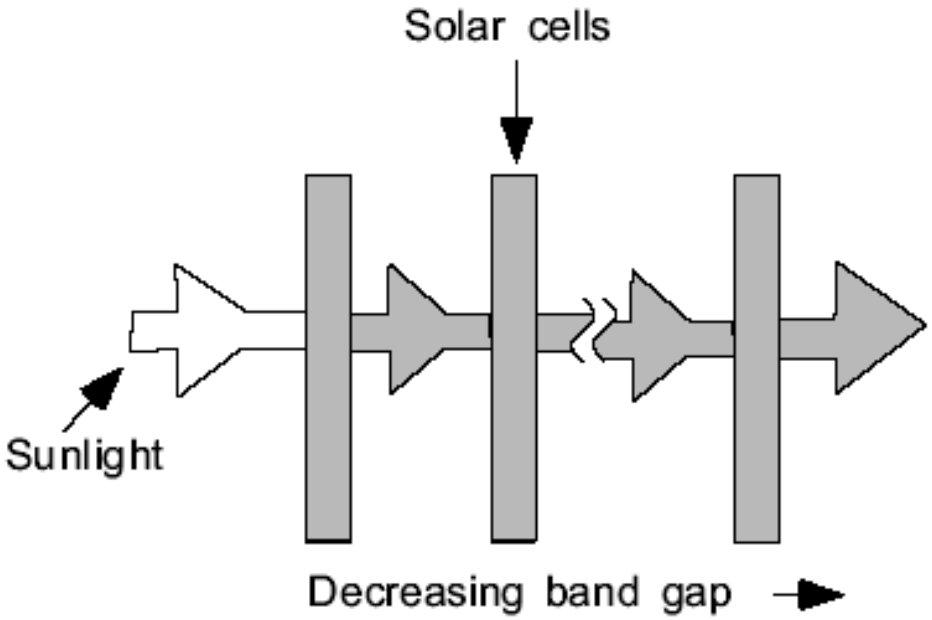
- This is an idealized result. In real life, $\eta < \eta_{\max}$ due to non-radiative recombination, contact resistance, reflection losses, etc.

Strategies to Exceed Shockley-Queisser Efficiency Limit:



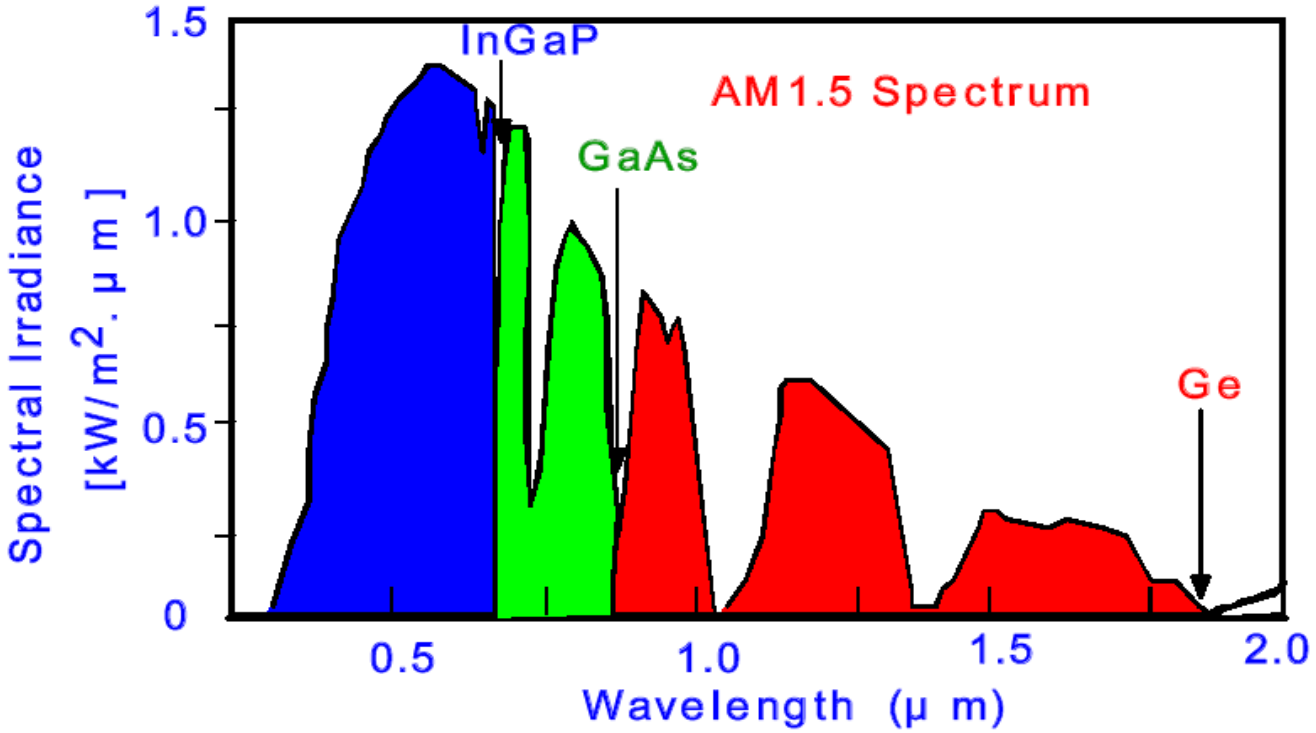
- Multi-junction cells (“Tandem cells”)
- Multiple electron-hole pairs per photon
- Intermediate-band solar cells
- Quantum-dot solar cells
- Thermophotovoltaic cells

Multiple Junctions: Tandem Cells



- Current output matched for individual cells
- Ideal efficiency for infinite stack is 86.8%
- GaInP/GaAs/Ge tandem cells (efficiency 40%)

Triple Junction Solar Cell



AM1.5 Spectrum and Wide Band Spectral Response by Multi-Junction Solar Cell

Triple Junction Solar Cell

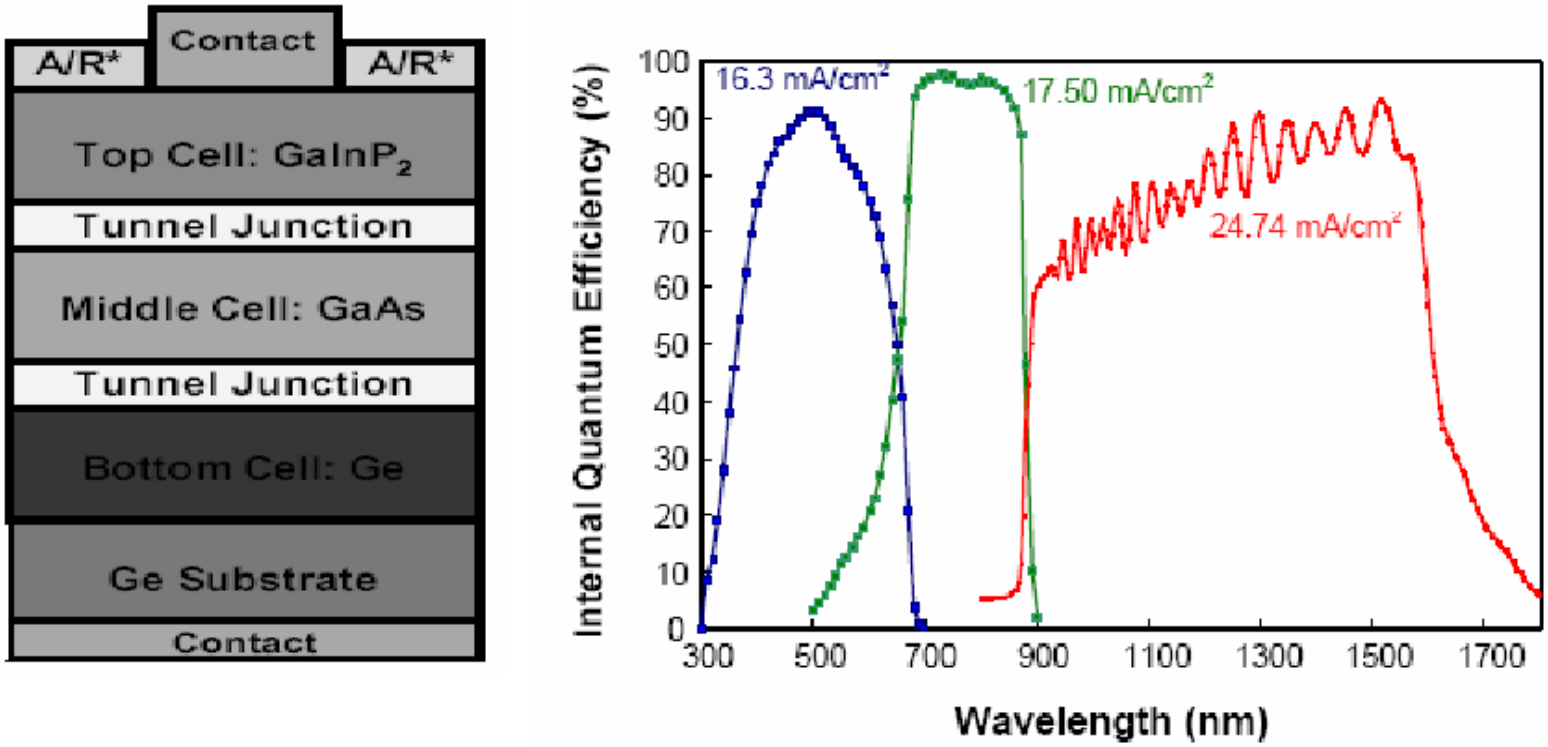
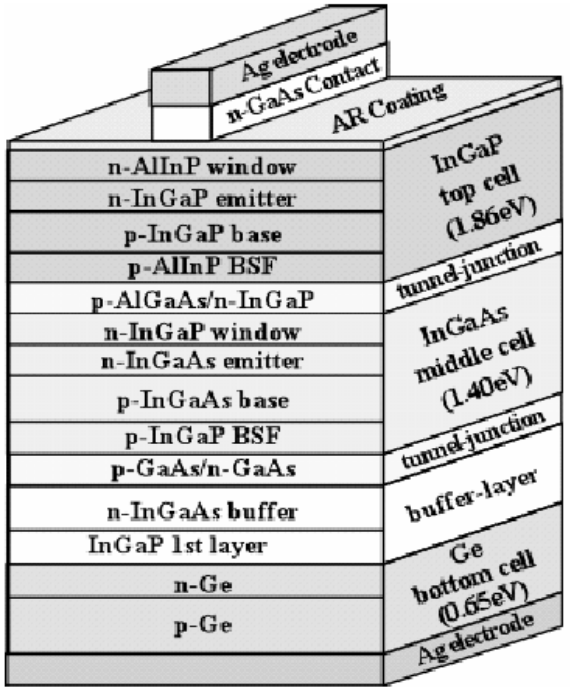
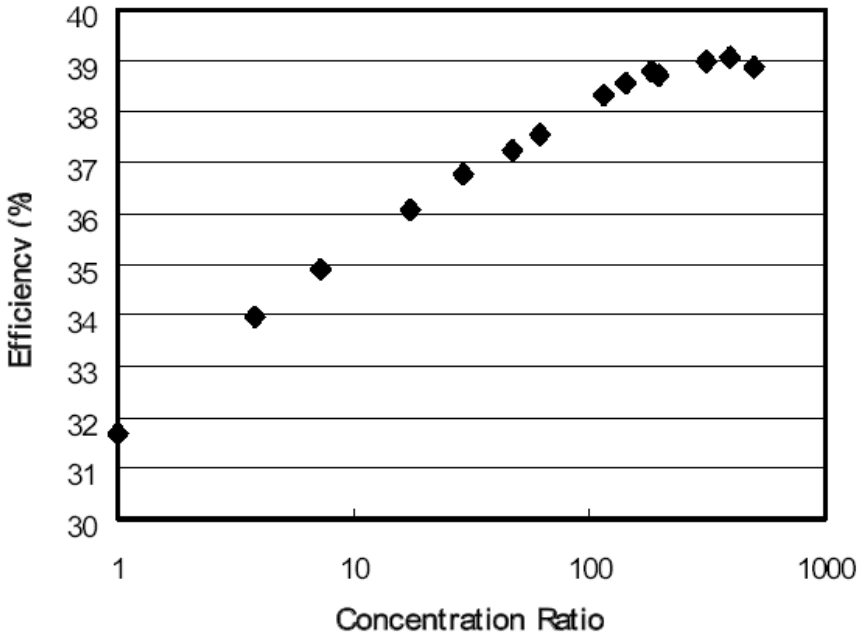


Figure 2: Triple junction GaAs solar cell structure with internal quantum efficiency of three cell covering the entire Sun's spectrum

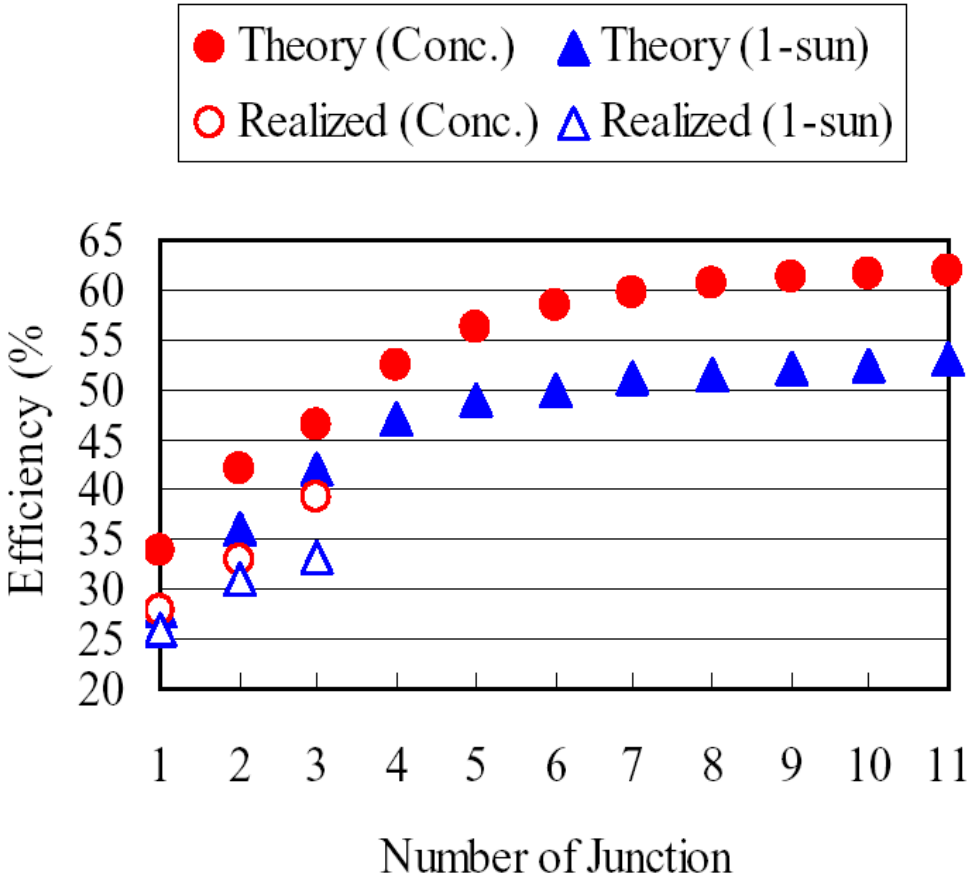
Triple Junction Solar Cell



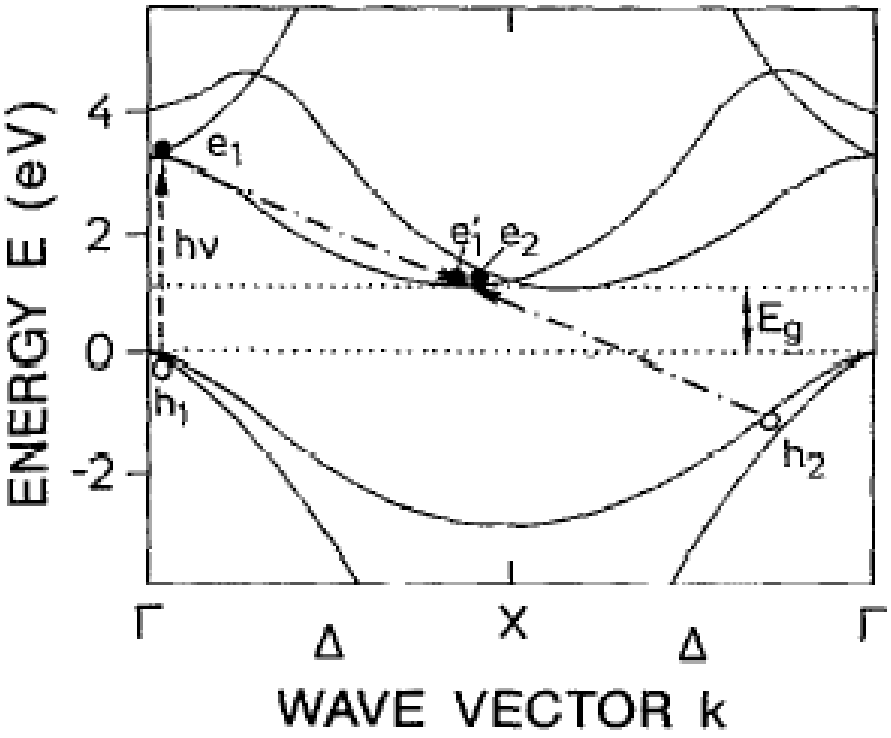
39.2 % at 200-suns
38.9% at 489-suns
by in-house measurement



Multi-Junction Solar Cells

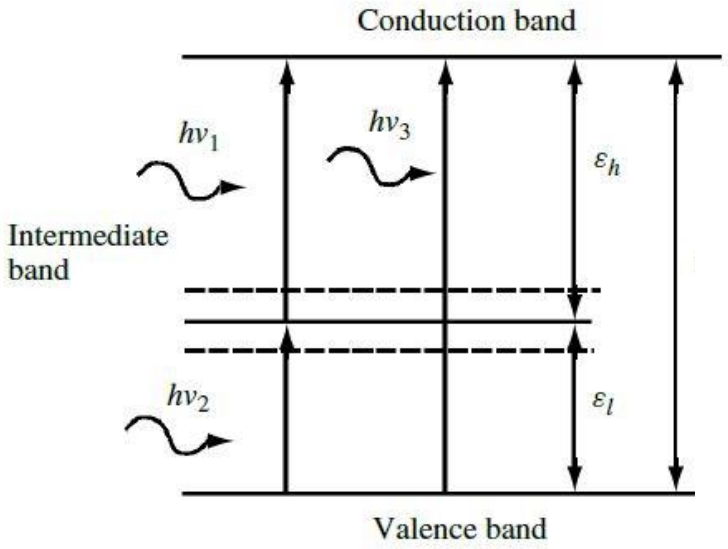


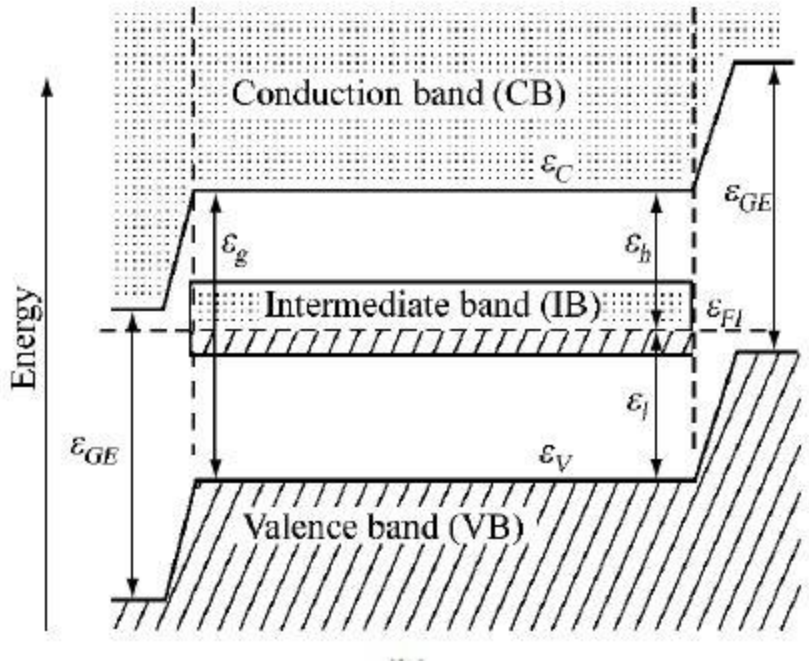
Multiple E-H pairs



- Many E-H pairs created by incident photon through impact ionization of hot carriers
- Theoretical efficiency is 85.9%

Intermediate-Band PV cell

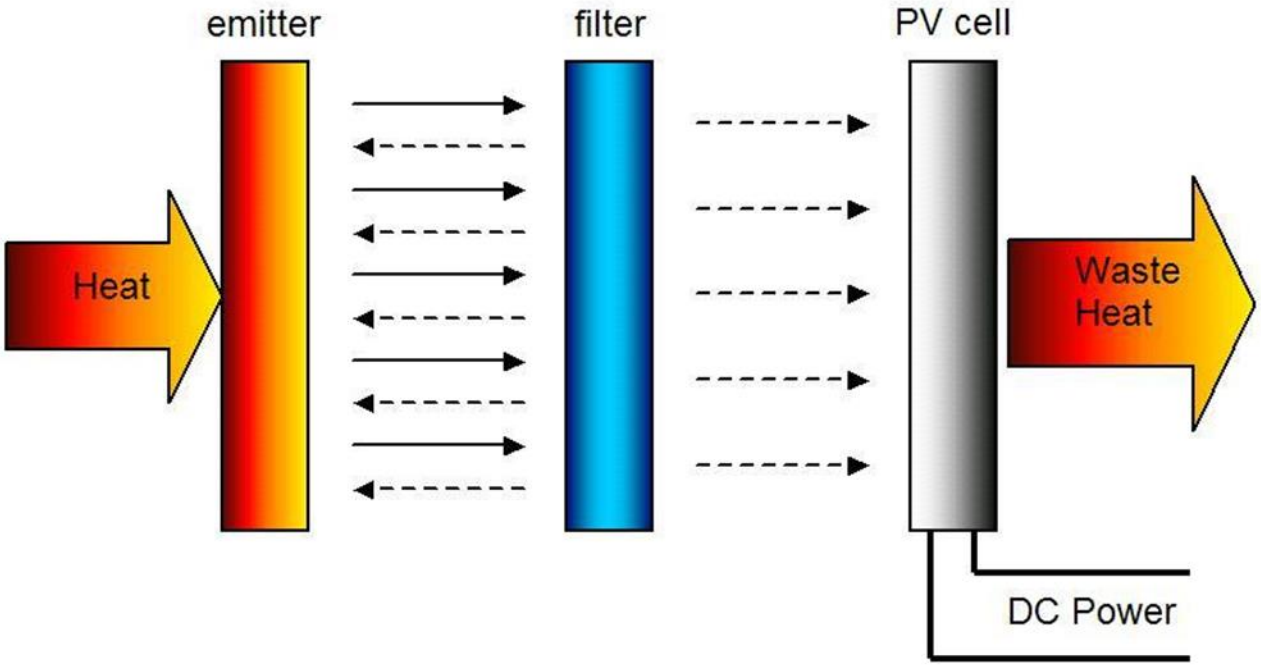




Intermediate band created by:

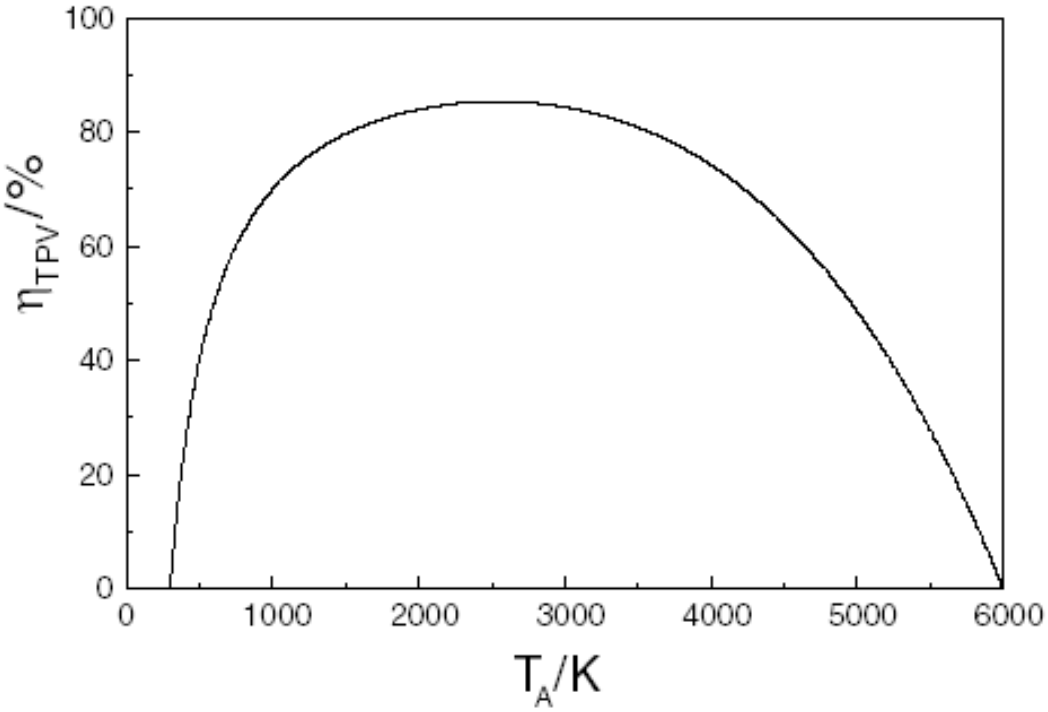
- Impurity levels
- Quantum dot states (“quantum dot solar cell”)

Thermophotovoltaic Cell



- Filter passes photons of energy equal to bandgap of solar cell material
- Emitter radiation matched with spectral sensitivity of cell

Thermophotovoltaic Cells



$$\eta_{\mathrm{TPV}} = \left(1 - \frac{\pi}{\Omega_S}\frac{T_A^4}{T_S^4}\right)\left(1 - \frac{T_0}{T_A}\right)$$

- Theoretical efficiency almost twice of ordinary photocell

Comparison and history of PV conversion efficiencies