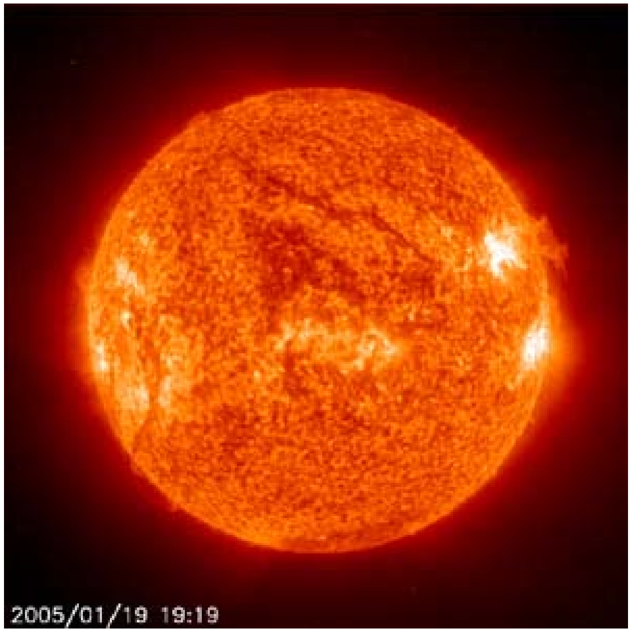
Photovoltaic Energy Conversion

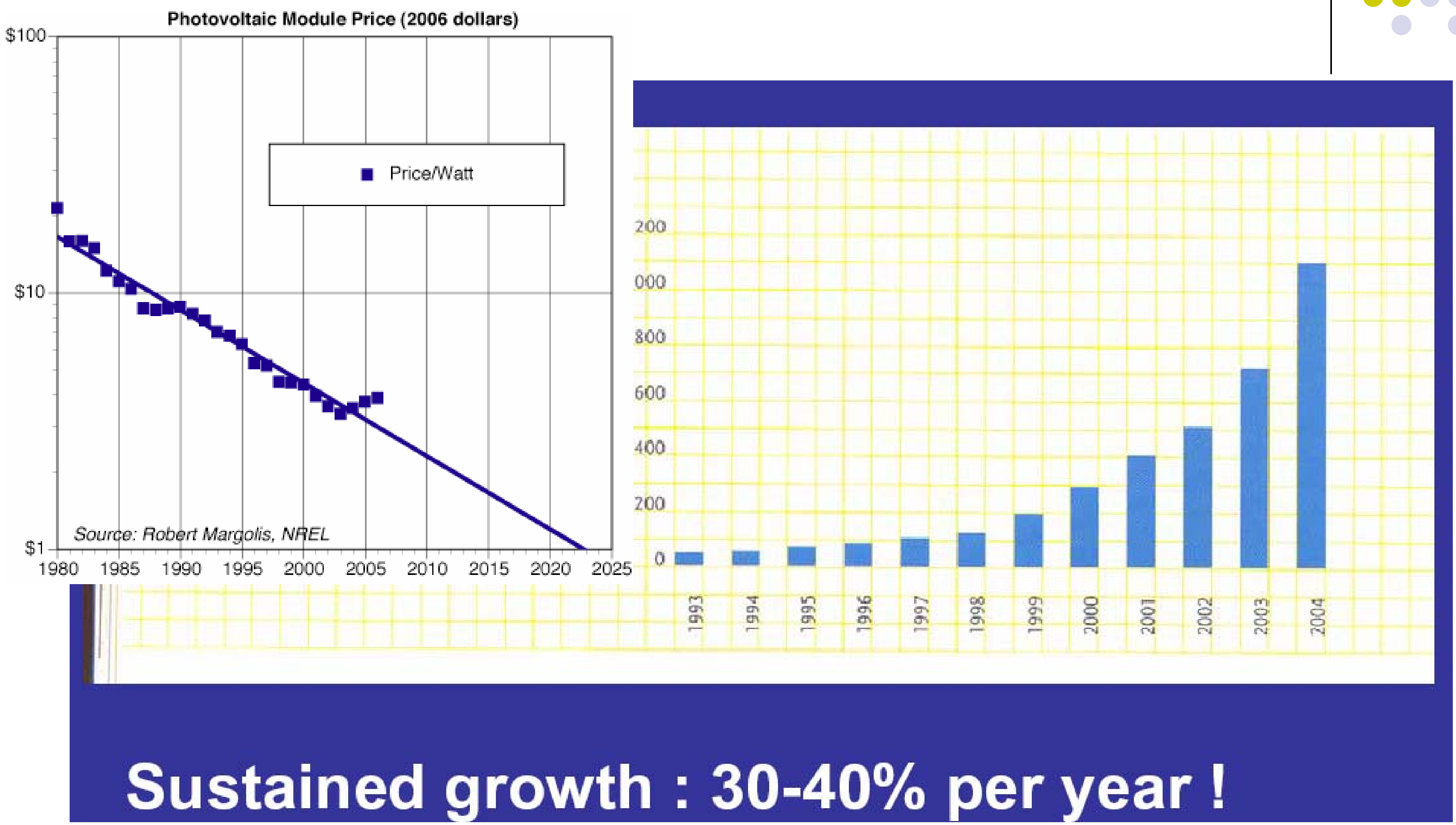
Frank Zimmermann



Solar Electricity Generation

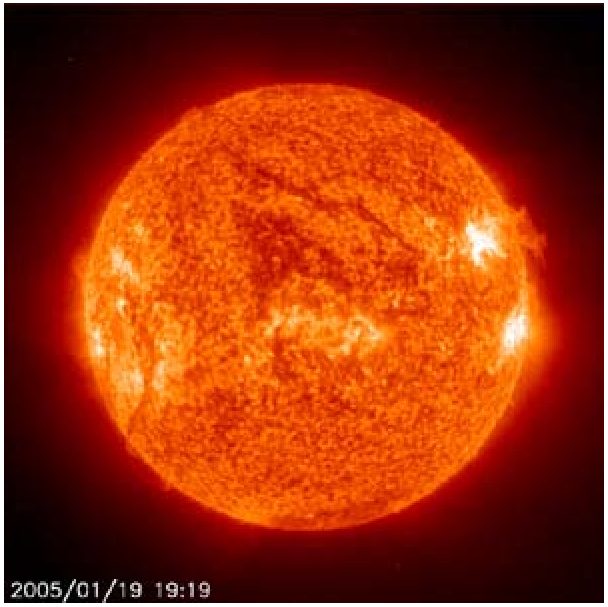
- Consumes no fuel
- No pollution
- No greenhouse gases
- No moving parts, little or no maintenance
- Sunlight is plentiful & inexhaustible
- Still more expensive than fossil fuels/nuclear, but cost coming down.
- Cost competitive **today** with electricity from coal if cost of carbon capture is factored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

Photovoltaics: Explosive Growth



Take Advantage of Solar Megatrend

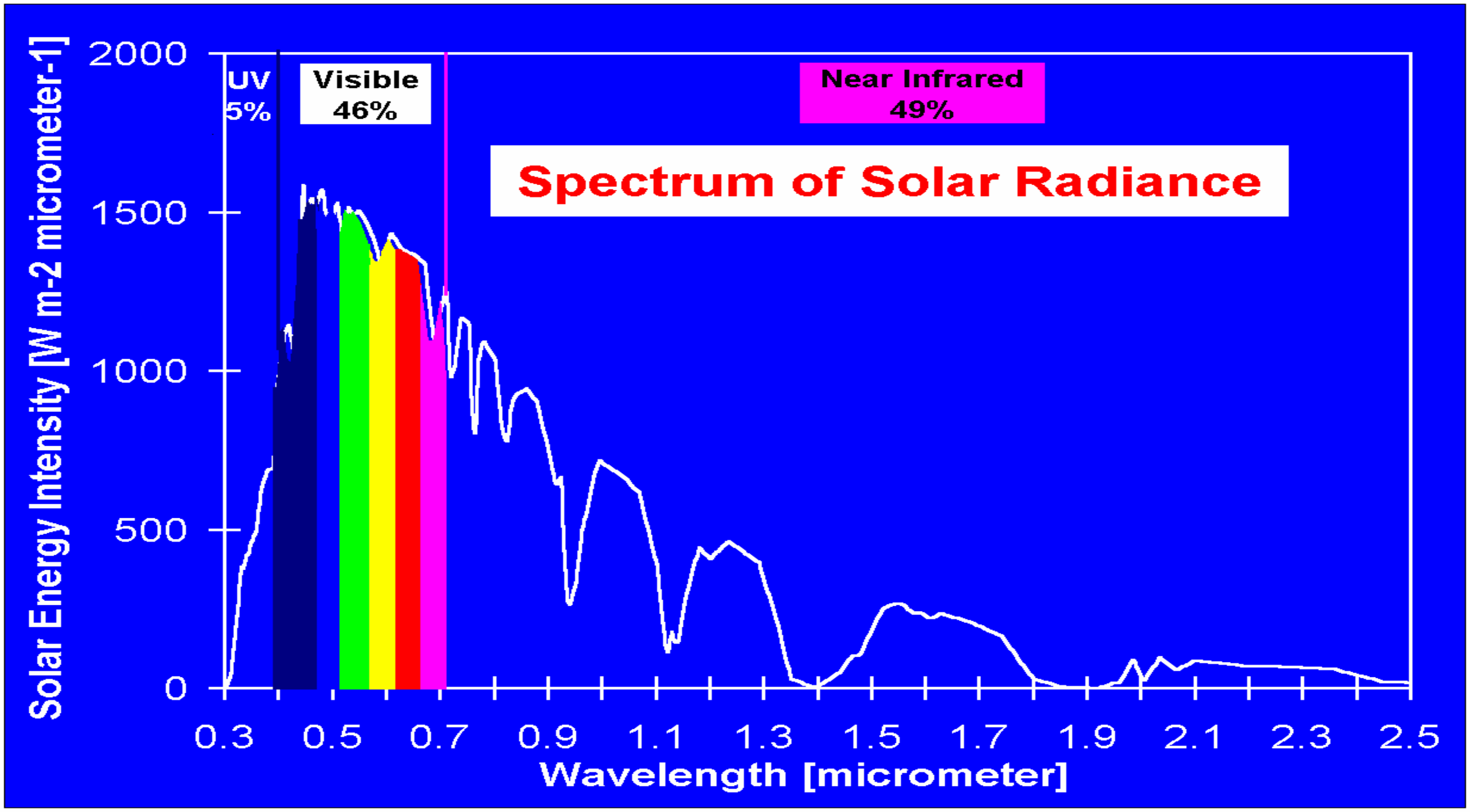
- Buy Solar Energy Stocks?
- Make Photovoltaics your Profession!



Challenges

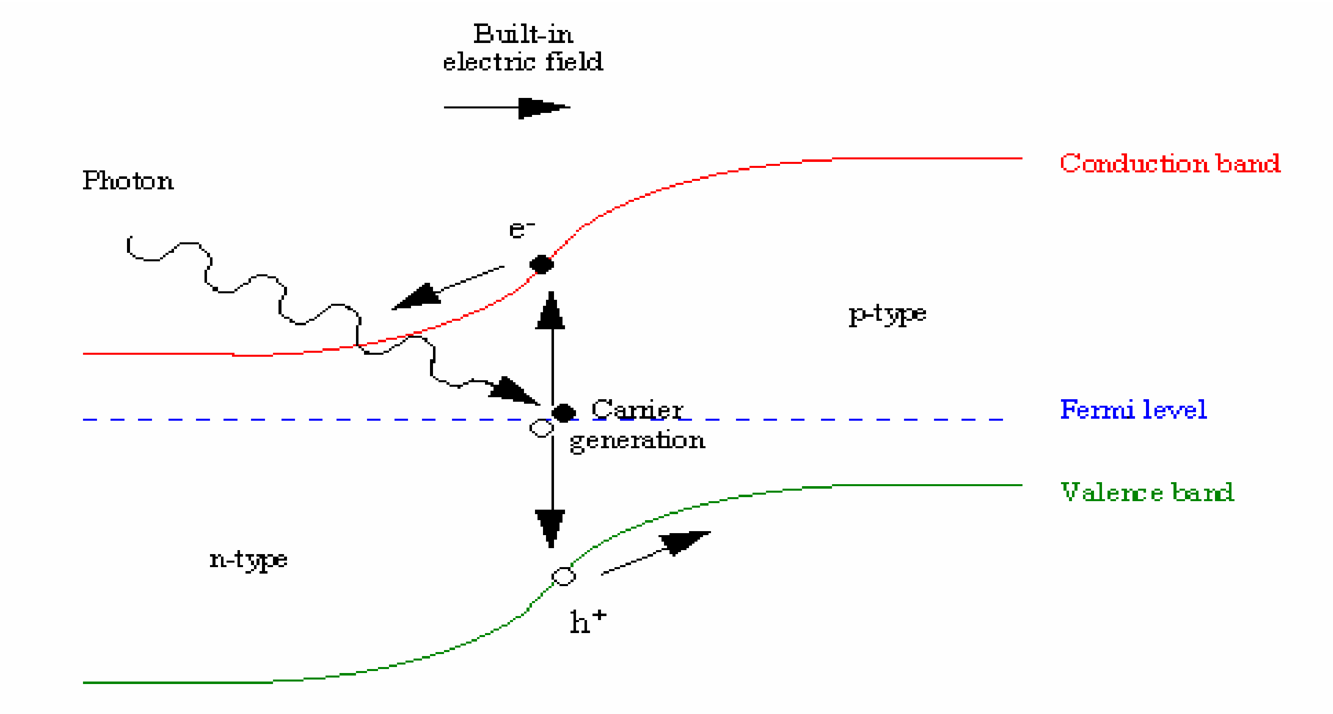
- Make solar cells more efficient
  - Theoretical energy conversion efficiency limit of single junction solar cell is 31%
  - Actual efficiencies are even lower: ≤ ~20%
- Make solar cells cheaper
  - Factor of 2 – 5 cost reduction required to achieve “Grid Parity”
- Require high reliability, long service life
- Use only abundant, nontoxic materials

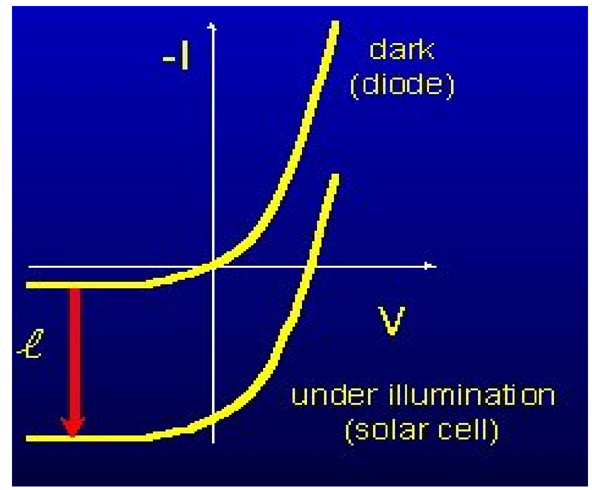
Solar Energy Spectrum



- Power reaching earth 1.37 KW/m^2

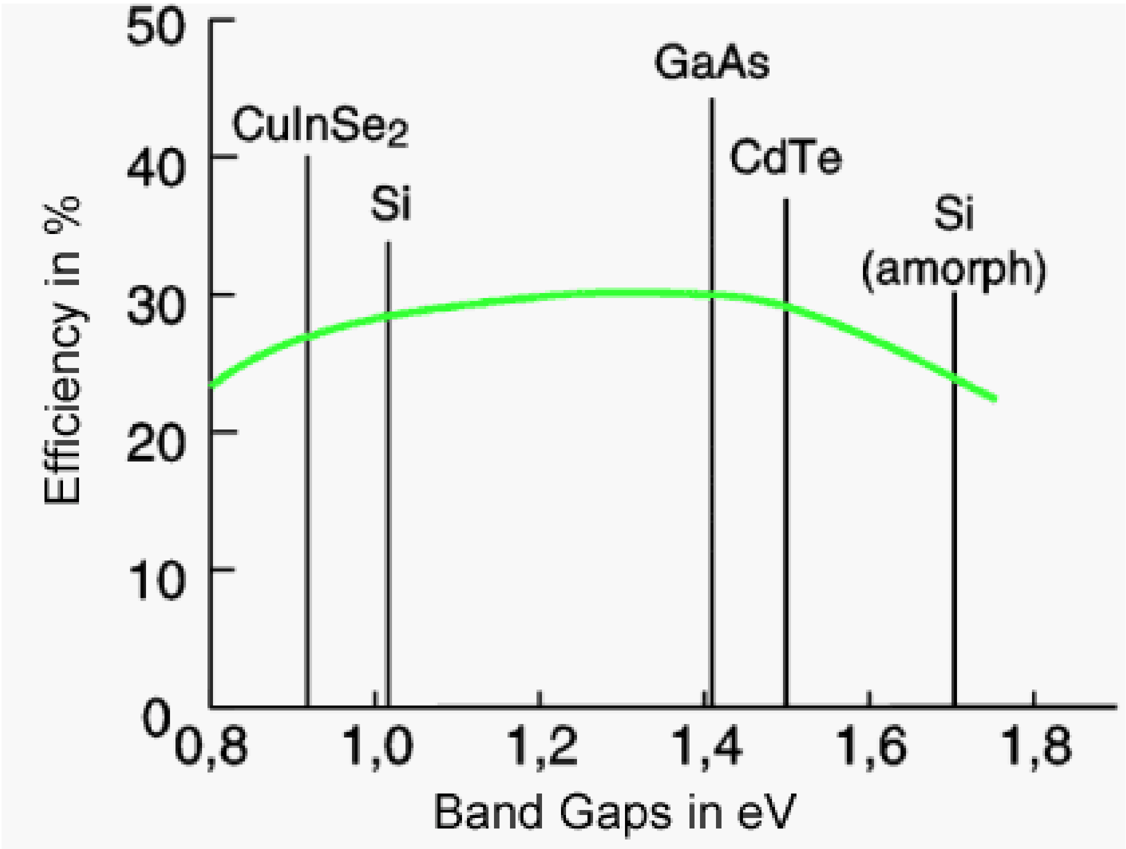
Solar cell – Working Principle





- Operating diode in fourth quadrant generates power

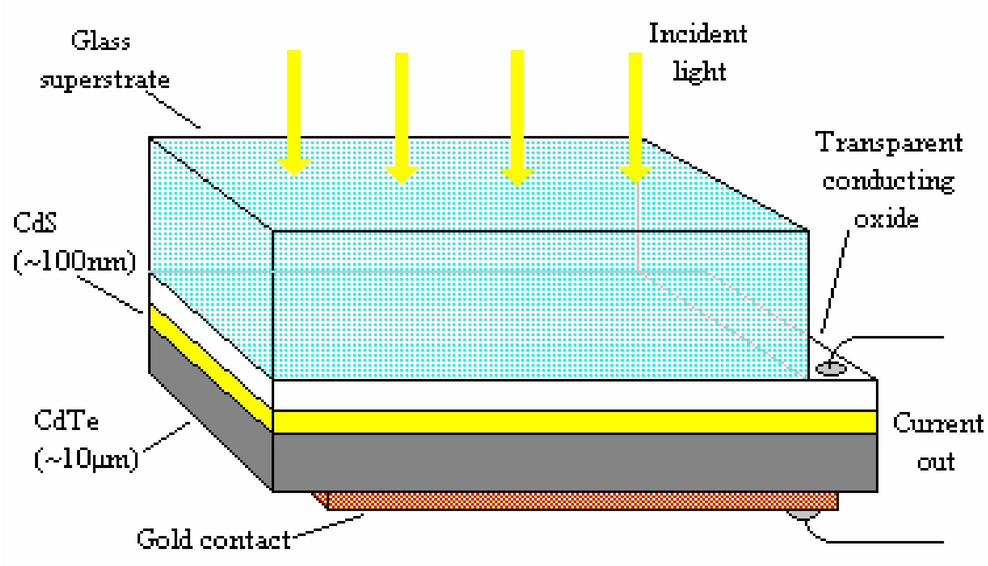
Semiconductor Bandgaps



Thin Film Solar Cells

- Produced from cheaper polycrystalline materials and glass
- High optical absorption coefficients
- Bandgap suited to solar spectrum
- Poly-Si
- CdTe
- CIGS (Copper-Indium-Gallium-Selenide)
- Organic and Dye-Sensitized Solar Cells

CdTe/CdS Solar Cell

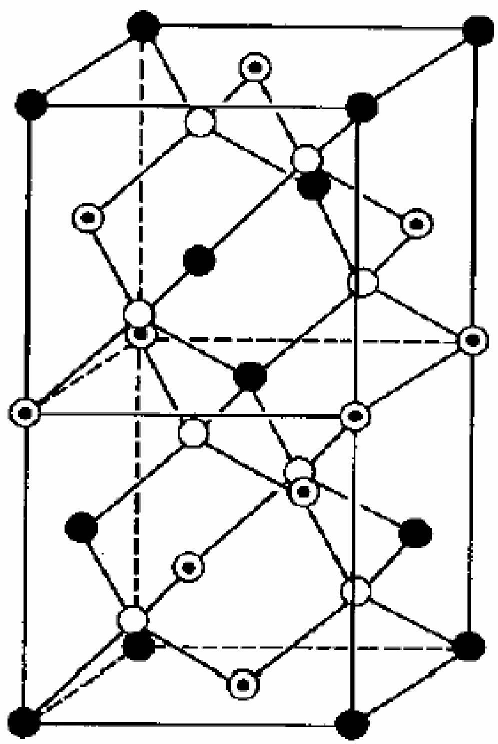


- **<u>CdTe</u>** : Bandgap 1.5 eV; Absorption coefficient 10 times that of Si
- **<u>CdS</u>** : Bandgap 2.5 eV; Acts as window layer

Limitation :

Poor contact quality with p-CdTe (~ 0.1 Ωcm^2)

$CuInSe_2$ (with Ga: “CIGS”)



Chalcopyrite Structure

Direct Band Gap : 1 eV

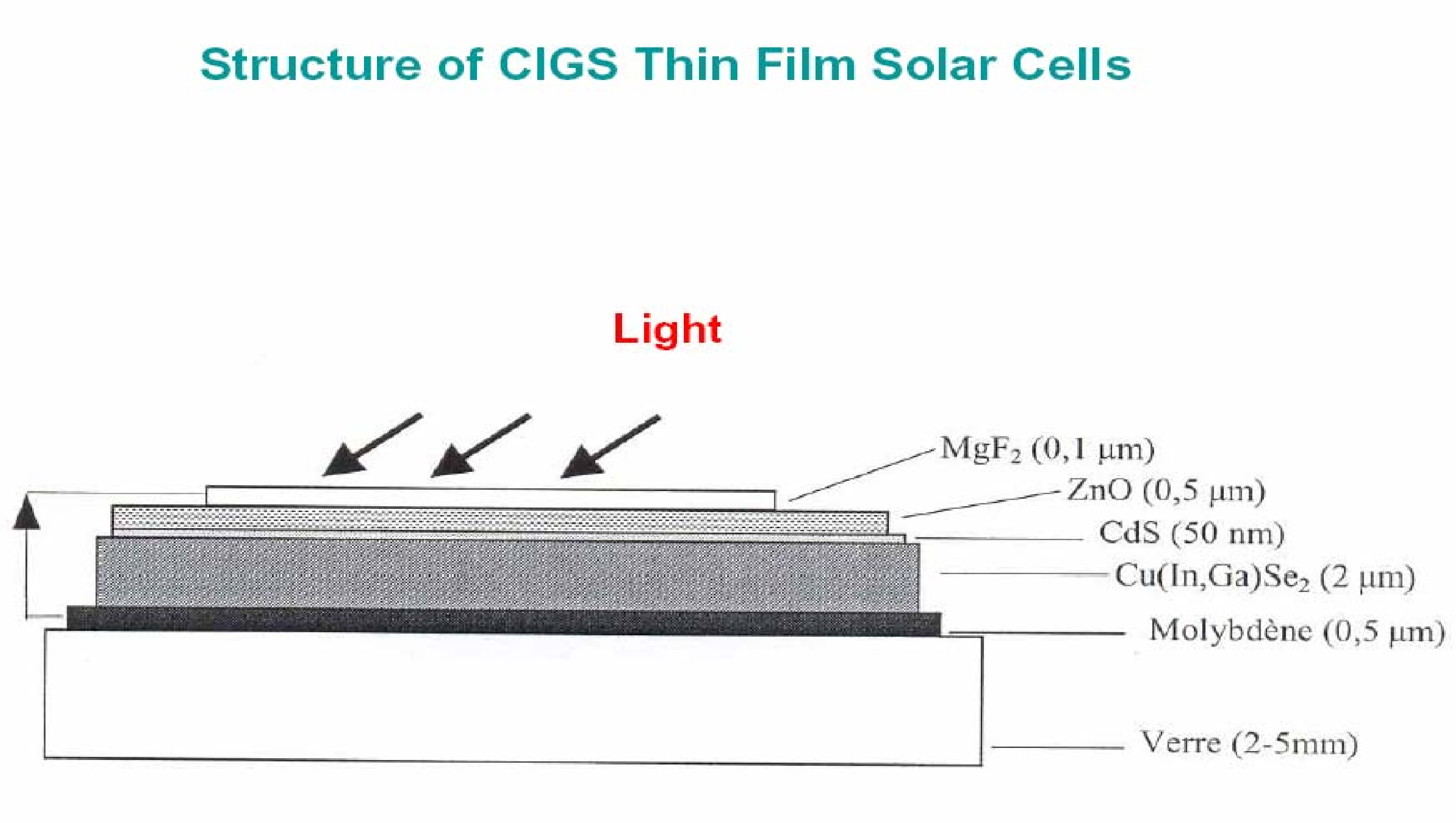
High absorption coefficients (10^4 -10^5 cm^{-1})

Thin film absorbers (1 -2 micron)

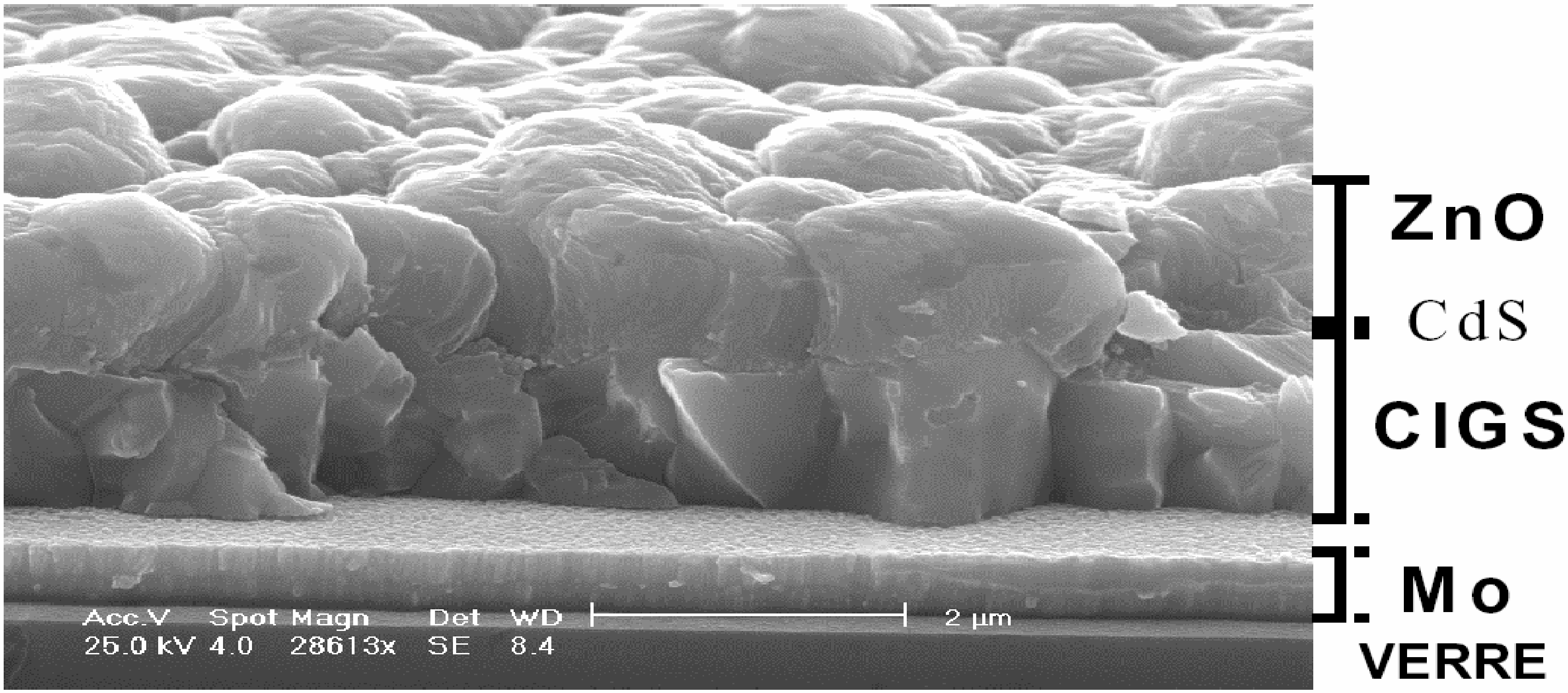
P type – n type

Tolerant to defects and grain boundaries

CIGS Solar Cell

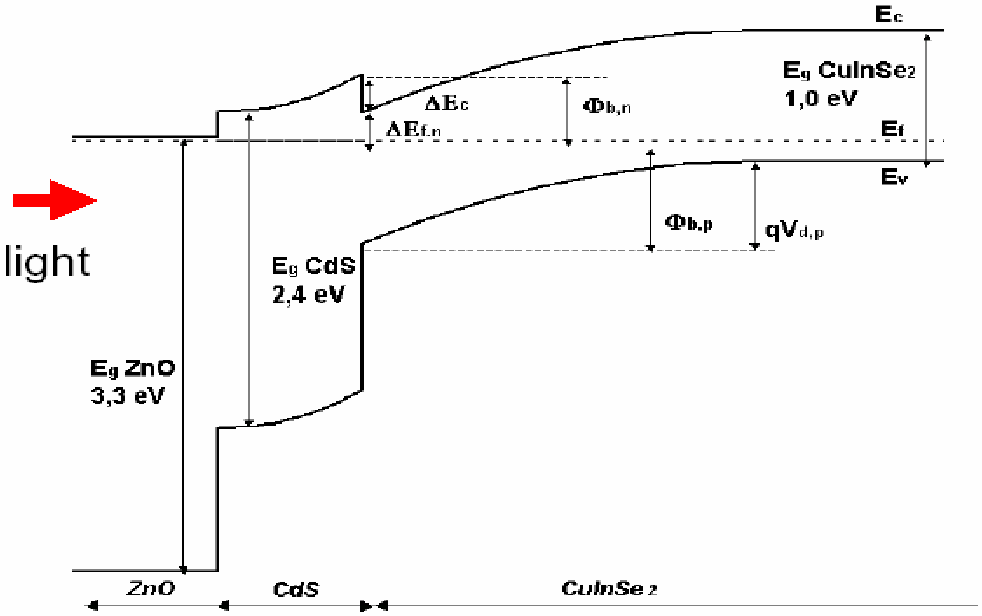


CIGS Cell Cross Section

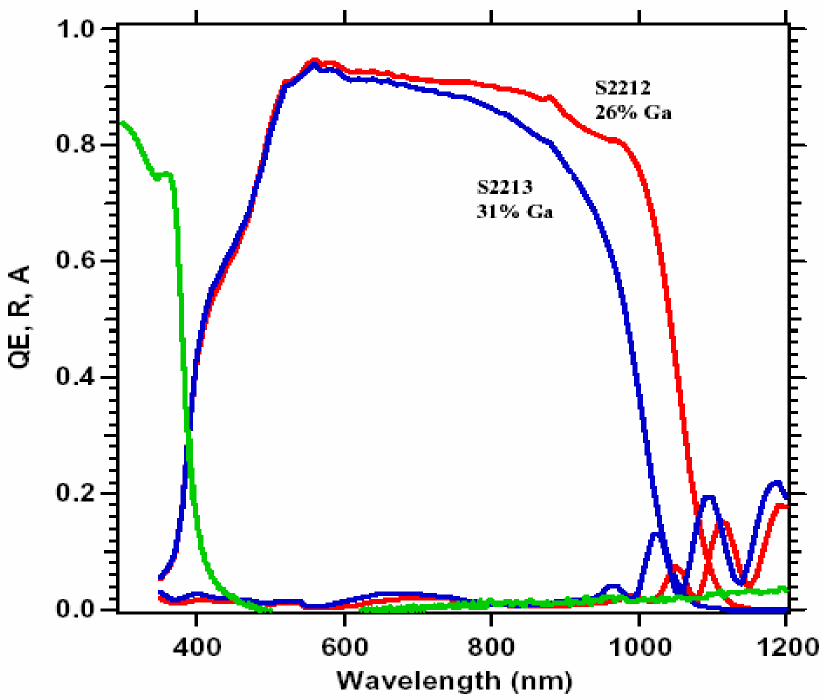


Source : ZSW, Centre de recherche sur l'Energie Solaire et l'Hydrogène,Stuttgart

Band Diagram CIGS Solar Cell

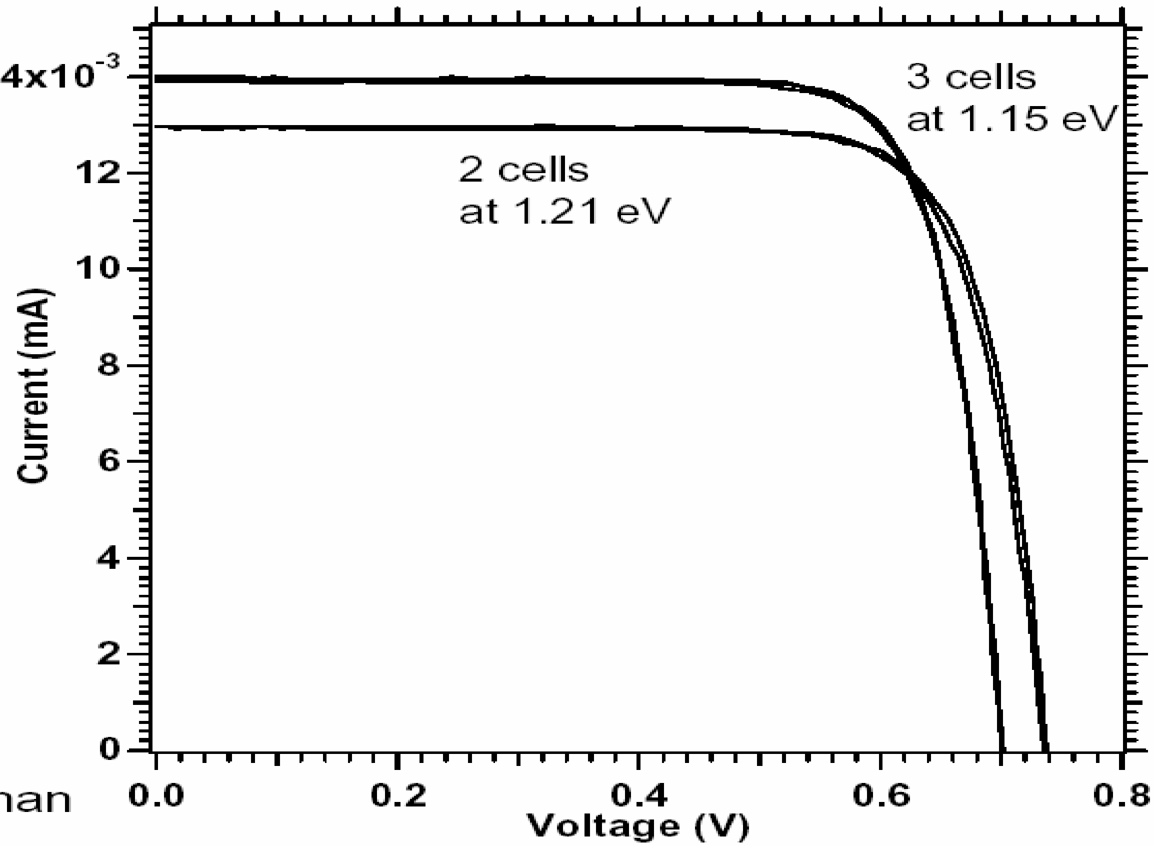


Spectral response



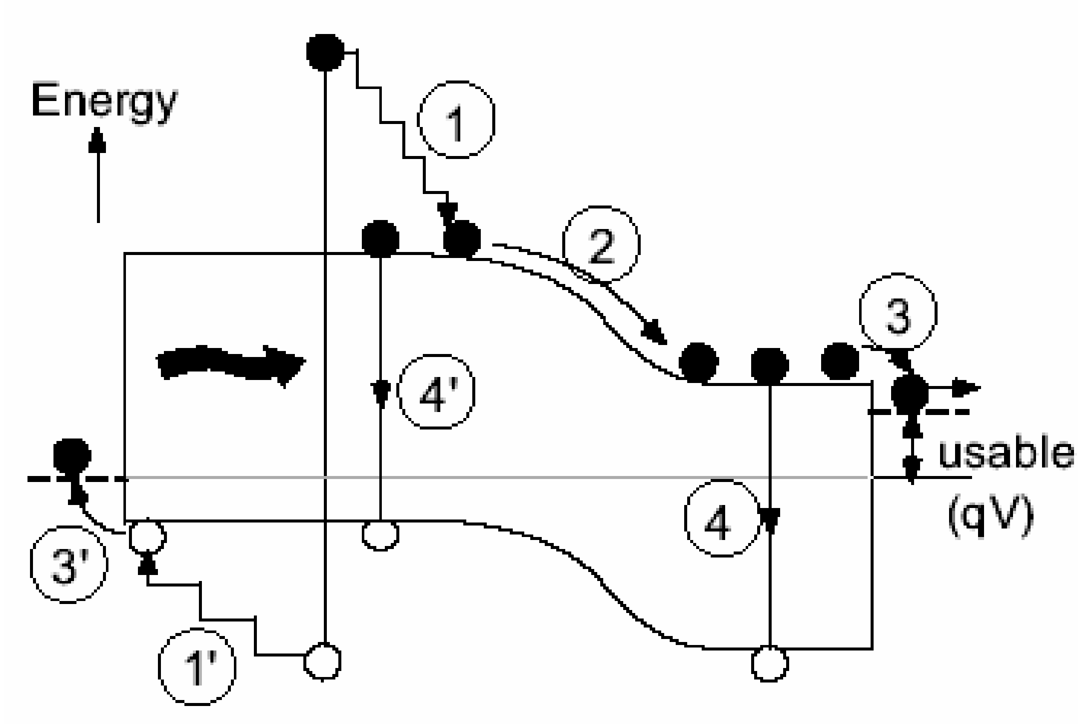
By Courtesy of Dr. K. Ramanathan et al.,
NREL, EMRS 2004

I-V Curves CIGS Solar Cell



By Courtesy
Dr. K. Ramanathan
E MRS 2004

Efficiency Losses in Solar Cell



1 = Thermalization loss

2 and 3 = Junction and contact voltage loss

4 = Recombination loss

Detailed Balance Efficiency Limit

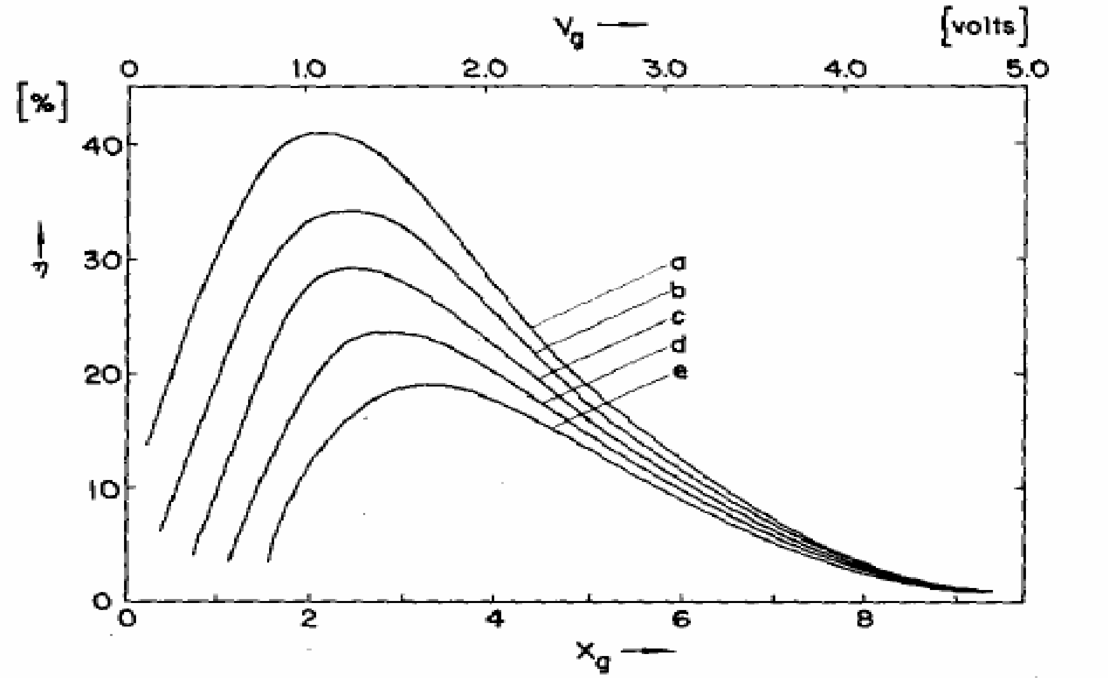
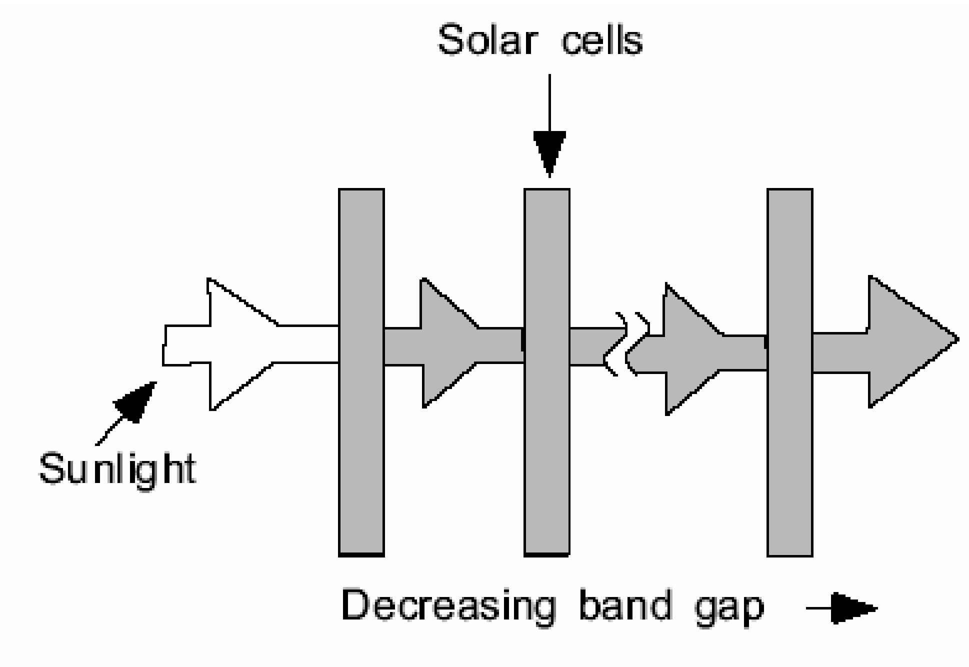


FIG. 5. Efficiency η for a blackbody solar cell at $T_c=300°K$, with sun at $T_s=6000°C$, as a function of energy gap for different values of the parameter f: curve (a) $f=1$; (b) $f=10^{-3}$; (c) $f=10^{-6}$; (d) $f=10^{-9}$; (e) $f=10^{-12}$.

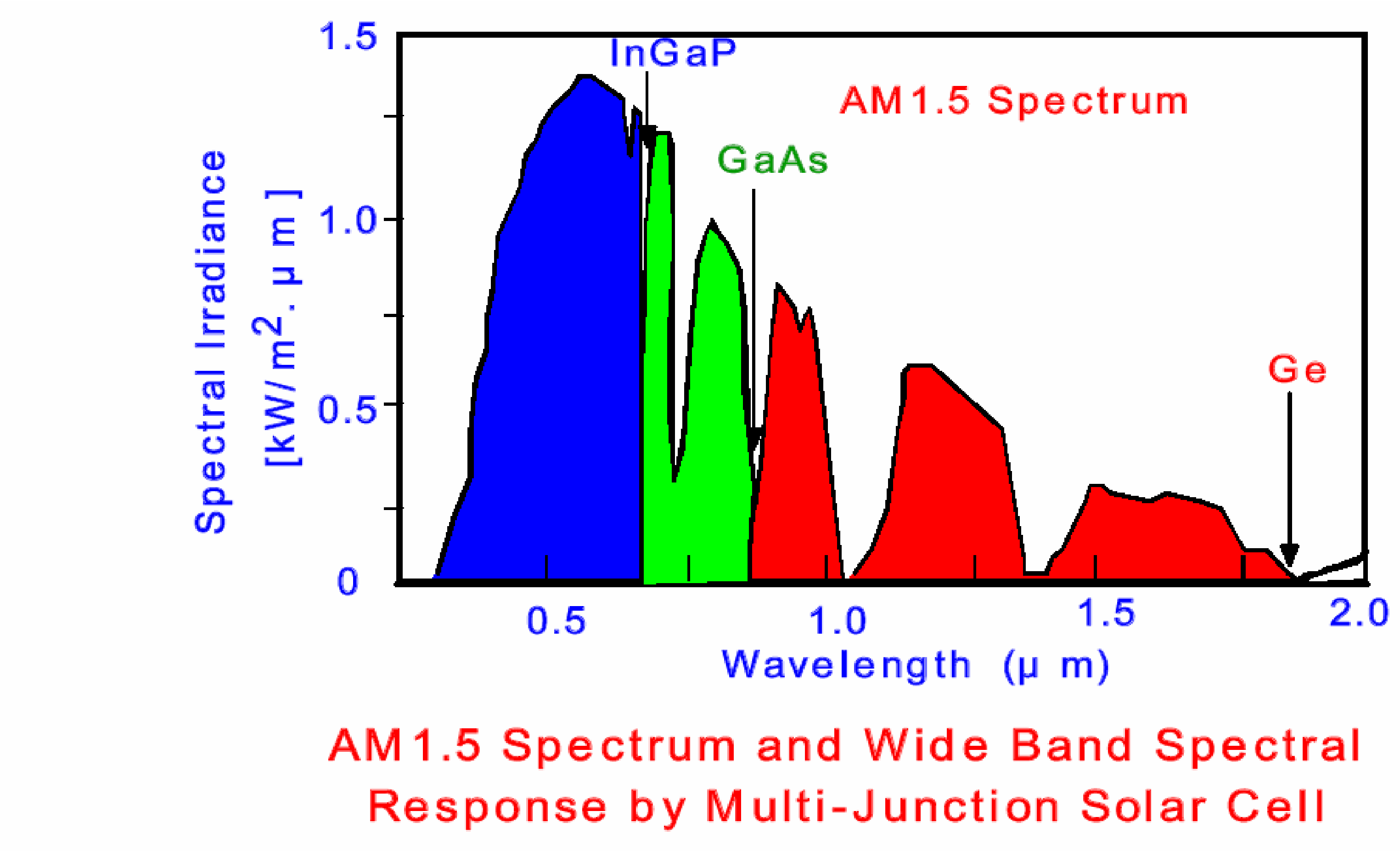
Shockley and Queisser (1961)

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



Triple Junction Solar Cell

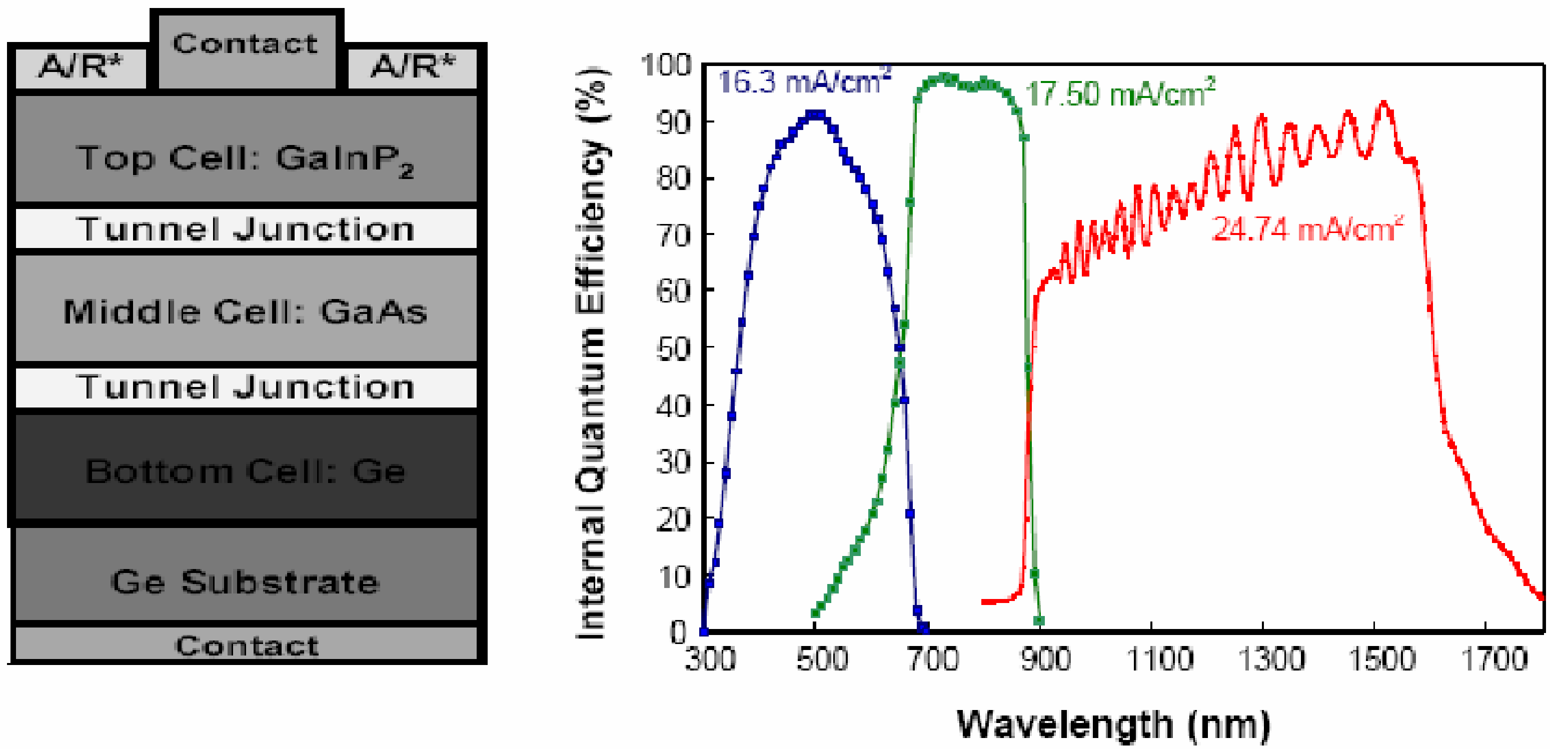
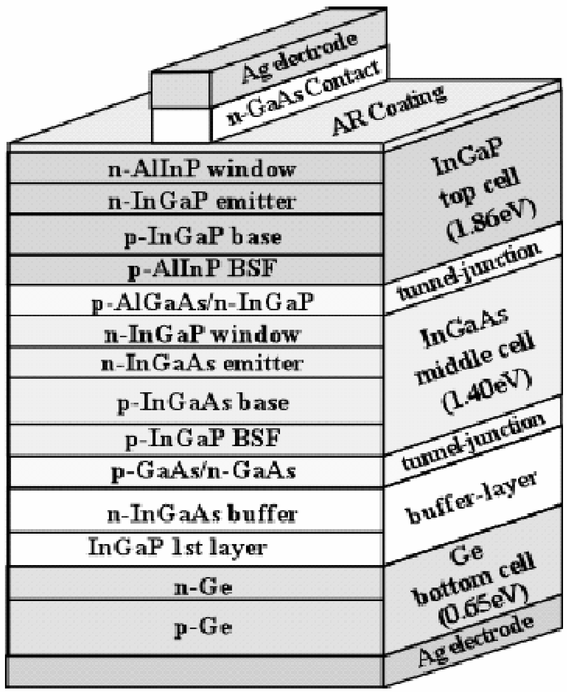
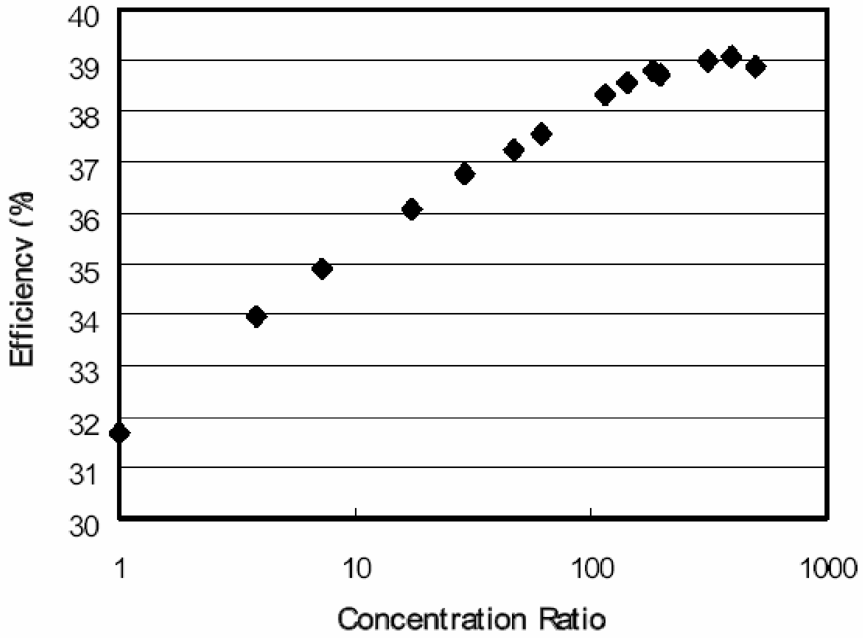


Figure 2: Triple junction GaAs solar cell structure with internal quantum efficiency of three cell covering the entire Sun's spectrum

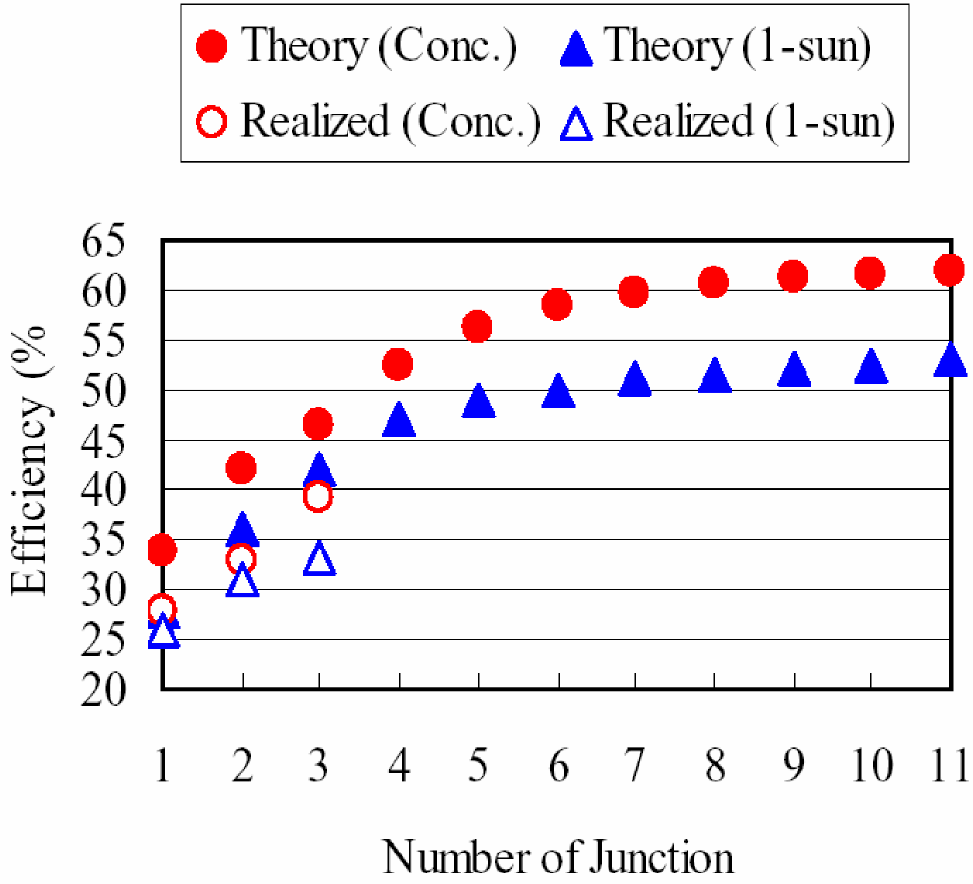
Triple Junction Solar Cell



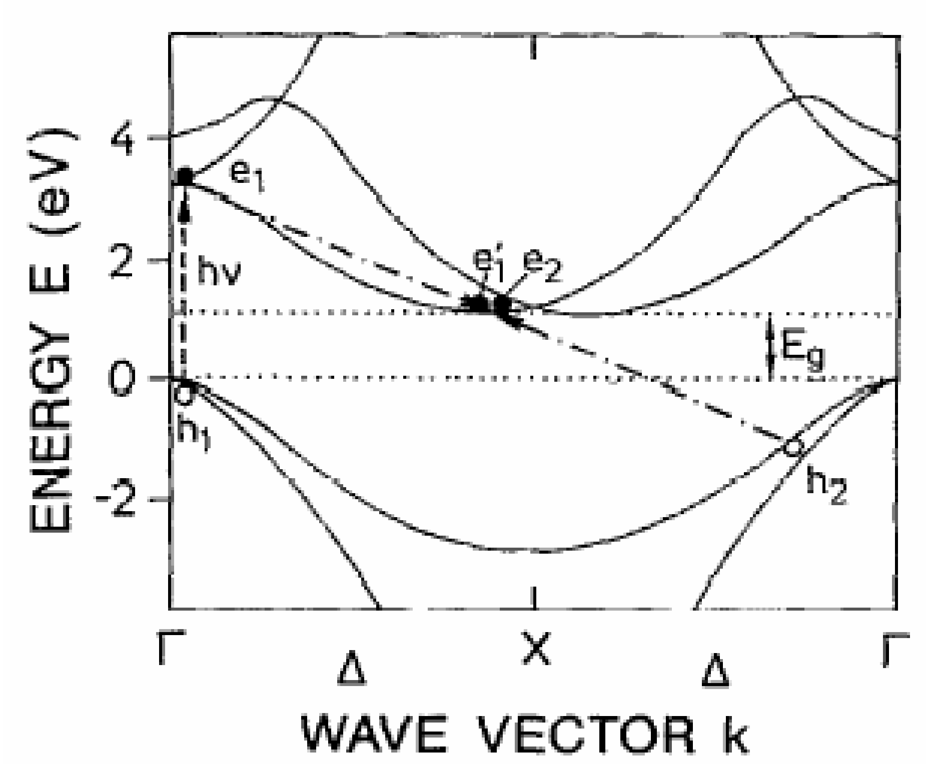
39.2 % at 200-suns
38.9% at 489-suns
by in-house measurement



Multi-Junction Solar Cells

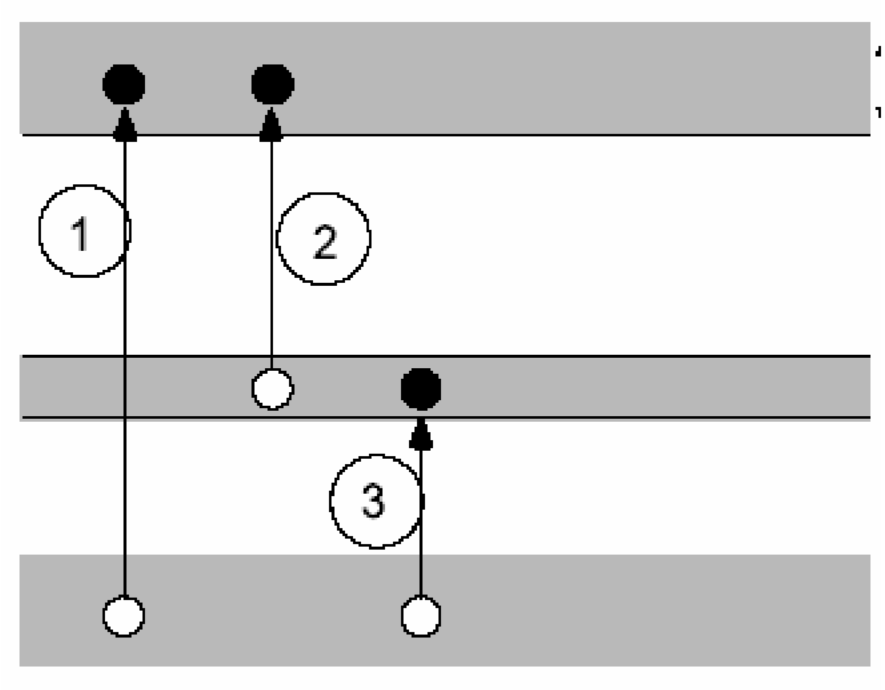


Multiple E-H pairs



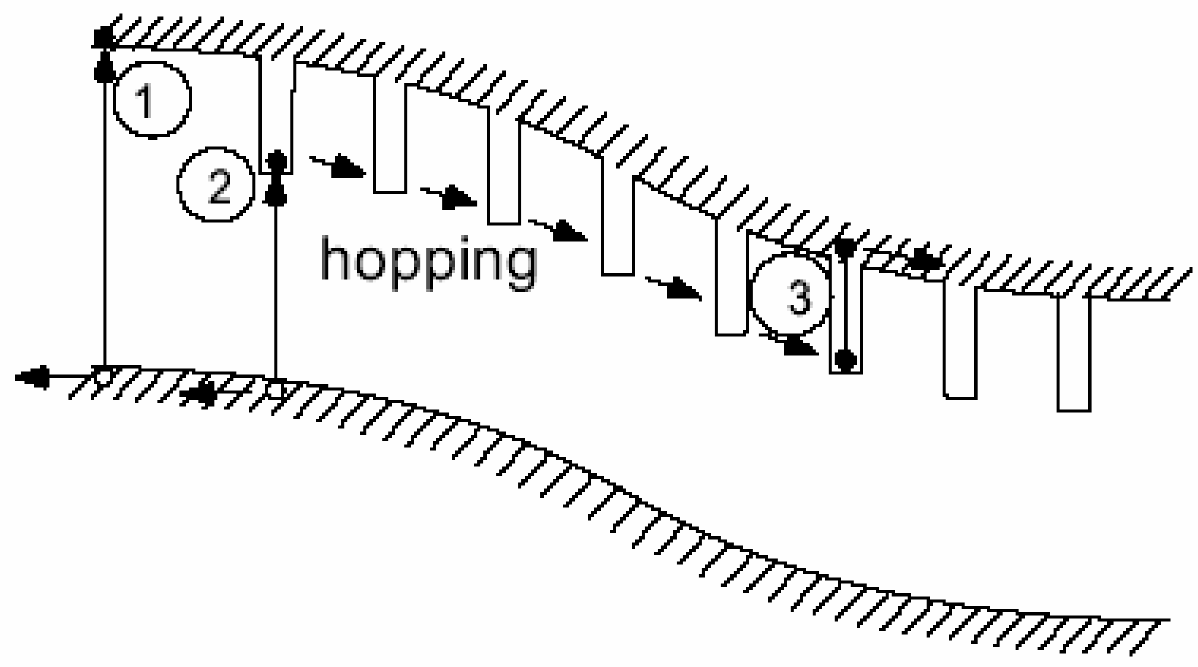
- Many E-H pairs created by incident photon through impact ionization of hot carriers
- Theoretical efficiency is 85.9%

Multiband Cells



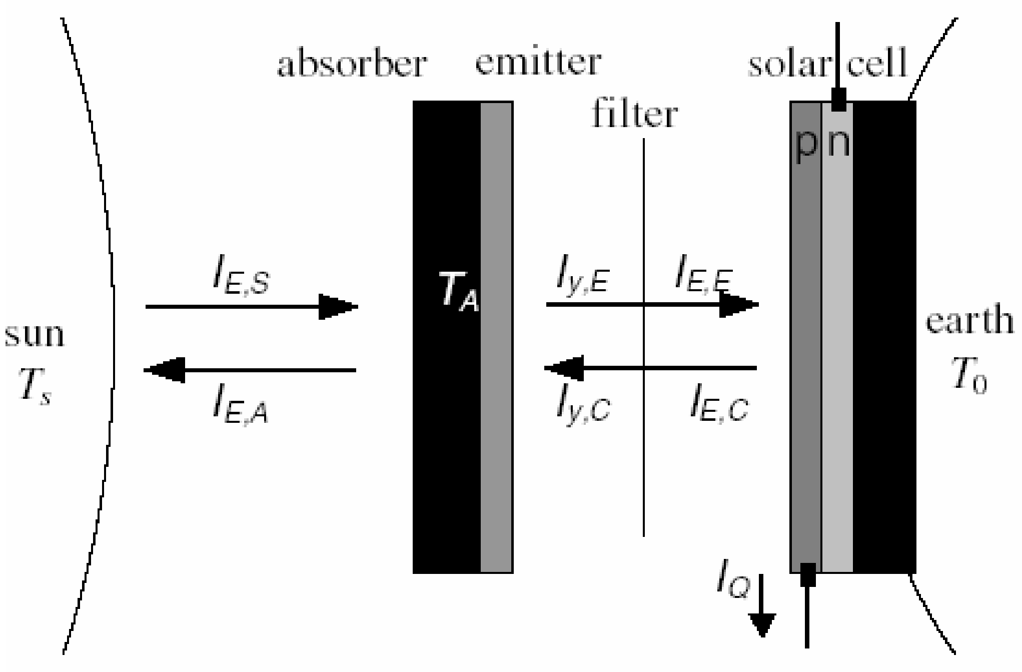
- Intermediate band formed by impurity levels.
- Process 3 also assisted by phonons
- Limiting efficiency is 86.8%

Multiple Quantum Well



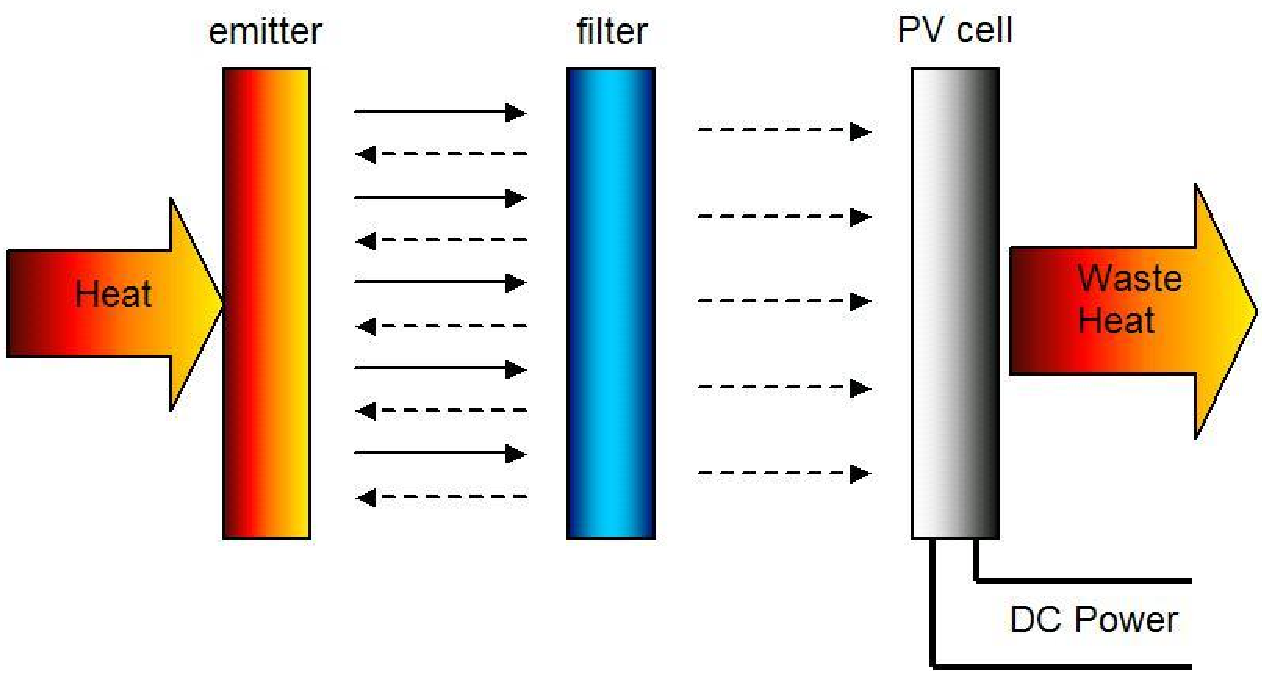
- Principle of operation similar to multiband cells

Thermophotovoltaic Cell

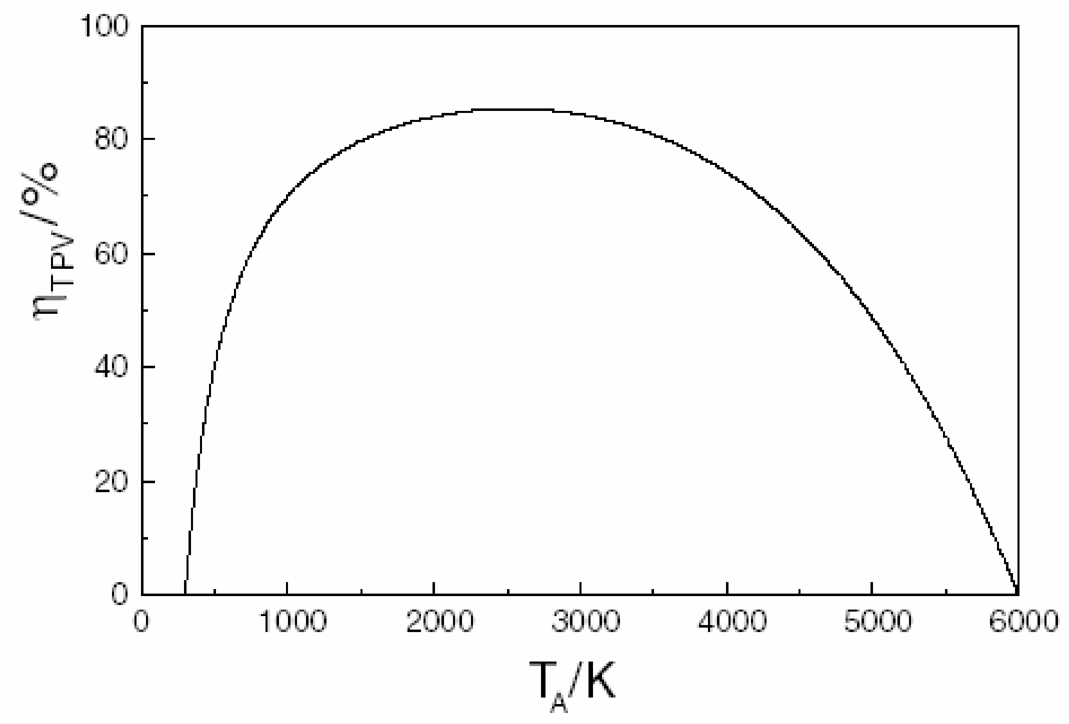


- Filter passes radiations of energy equal to bandgap of solar cell material
- Emitter radiation matched with spectral sensitivity of cell
- High Illumination Intensity (~ 10 kW/m^2)

Thermophotovoltaic Cell



Thermophotovoltaic Cells



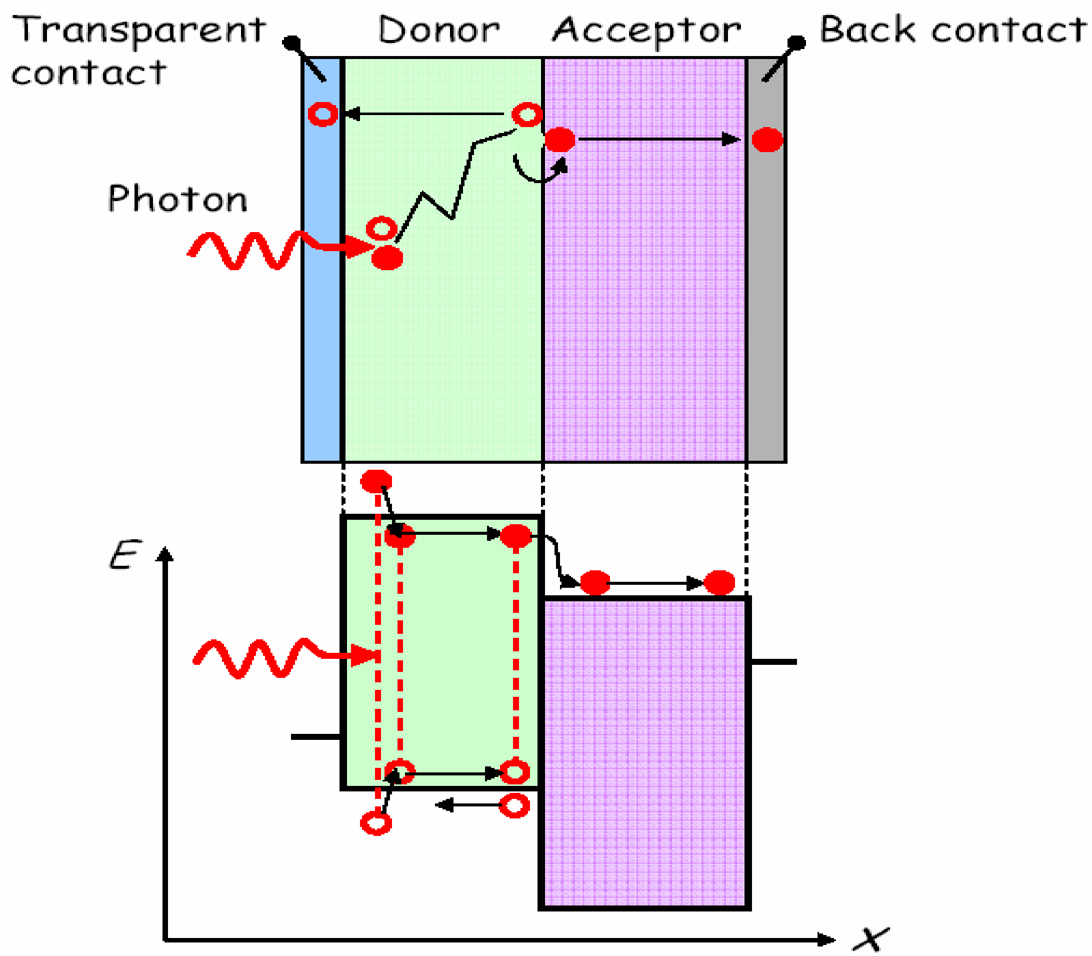
$$\eta_{\mathrm{TPV}} = \left(1 - \frac{\pi}{\Omega_S}\frac{T_A^4}{T_S^4}\right)\left(1 - \frac{T_0}{T_A}\right)$$

- Theoretical efficiency almost twice of ordinary photocell

Organic Solar Cells

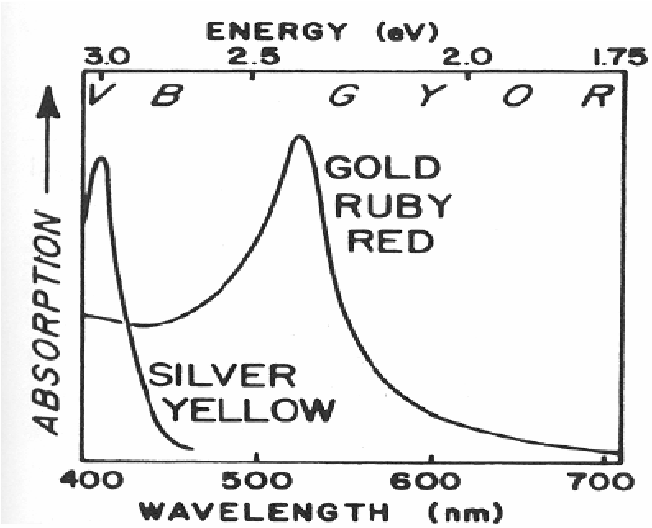
- A typical cell operation
    1. Photon absorption
    2. Exciton diffusion
    3. Charge transfer
    4. Charge separation
    5. Carrier collection

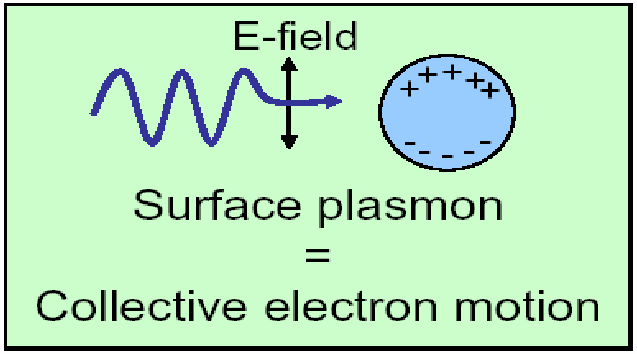
- Band diagram



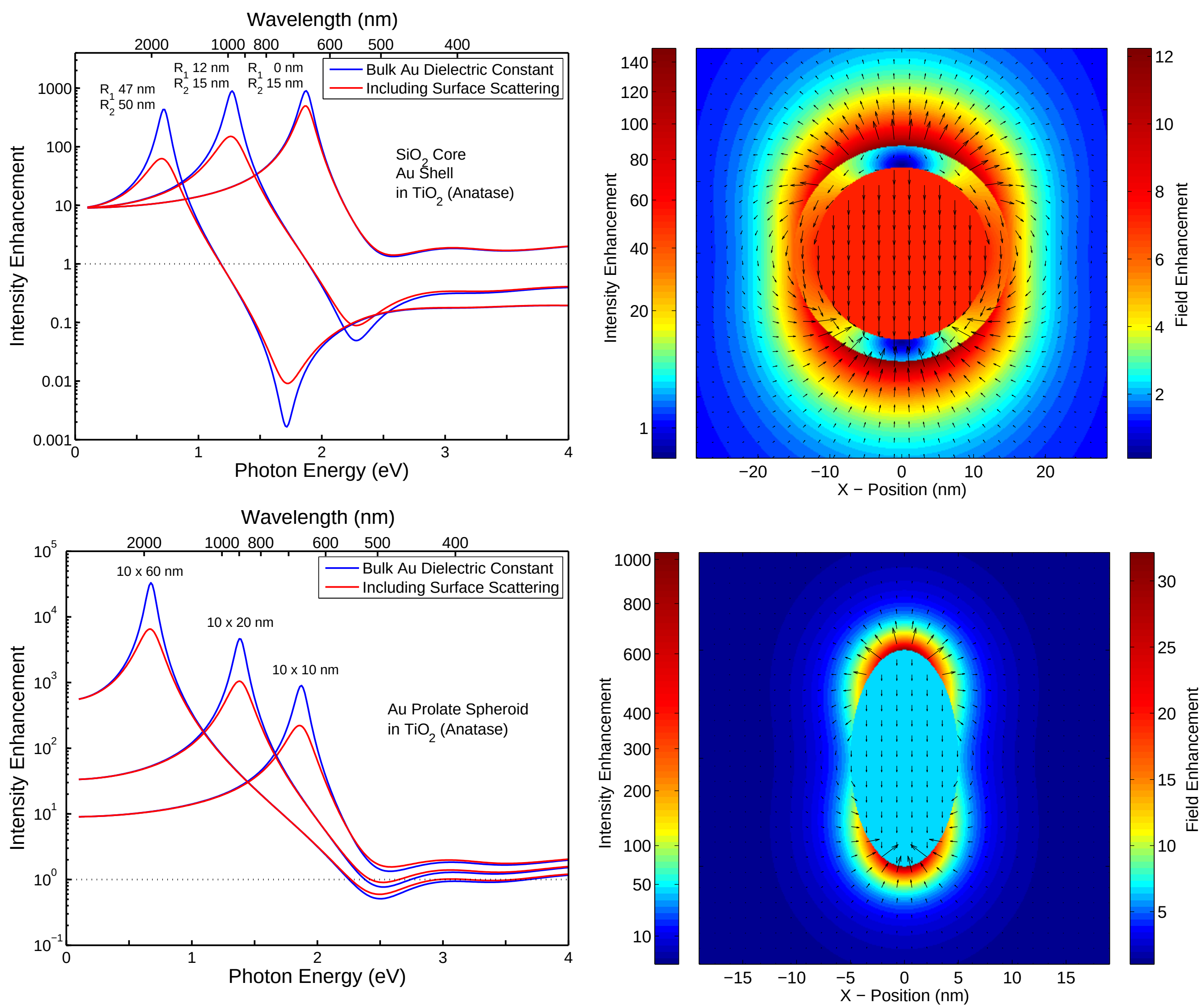
Plasmon Resonances of Metal Nanoparticles

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



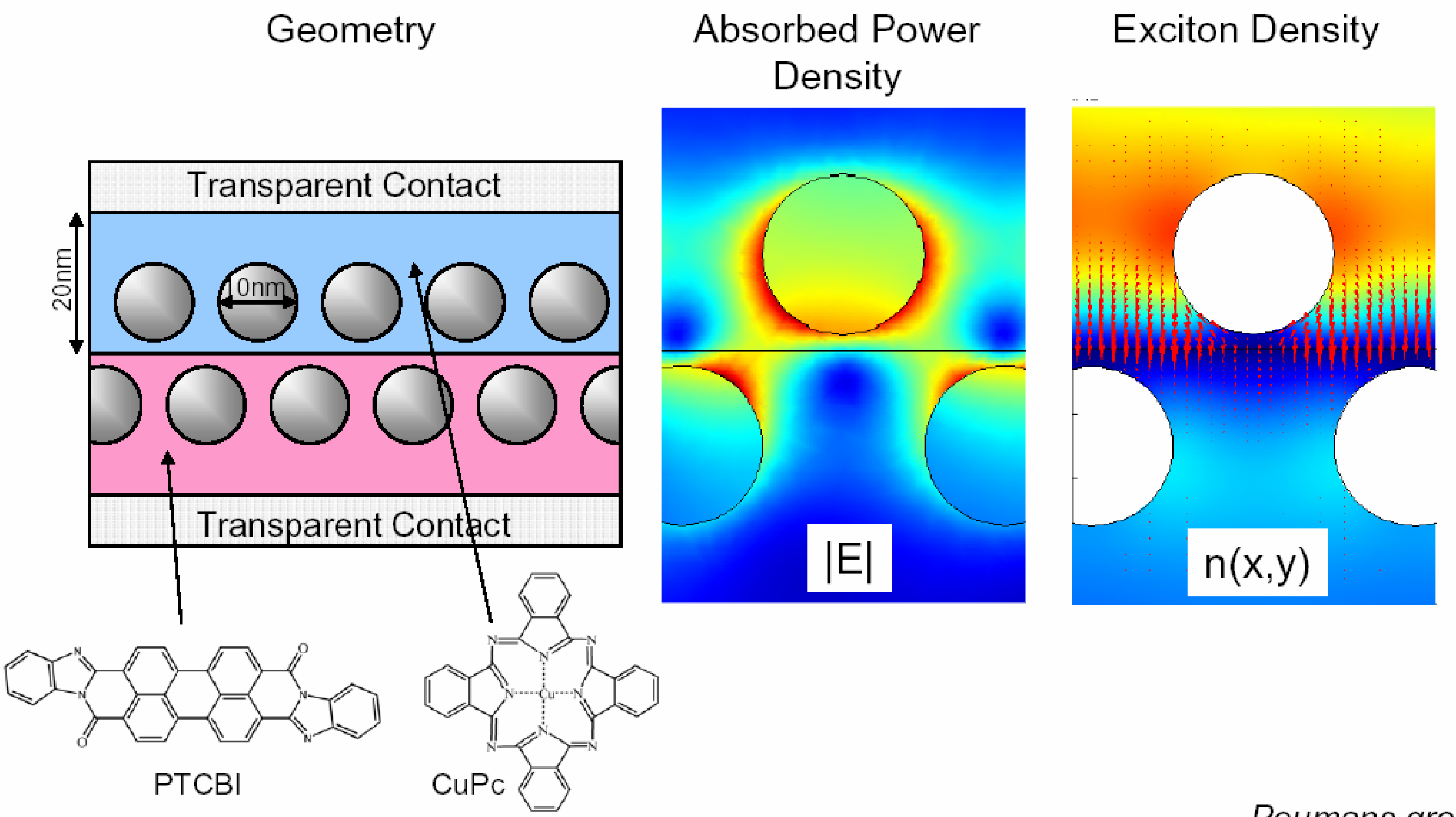


Plasmon Resonances of Metal Nanoparticles



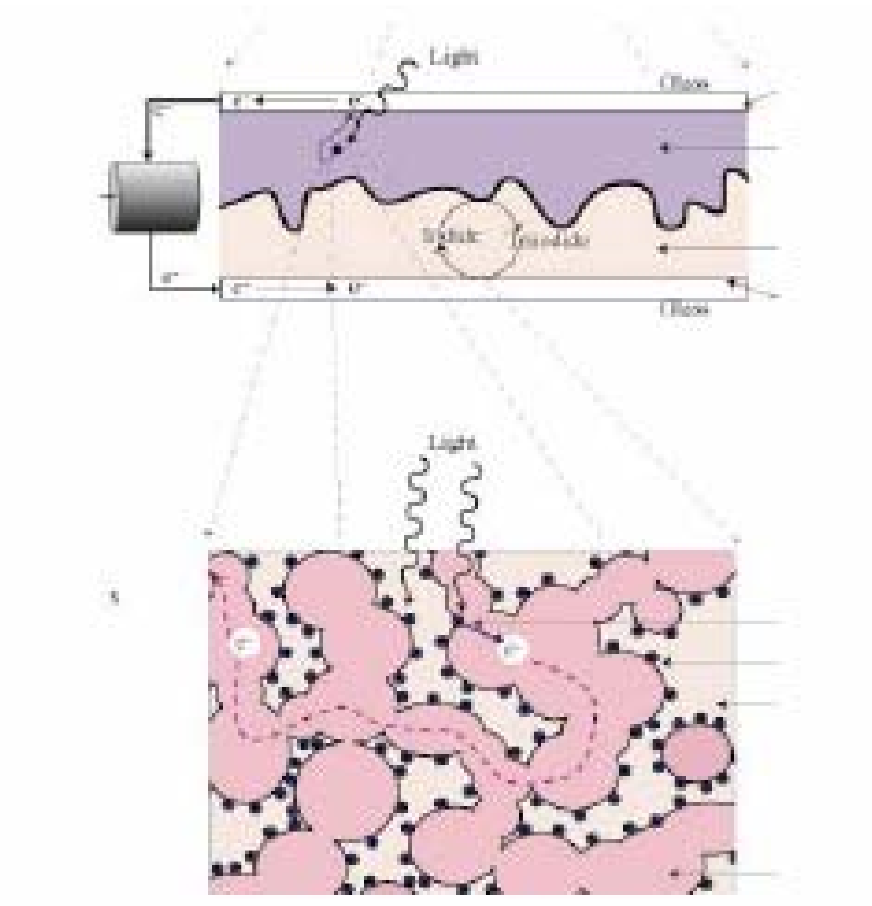
Light Concentration using Nanoparticle Plasmon Resonances

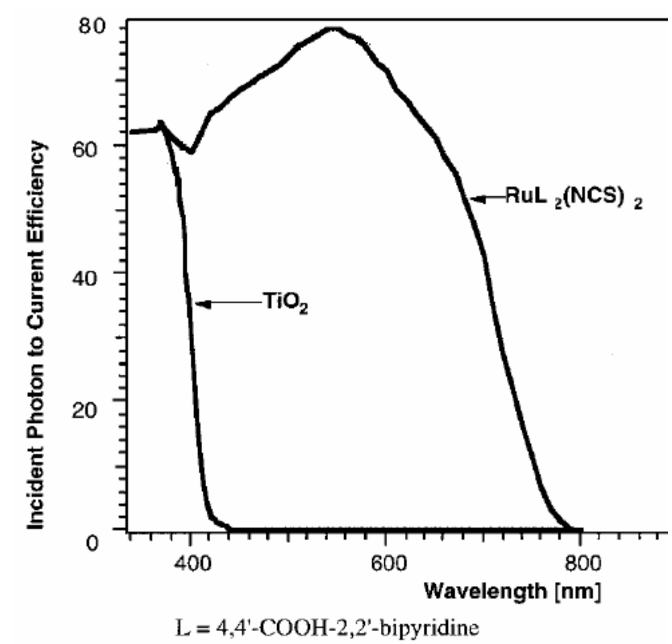
- Zig-zag configuration concentrates electromagnetic power at active junction



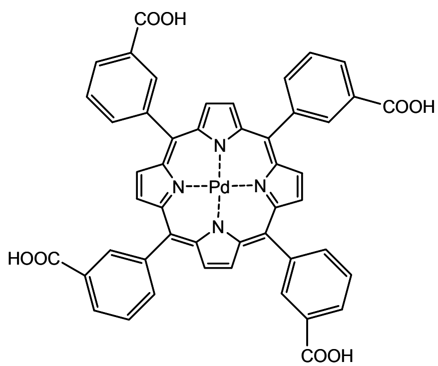
Peumans group

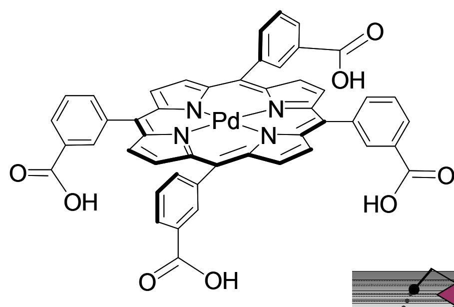
Dye Sensitized Solar Cells

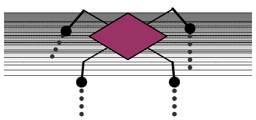


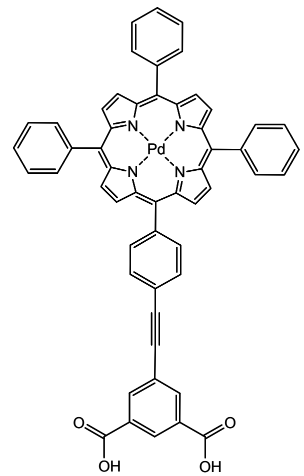


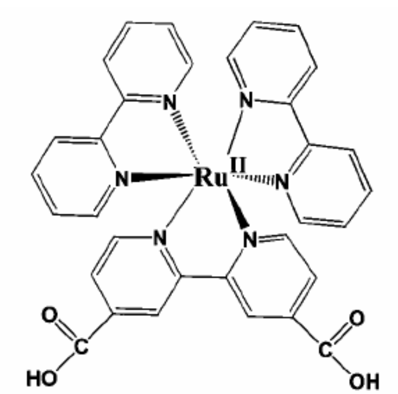
Dye Sensitizer Molecules

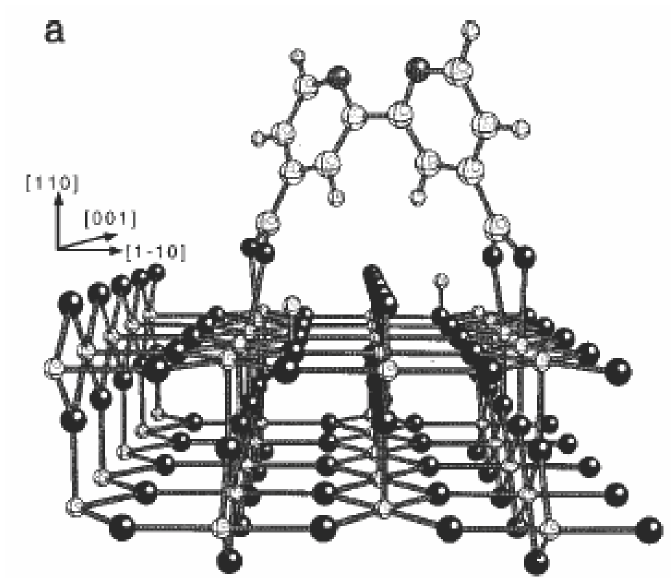












Dye Sensitized Solar Cells