

UCONN ENGR_ECE 4243-6243 Course outline Chapter 15 F. Jain

L13 11292016-Solar Cells Part I (Sections 6.1-6.8)

L14 Solar cells Part-II Tandem cells, MEG, and QD Solar Cells

	Notes page	Slide#
6.1. Introduction and Overview-I	442	2-3
6.2 Solar Spectrum and Air Mass m	445	4-5
6.3 Absorption of Photons in Semiconductors, Materials, Concentrated Solar	446	6-10
6. 4. Photovoltaic Effect: V_{oc} , I-V equation, V_m - I_m , Fill factor	451	11-15
6.5 Conversion Efficiency and Losses	459	16-18
6.6 Solar Cell Materials and Technologies: Generation I	461	19
6.7 Solved Examples	465	-
6.8.1 Solar Cell Design: Design Solution AM1 (m=1)	469	20-28
6.8.2 Solar cell design for AM 0 (outer space)	480	-
6.9 Fabrication & Simulation of Solar Cells	486	-
6.10 Tandem Solar cells	488	29-33
6.11 Tandem, MEG, and QD Solar Cell	494	34-50
6.12 Problem set and solutions	514	-see HW12/solutions-
6.13 Derivation of V-I equation in n-p solar cell	524	-
6.14 Solar cell summary, Popquiz questions	531	51-54

Operating conditions and applications:

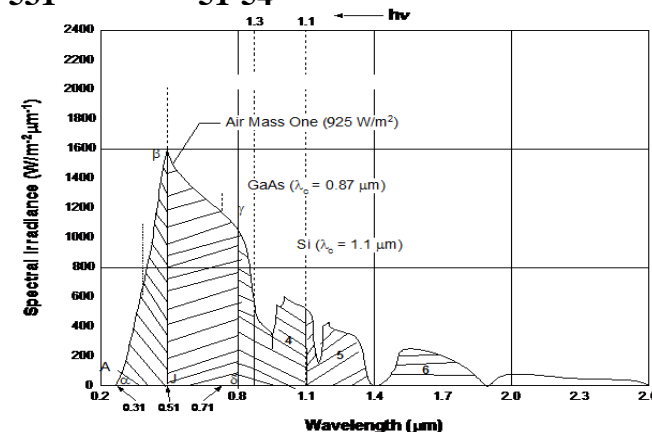
1. Terrestrial applications (as is) & Concentrated Solar Power (CSP)
2. Space application for satellites

Critical parameters:

Conversion efficiency, cost/Watt-peak, sustainable materials.

Costs:

*Solar cell cost 25%, Modules/panels cost 25%, and
Panel installation cost 50%*



Photon absorption and creation of electron-hole pairs

Photons are generally absorbed in semiconductors when their energy is above the band gap E_g . This involves generation of electron-hole pairs (EHPs). An absorbed photon produces one EHP.

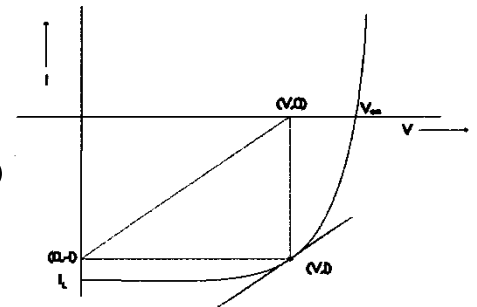
Separation of electrons and holes before they recombine requires the presences of a barrier such as:

p-n junction (homojunction or heterojunction)

Schottky interface (MS, metal-semiconductor) or MIS (metal-thin insulator ~20Å-semiconductor).

Conversion efficiency η_c ($V_m I_m / P_{in}$)

The maximum power transfer (V_m, I_m) is related to *Fill factor FF* is defined as $(V_m I_m) / (V_{oc} I_{sc})$. It corresponds to fitting a maximum rectangle in the I-V characteristic.



Material Selection

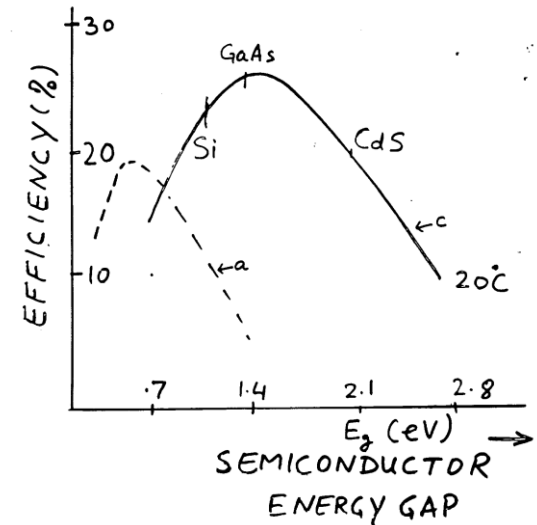
The maximum power that a cell can deliver is $I_{sc} * V_{oc}$.

Short circuit current I_{sc} depends on the band gap E_g ;

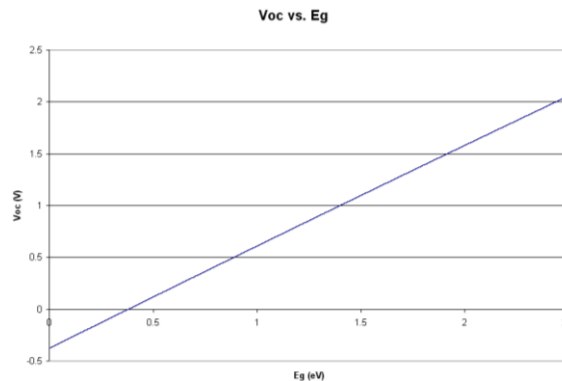
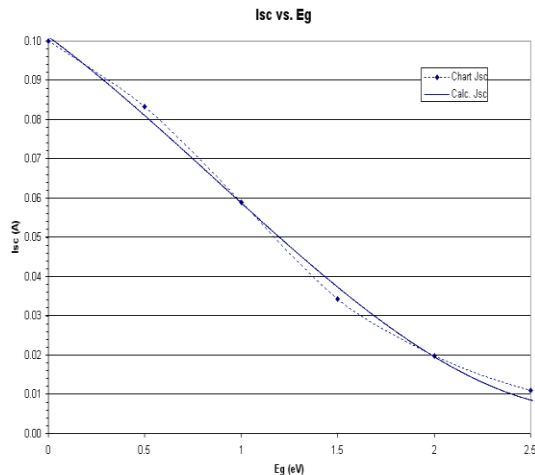
It is high for smaller energy gap semiconductors,

Open circuit voltage V_{oc} [$\sim (kT/q) * \ln(I_{sc}/I_s)$] depends on the ratio of I_{sc} or I_L and reverse saturation current I_s . Since the reverse saturation current decreases as we increase the band gap E_g , it is low for higher energy gap materials.

As a result the product of $I_{sc} * V_{oc}$ peaks at $E_g = 1.4$ eV. See Fig, 15. pp. 422; Figs. 34 and 35 below.



$$\eta \propto V_{oc} J_{sc}$$



Solar cell summary equations p. 431-432

Air mass m is defined

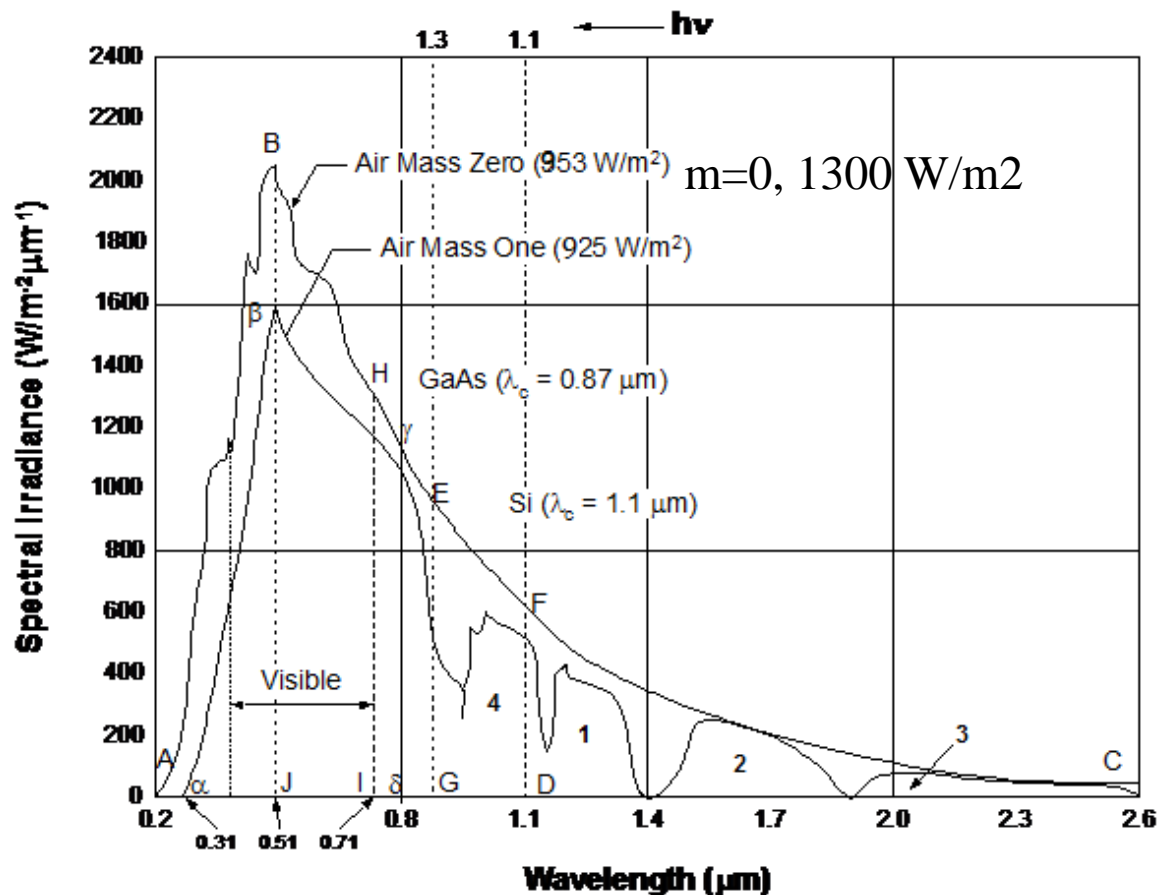
$$m = \frac{\text{optical pathlength of the sunlight at the time of measurement}}{\text{pathlength when the sun is at zenith}}$$

Air Mass	Condition	Power Density
$m=0$	Outer space	130 mW/cm ²
$m=1$	Zenith	92 mW/cm ²
$m=2$	is used as more representative	74 mW/cm ²

Air mass $m=2$ or AM $m=1.5$ are taken as a typical average for the day.

At $m=2$, we have 74mW/cm² which produces $I_{SC} = 27\text{mA}$ for a cell sample of 1cm².

Solar spectrum under $m=0$, $m=1$



Absorption (Fig. 4, p. 434)

Absorption coefficient α depends on the material. Direct gap semiconductors have higher value near the energy gap E_g than indirect gap semiconductors.

a. Direct band-to-band with no phonon involvement.

$$\alpha = A(h\nu - E_g)^{\frac{1}{2}} \quad (2)$$

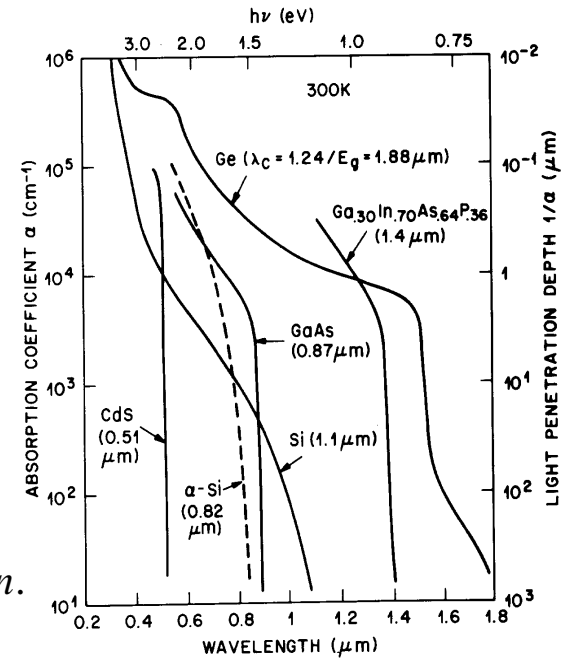
b. Indirect band-to-band with phonon absorption or emission.

$$\alpha(h\nu) = \frac{C(h\nu - E_g + E_p)^2}{e^{\frac{E_p}{kT}} - 1} + \frac{C(h\nu - E_g - E_p)^2}{1 - e^{-\frac{E_p}{kT}}} \quad (3)$$

(phonon absorption) + (phonon emission)

Fig. 5 shows photon flux or solar power or intensity $I(x)$ decreases as the light propagates in the semiconductor.

At $m=2$, we have 74mW/cm^2 average power incident which produces $I_{SC} = 27\text{mA}$ for a cell of 1cm^2 .



$$I(x) = I_0 e^{-\alpha x}$$

$$\Phi(x) = \Phi_0 e^{-\alpha x}$$

Material selection for a solar cells:

The material selection depends on if the cell is to be used with concentrator or as is.

Material could be single crystalline, polycrystalline, or amorphous.

Generally the materials fall in two categories:

(1) high efficiency ($> 25\%$) cells, and
(2) low efficiency ($\sim 10\%$) but inexpensive to fabricate cells. In the case of high efficiency cells, Olson and Friedman [1] have tabulated a number of material systems. These include: GaAs-GaInP, CuInSe/CdS, GaAs-CuInSe₂ and CuInGaSe (CIGS) cells.

Amorphous Si cells are used in portable electronics. Other popular materials include Si ribbon or polycrystalline Si.

Material selection for a solar cells: Competing solar panels

p-CdTe/n-CdS cells are $\eta = 16.5 - 20\%$ (First Solar).

Doping of CdTe is due to vacancies. CdTe becomes \rightarrow n type with Te vacancies and p type with Cd vacancies.

Deposition of CdTe is followed by processing including annealing at temperature $T > 400^\circ\text{C}$ in the presence of ($\text{CdCl}_2 + \text{Oxygen}$) which gives optimal efficiency. CdTe films grown at low temperature becomes re-crystallized during this step. This improves the carrier life time which approaches $\tau_n \sim 2\text{ns}$. These cells give an open circuit voltage of $V_{oc} \sim 810\text{mV}$.

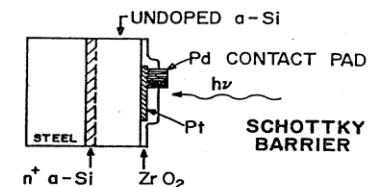
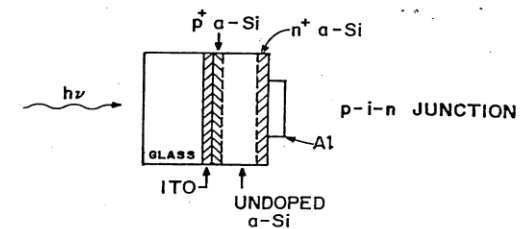
Crystalline Si wafers: $\eta = 20\text{-}25\%$

Polycrystalline-Si wafers cells: $\eta = 12.5\text{-}20\%$.

(REF. M.A. Green, Progress in Photovoltaics; Research and Appl., Vol 17, pp. 183-189, 2009.)

aSi-on nanoSi-on glass $\eta = 11\text{-}12\%$.

Amorphous-Si cells are $\eta = 10.1\%$.



Concentrated Solar Photovoltaic (CSP)

High efficiency (44-42% triple-junction e.g. Ge/GaAs/GaInP) solar cells are used with solar concentrators. **Spire Corp.**

- Concentration (lenses/reflectors) is cost effective in module costs.
- Olson and Friedman [1] suggest that a 1000 MW power plant using 1000X concentration would require less than 5000 m² in cell area.

Multi-junction and tandem cells are used in material system, which are expensive to fabricate. This way we increase their efficiency. Figure 1 shows a tandem cell that is built on p-GaAs substrate. It has two n-p junctions and one p+-n+ GaAs tunnel junction. The tunnel junction is between the TOP and BOTTOM solar cells. The tunnel junction provides the interface between the two cells. This enables a series connection between two n-p cells having the same series current. See Fig. 47, p. 467 or Fig. 1 page 430.

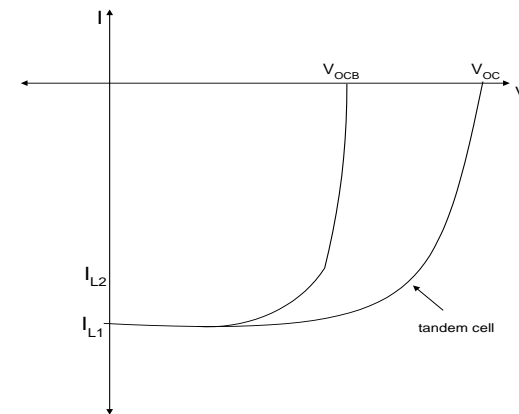
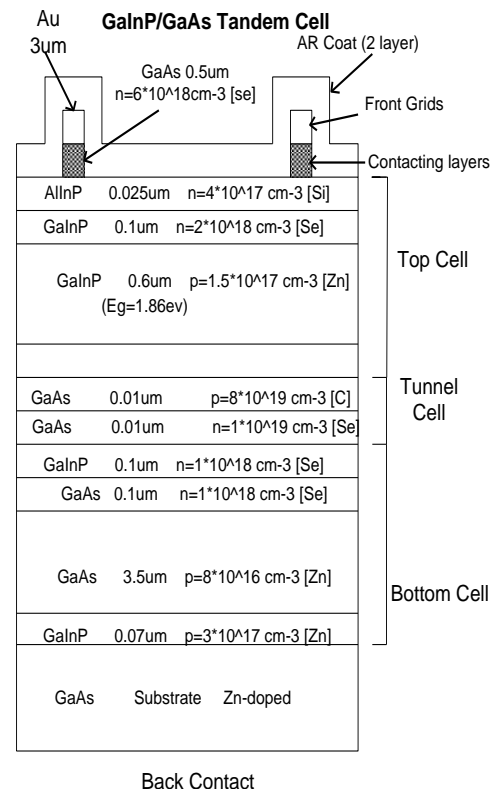


Fig. 2. I-V Characteristics of a tandem cell.

Concentrated Solar Photovoltaic (CSP)

Short circuit current increases and efficiency also increases. Fig. 24, p. 456

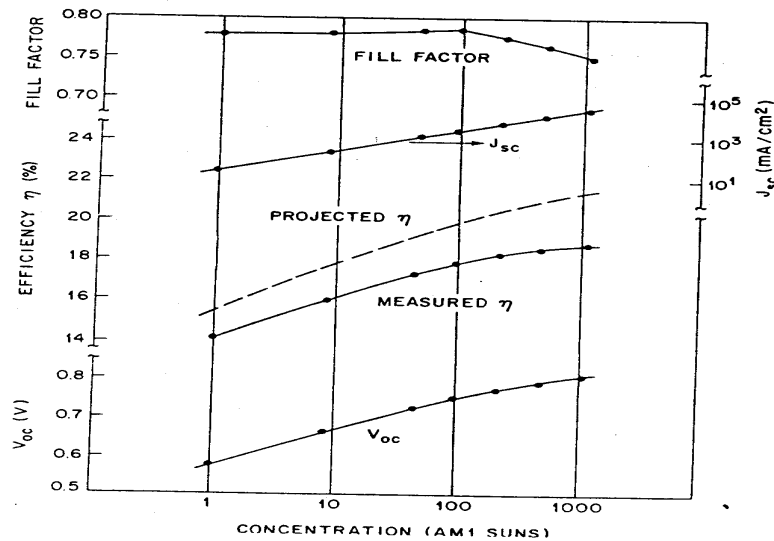
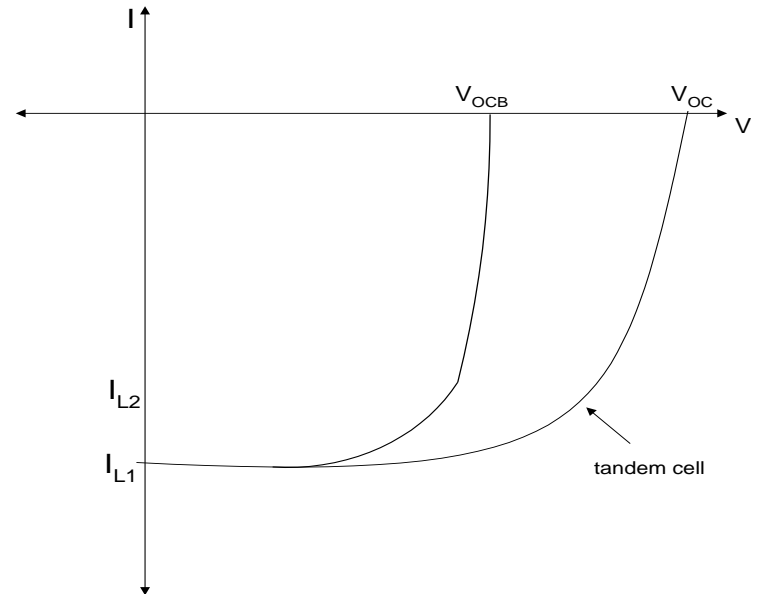
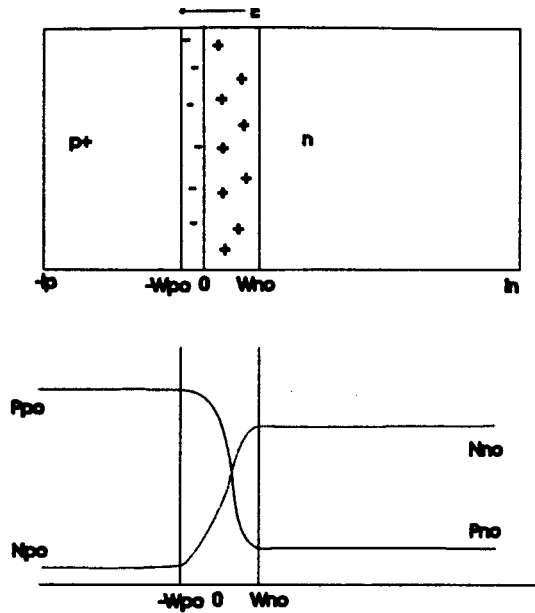


Fig. 46 Efficiency, open-circuit voltage, short-circuit current, and fill factor versus solar concentration.



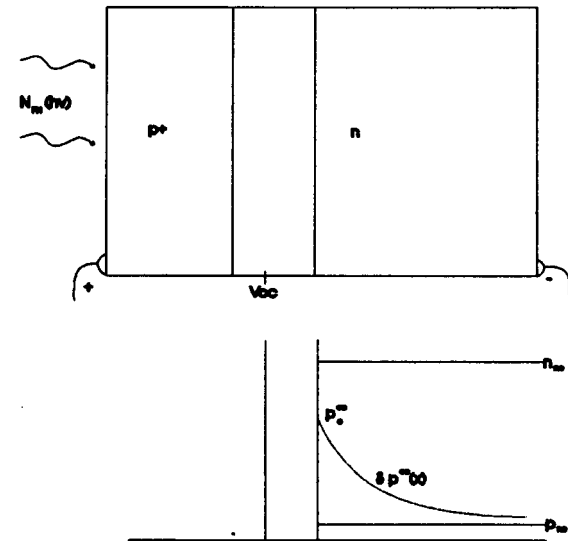
Photovoltaic effect:



P-n junction under equilibrium

$$V_{bi} = \frac{kT}{q} \ln \frac{p_{po}}{p_{no}}$$

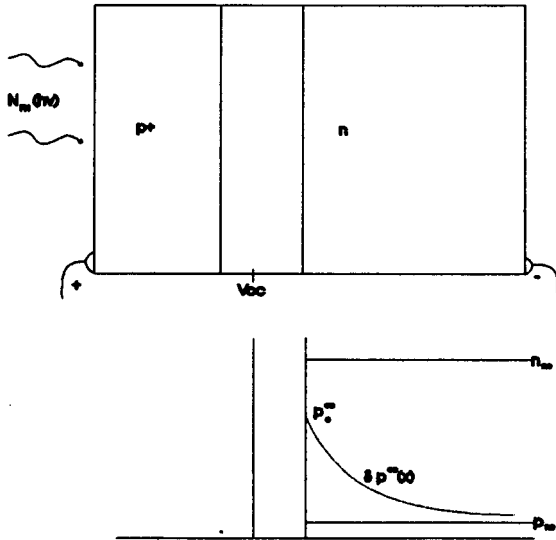
$$(27) \quad I = I_s \left(e^{\frac{qV}{kT}} - 1 \right) - I_L (\text{or } I_{sc})$$



P-n junction under illumination
with no load.

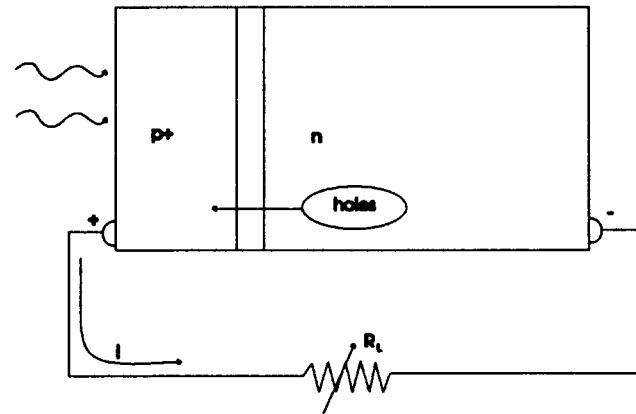
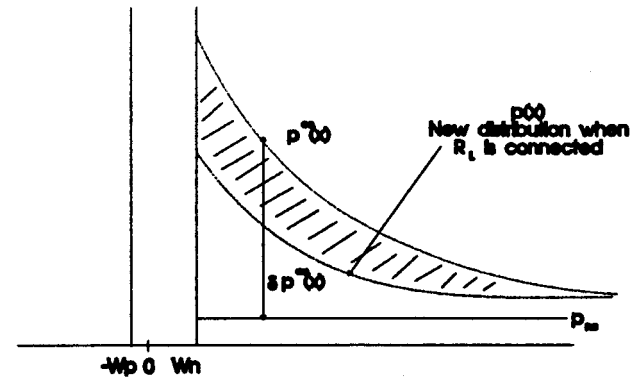
$$p_e^{oc} \cong p_{no} e^{\frac{qV_{oc}}{kT}}$$

Photovoltaic effect:



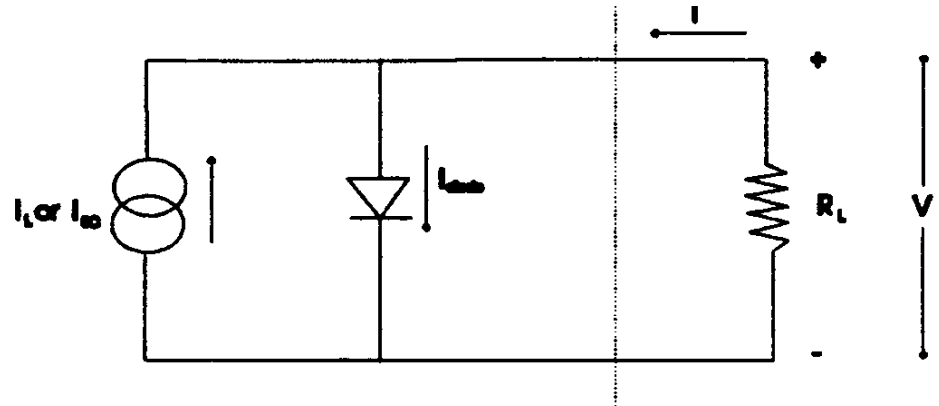
P-n junction under illumination
with no load.

$$p_e^{oc} \cong p_{no} e^{\frac{qV_{oc}}{kT}}$$

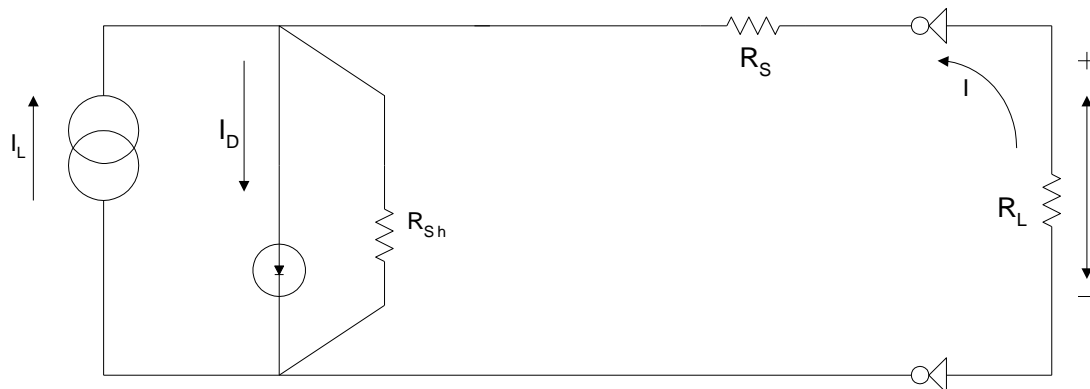


P-n junction under illumination
with load.

Equivalent Circuits:



$$I = I_s \left(e^{\frac{qV}{kT}} - 1 \right) - I_L \text{ (or } I_{sc} \text{)} \quad (27)$$



Open Circuit Conditions:

V-I Equation : Equivalent Circuit Approach

Generally, the behavior of a solar cell is modeled by the following equations. I_L or I_{SC} is the current under short circuit condition generated by absorption of photons.

Open circuit voltage is obtained by putting $I=0$ in Eq. 27 and rearranging terms.

$$V_{oc} = \frac{kT}{q} \ln \left(\frac{I_L + I_s}{I_s} \right) \quad (36)$$

Maximum Power Point

$$I = I_s \left(e^{\frac{qV}{kT}} - 1 \right) - I_L (\text{or } I_{sc}) \quad (27) \quad V_{oc} = \frac{kT}{q} \ln \left(\frac{I_L + I_s}{I_s} \right) \quad (36)$$

Maximum power point (V_m , I_m) is obtained using

$$\frac{\partial V}{\partial I} = -\frac{V}{I} \quad (40a)$$

,or

$$\frac{\partial I}{\partial V} = -\frac{I}{V} \quad (40b)$$

Combining (40a, 40b) and Eq. (36)

$$V_m = V_{oc} - \frac{kT}{q} \ln \left[1 + \frac{qV_m}{kT} \right] \quad (48)$$

$$I_m = I_s \left[e^{\frac{qV_m}{kT}} - 1 \right] - I_L$$

(49)

$$I_L = I_{sc}$$

Fill Factor

Fill Factor: FF: The fill factor is related to the shape of the V-I plot.

$$FF = \frac{V_m I_m}{V_{oc} I_L} = \frac{P_m}{V_{oc} I_L} = \frac{\text{Area of inner rectangle}}{\text{Area of outer rectangle}} \quad (50)$$

Conversion Efficiency

The conversion efficiency is defined as the ratio of maximum electrical power output to the optical power incident. It is defined as

$$\eta_c = \frac{V_m I_m}{\text{Incident Solar Power}} = \frac{V_m I_m}{P_{in}} = \frac{V_m I_m}{V_{oc} I_L} \bullet \frac{V_{oc} I_L}{P_{in}} = FF \left(\frac{V_{oc} I_L}{P_{in}} \right) \quad (51)$$

Losses in Solar cells

LOSSES: 1. Surface reflection:

Calculate reflectivity $R = \text{Reflectivity of Si} = R =$

$$\left(\frac{n_r - n_{air}}{n_r + n_{air}} \right)^2 = \left(\frac{3.435 - 1}{3.435 + 1} \right)^2 = 0.3$$

Remedy: Design an antireflection coating using n_{r2} film. Let us design for 1.5eV photons.

$$\lambda = \frac{1.24}{h\nu} = \frac{1.24}{1.5\text{eV}} = 0.826 - \mu\text{m} \quad t = \frac{\lambda}{4n_{r2}} (2l - 1) \quad t = \frac{0.8266 * 10^{-4}}{4 * 1.8} (2l - 1)$$

$, l = 1, 2$

2. Long wavelength photons are not absorbed as when $h\nu < E_g$. the absorption coefficient is very small.

3. Excess photon energy loss : Calculation (see design set page 414):

Photon energy above E_g is not used to generated electron-hole pairs (EHPs). This does not contribute to short circuit current I_{SC} or I_L .

$$h\nu \geq E_g$$

Excess Energy Losses in Solar cells

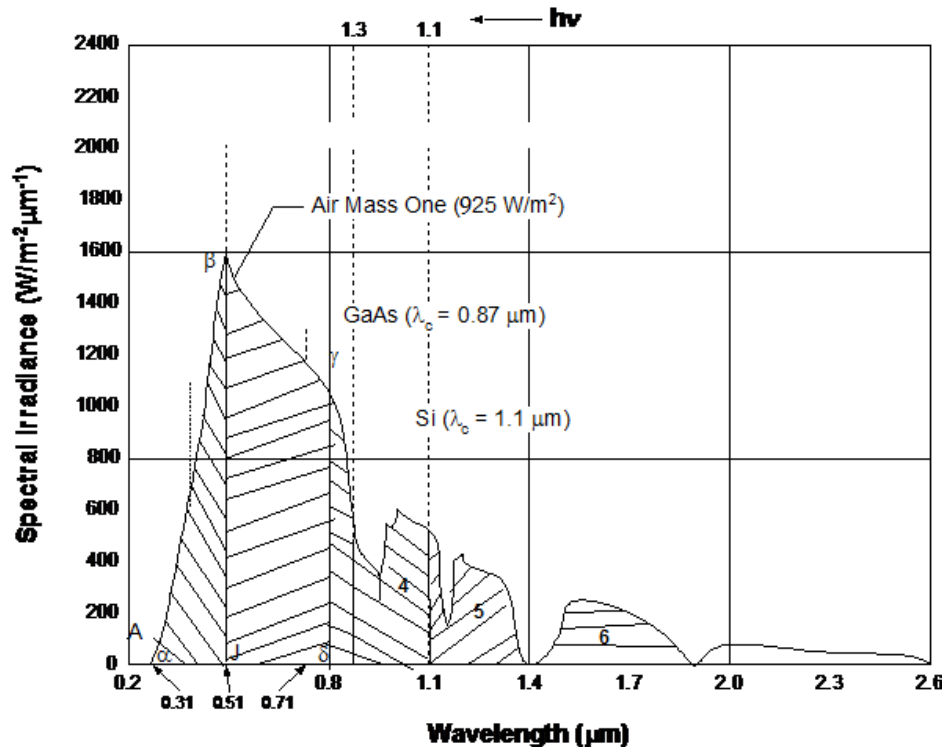
Compute these losses: AM1 plot above $h\nu > 1.1\text{eV}$

Regions are Triangle $\alpha\beta J$, Trapezoid $J\beta\gamma\delta$, Trapezoid marked as #4, small rectangular regions #5 & #6.

Δ (triangle) $\alpha\beta J \Rightarrow$ Photon energy at $\alpha = \frac{1.24}{0.31} = 4\text{eV}$

Photon energy at $J = \frac{1.24}{0.51} = 2.43\text{eV}$

Average photon energy $h\nu_{ave} = \frac{4 + 2.43}{2} = 3.21\text{eV}$



Excess photon energy not used in generating EHP = $3.21 - 1.1 = 2.11\text{eV}$.

Area of the triangle $\Delta \alpha\beta J =$

$$\beta J * \frac{\alpha J}{2} = 1550 * \frac{(0.51 - 0.31)}{2} = 155\text{W} / \text{m}^2$$

Excess energy not used in triangle $\Delta \alpha\beta J$ is =

$$\frac{155}{3.21} * 2.11 = 101\text{W} / \text{m}^2$$

6.6 Solar Cell Materials and Technologies: Generation I

Flat Plate Arrays

Silicon Based

Single crystal wafers

Ribbon

Polycrystalline cast ingots

Thin Films

Cu₂S/CdS polycrystalline Films

GaAs thin layers on Sapphire ribbons

Amorphous Si and Chalcogenide glasses films on steel

Doped polyacetylene and other semi conducting polymers

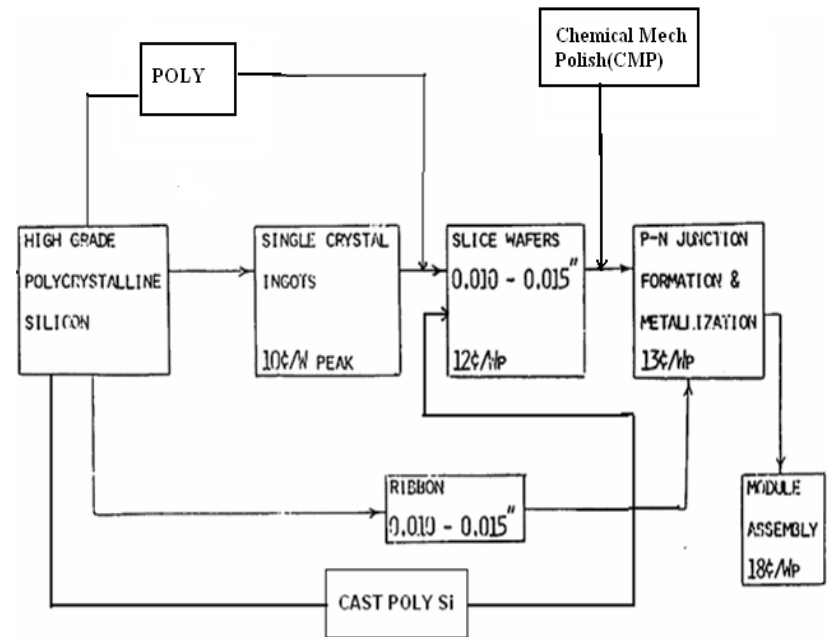
Arrays with Solar Concentrators

Silicon wafers (30-50X)

Gallium arsenide (50-200X)

Graded heterostructures (50-5000X): thermal photovoltaic

Tandem cells Multi Junction cells



IDOE COST GOAL FOR 1986 (IN 1975 DOLLARS): 50¢/Wp

Solar Design p. 456.

Design a p^+ -n Si solar cell for terrestrial applications Air Mass $m=1$.

Given:

Material = n-Si, Resistivity = $10\Omega\text{-cm}$ (see tables to find N_D)

Average power incident P_{in} for air mass $m = 1$ is 92.5 mW/cm^2

(See attached Fig.25, Ref. Sze, Page 289)

Specification desired:

Fill factor ≥ 0.9 and power conversion efficiency $\geq 12\%$.

- Evaluate the surface reflection loss. How would you design an antireflection coating to eliminate this loss (provide index and thickness of this coating).
- Determine the optimum loading condition (V_{mp} , I_{mp}), and compute fill factor for your cell and show that it is > 0.9 (change the ideality factor n if the fill factor is < 0.9).
- Evaluate the other important losses and show that cell would be over 12% efficient.
- Determine the doping concentrations and minimum thickness of n-region.

Assume:

Diffusion lengths (L_n , L_p) and minority lifetimes (τ_n , τ_p) as given in previous problems.

Given that the p^+ region is 0.25 micron thick and having a doping level $N_A = 10^{20} \text{ cm}^{-3}$.

I_L or I_{SC} : The photo generated current I_L (or I_{SC}) decreases as a function of the semiconductor band gap E_g . The open circuit voltage increases with E_g .

Design steps

- Select a cell structure and absorber layer thickness and material. Find the photo-generated I_{sc}
- Design anti-reflection coating.

- Select doping levels, find reverse saturation current I_s and compute V_{oc} ,

$$I_s = \frac{qAD_n n_{p0}}{L_n} + \frac{qAD_p p_{n0}}{L_p} \quad V_{oc} = \frac{kT}{q} \ln \left(\frac{I_s + I_{sc}}{I_s} \right)$$

- Find V_{mp} , I_{mp} or V_m , I_m and fill factor FF.

$$V_m = V_{oc} - \frac{kT}{q} \ln \left[1 + \frac{qV_m}{kT} \right]$$

$$I_m = I_s \left(e^{\frac{qV_m}{kT}} - 1 \right) - I_{sc}$$

Design steps cont.

There are some ways to obtain a fill factor of 0.9.

One-way is to reduce I_s by increasing the doping of the substrate.

The other way is to use a heterojunctions. Both results in high V_{OC} .

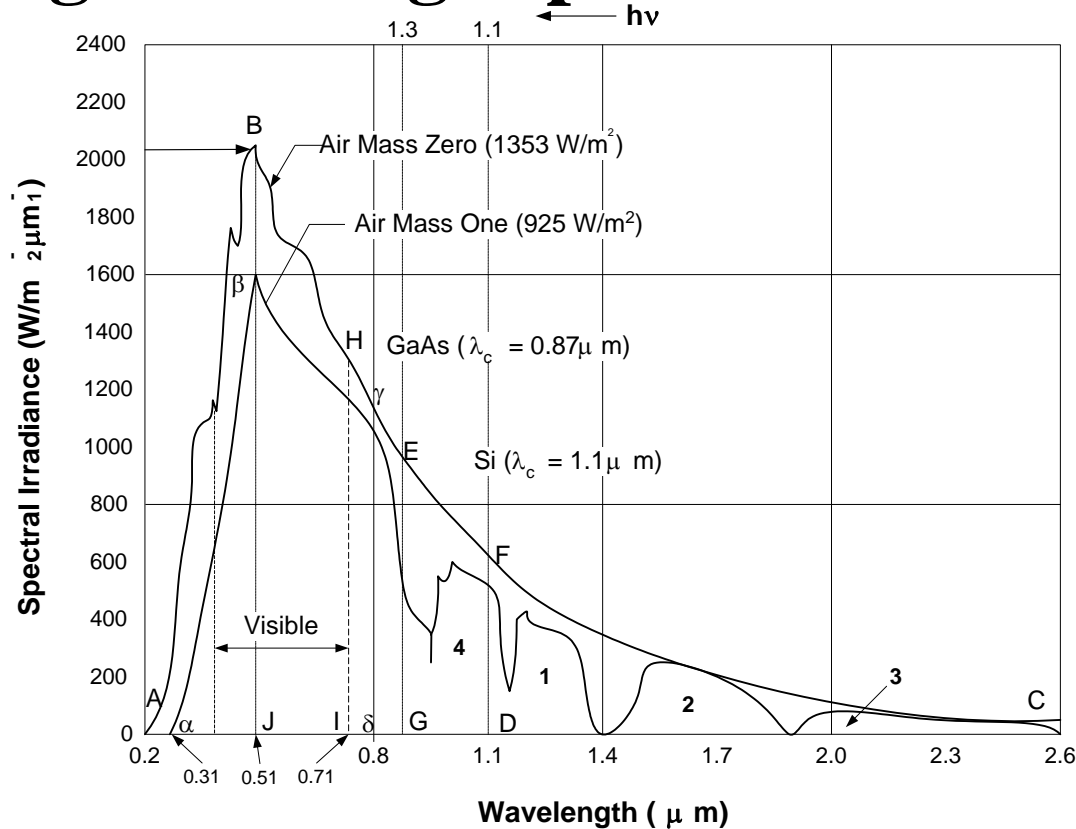
Reducing I_s or Increasing V_{OC}

Increase the doping of the substrate. Let $N_D = 100 \times 4 \times 10^{14} = 4 \times 10^{16} \text{ cm}^{-3}$. We will keep N_A for p+ = 10^{20} cm^{-3} .

Reduce losses due to:

- Long wavelength ($h\nu < E_g$ of 1.1eV for Si)
- Excess photon energy not used in generating electron-hole pairs.
- Voltage factor (qV_{OC}/E_g)
- Fill Factor FF.
- Current collection efficiency
- (a measure of higher light generated current I_{SC})

Long wavelength photons not absorbed



With reference to the figure, in area of region 1, 2 & 3, the solar power is:

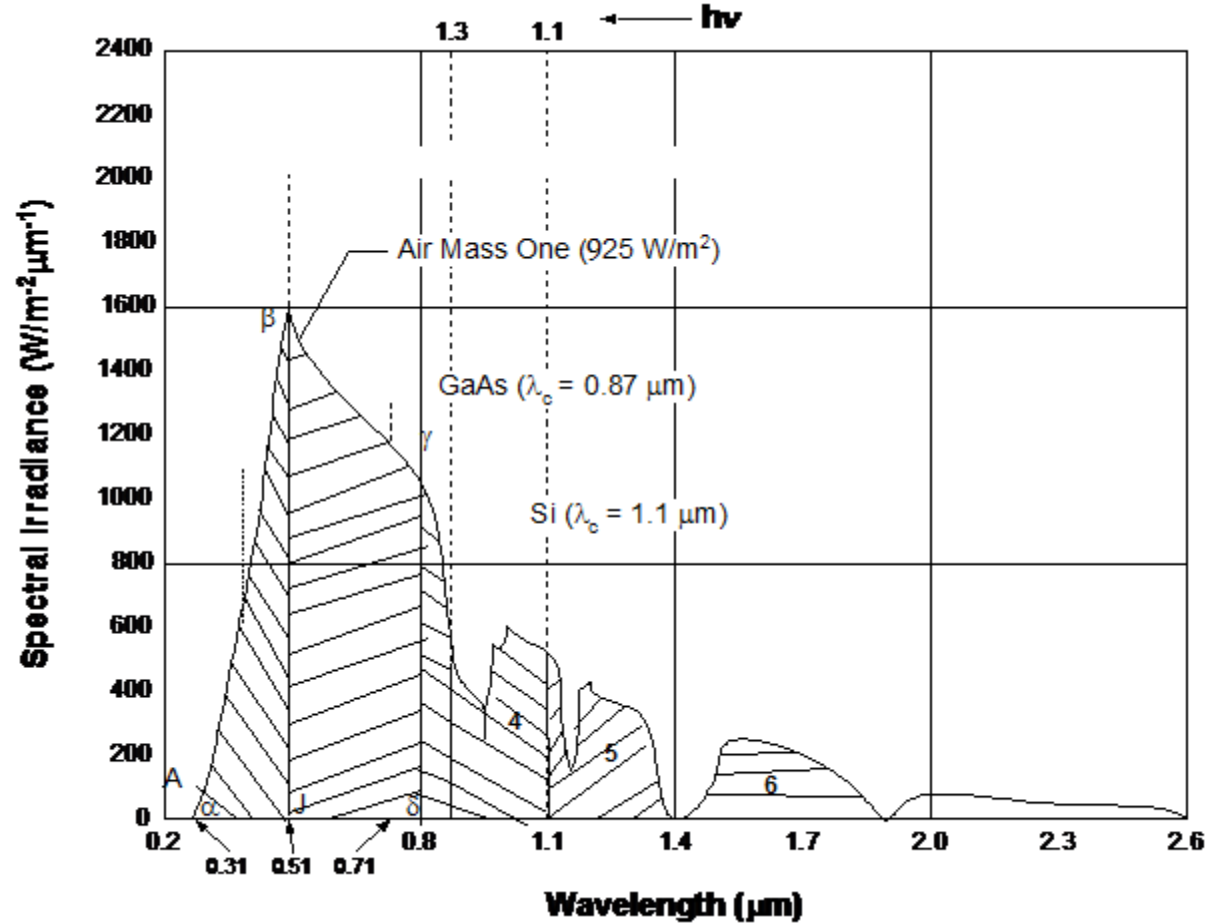
Region #1 68.4 W/m^2

Region #2 72.69 W/m^2

Region #3 35.77 W/m^2

Total long wavelength ($h\nu < E_g$ of 1.1 eV for Si) photons losses = 176.86 W/m^2 23

Excess photon energy



For the AM1 power plot above $h\nu > 1.1\text{eV}$, we have 5 regions.

- Regions are 1) Triangle $\alpha\beta J$, 2) Trapezoid $J\beta\gamma\delta$, 3) Trapezoid marked #4, 4) Rectangle $\gamma\gamma'J\delta$, and 5) Δ triangle $\gamma\gamma'\beta$.

$$\text{Area of the } \Delta\alpha\beta J = \beta J * \frac{\alpha J}{2} = 1550 * \frac{(0.51 - 0.31)}{2} = 155 \text{ W} / \text{m}^2$$

$$\text{Excess energy not used} = \frac{155}{3.21} * 2.11 = 101 \text{ W} / \text{m}^2$$

$$\text{Trapezoid } J\beta\gamma\delta \Rightarrow h\nu \text{ at } \beta J \Rightarrow \frac{1.24}{0.71} = 2.43 \text{ eV}$$

$$h\nu \text{ at } \gamma\delta \Rightarrow \frac{1.24}{0.84} = 1.476 \text{ eV} \quad h\nu_{ave} = \frac{1.476 + 2.43}{2} = 1.953 \text{ eV}$$

$$\text{Area} = \text{Rectangle } \gamma\gamma'J\delta + \Delta\gamma\gamma'\beta$$

$$= 950 * (0.84 - 0.51) + (0.84 - 0.51) * (1550 - 950) / 2 = 412.5 \text{ W} / \text{m}^2$$

$$\text{Excess energy lost} = (412.5 / 1.953) * 0.843 = 178.05 \text{ W} / \text{m}^2$$

Trapezoid #4, Rectangle #5 & Rectangle #6 can be combined by a rectangle.

$$= 500 * (0.84 - 1.1) = 130 \text{ W} / \text{m}^2$$

$$h\nu_{ave} = \frac{\left(\frac{1.24}{0.84} + \frac{1.24}{1.1}\right)}{2} = \frac{1.476 + 1.127}{2} = 1.3eV$$

$$\text{Excess energy per photon} = h\nu_{ave} - E_g = 1.301 - 1.1 \sim 0.2eV$$

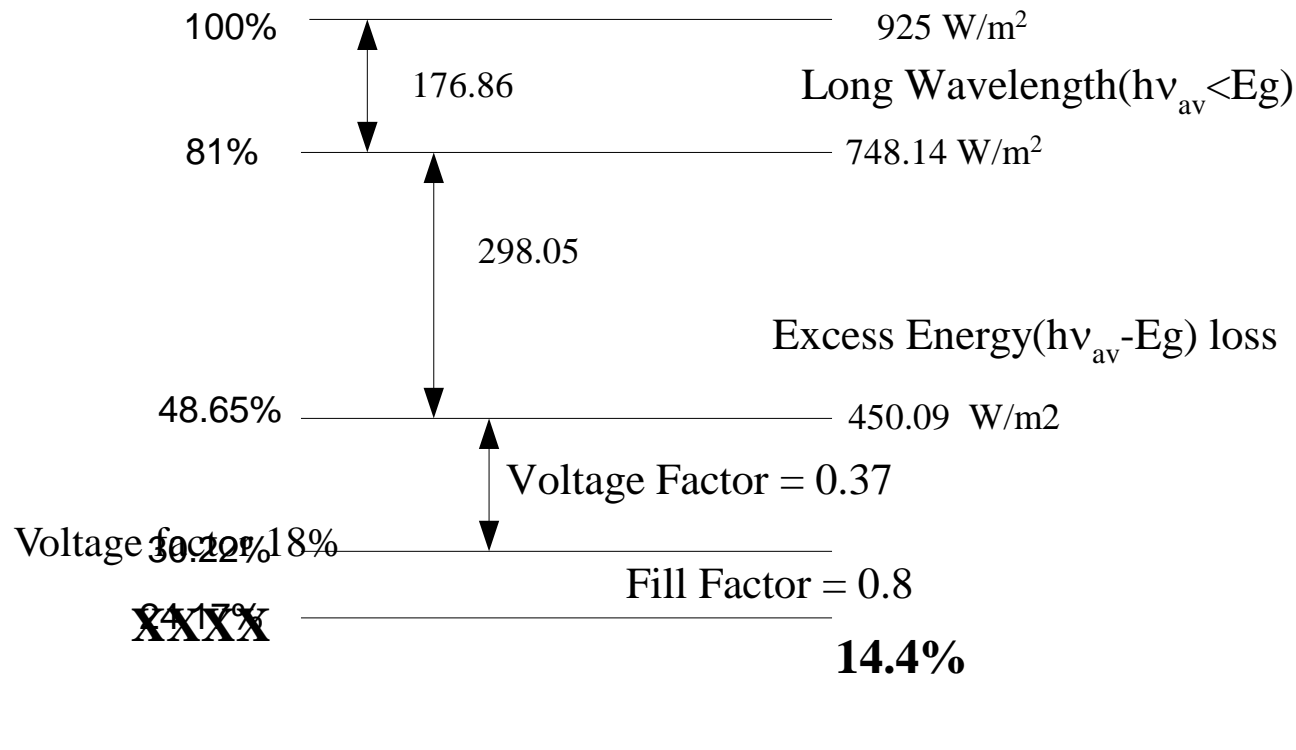
$$\text{Excess energy not used} = \frac{130}{1.3eV} * 0.2 \sim 19W / m^2$$

$$\begin{aligned} &\text{Add all excess energy lost without being used as} \\ &\text{EHP} = 101 + 178.05 + 19 \\ &\approx 298.05 \text{ W/m}^2 \end{aligned}$$

$$\text{(iii) Voltage factor} = \frac{qV_{oc}}{E_g} = \frac{0.4175}{1.1} = 0.379 \text{ or } 37.9$$

$$\text{(iv) Fill factor} = 0.8$$

These four losses are plotted as follows



14.4% is reduced ~ 80% loss due collection efficiency (which impacts short circuit current I_{SC}), we get 11.5%. Therefore, to design a cell at 12% the voltage factor needs to be improved by increasing V_{oc} . 27

Absorber layer thickness

(iv) Doping concentrations & minimum thickness of n-region.

$$P_{\text{abs}} \text{ in n-Si} = 925 - 176.86 = 748.14 \text{ W/m}^2$$

$$P_{\text{abs}} = P_{\text{in}} (1 - e^{-\alpha(\hbar\nu_{\text{ave}})d})$$

Where, d – thickness of n-region.

$$\hbar\nu_{\text{av}} = 1.9375\text{eV}, \alpha(\text{at } 1.9375\text{eV}) = 4 \times 10^3 \text{ cm}^{-1}$$

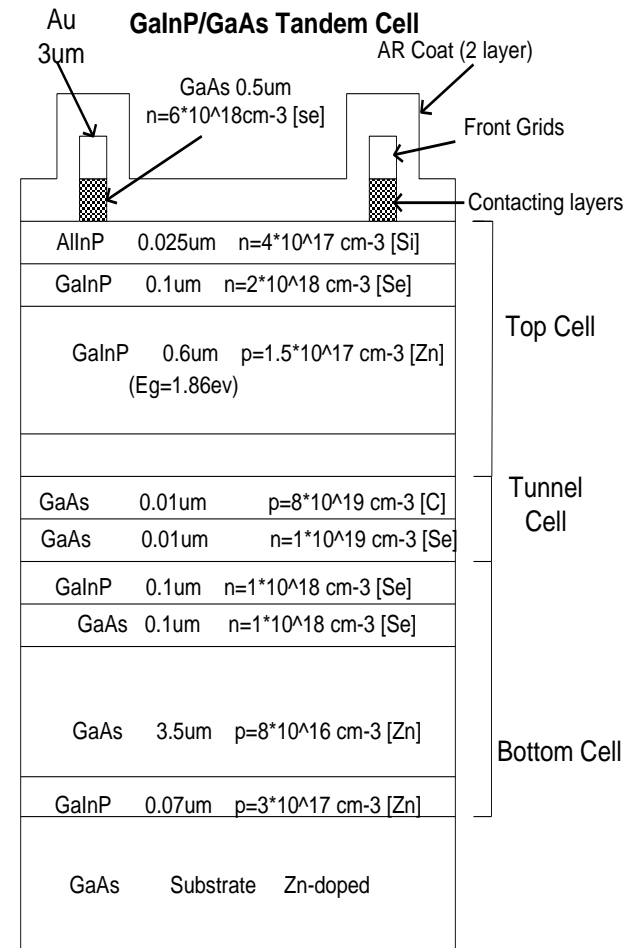
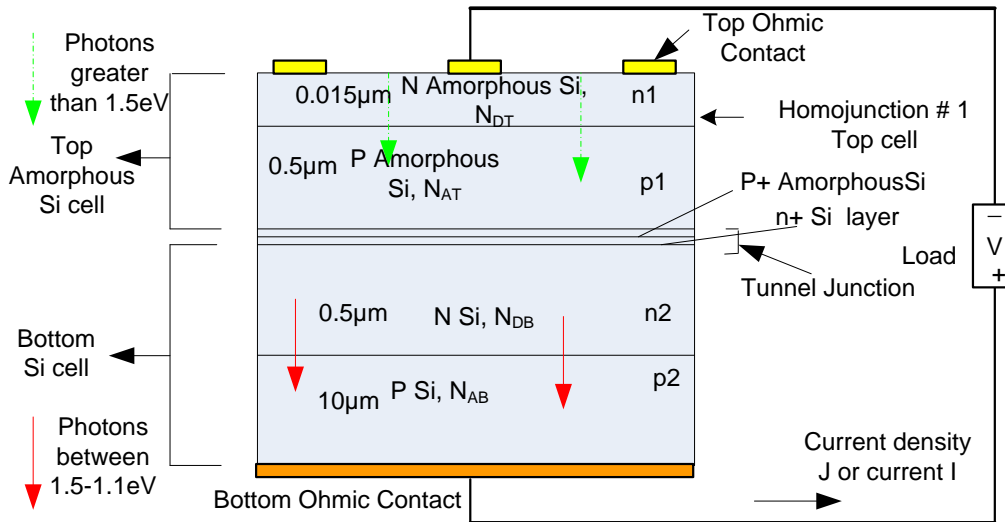
In reality, $d \approx 100 - 150 \mu\text{m}$ to absorb $\hbar\nu \geq E_g = 1.1\text{eV}$.

$$\frac{748}{925} = 1 - e^{-4 \times 10^3 \cdot d} \quad 0.808 = 1 - e^{-4000d}$$

$$d = \frac{-1}{4000} \ln(0.2) \approx 4.14 \mu\text{m}$$

In reality, $d \approx 100 - 150 \mu\text{m}$ to absorb $\hbar\nu \geq E_g = 1.1\text{eV}$

Multi-junction cells using tunnel junction interface



Multi-junction cells using tunnel junction interface

$$V = \frac{kT}{q} \left[\ln \left(\frac{J + J_{SCT}}{J_{ST}} + 1 \right) + \ln \left(\frac{J + J_{SCB}}{J_{SB}} + 1 \right) \right]$$

$$I = I_{ST} * \left[\exp \left(\frac{qV_T}{kT} \right) - 1 \right] - I_{SCT} \quad I = I_{SB} * \left[\exp \left(\frac{qV_B}{kT} \right) - 1 \right] - I_{SCB}$$

Here, the reverse saturation current density J_s is expressed as:

For the top cell:

$$J_{sT} = q [(D_{nT} n_{poT}/L_{nT}) + (D_{pT} p_{noT}/L_{pT})] \quad (4A)$$

For the bottom cell

$$J_{sB} = q [(D_{nB} n_{poB}/L_{nB}) + (D_{pB} p_{noB}/L_{pB})] \quad (4B)_{30}$$

Short circuit current density in top and the bottom cells

The short circuit current densities for the top and bottom cells are expressed in Eqs. 7 as:

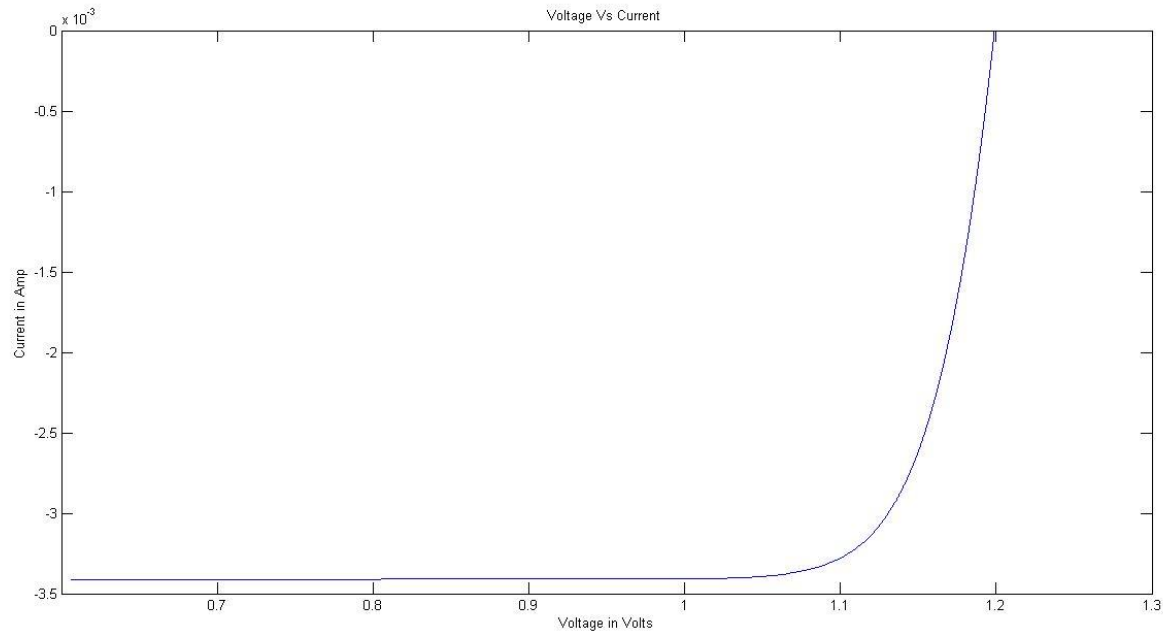
$$J_{SCT} = \sum_{\lambda} q \frac{I_0(\lambda) \Delta \lambda}{(hc / \lambda)} (1 - e^{-\alpha_T(\lambda) t_{pT}})$$
$$J_{SCB} = \sum_{\lambda} q \Delta \lambda \frac{I_0(\lambda)}{(hc / \lambda)} e^{-\alpha_T(\lambda) t_T} \left(1 - e^{\left(-\alpha_B(\lambda) t_{pB} \right)} \right)$$

where $I_0(\lambda)$ is the incident light intensity as a function of wavelength, h is Planck's constant, c is velocity of light, $\alpha_T(\lambda)$ and $\alpha_B(\lambda)$ are the absorption coefficient in top and bottom layers, respectively, and t_{pT} , t_T and t_{pB} are the thicknesses of p-absorbing layer (top cell), total thickness of top cell, and p-absorbing layer of the bottom cell, respectively. Also, k is the Boltzmann constant, and T the temperature.

Tandem Solar cell: Example

Thickness	Reverse Saturation	Short circuit current density	Tandem V_{oc}	Max current density J_{mp}	Max output V_{mp}	Fill Factor %
AmorphousSi (Top) = t_T =0.51 μm Crystalline Si (Bottom) t_B = 10.5 μm	$J_{ST} = 2.5923 \times 10^{-13} \text{ A/cm}^2$ $J_{SB} = 7.1752 \times 10^{-13} \text{ A/cm}^2$	$J_{SCT} = 0.0074 \text{ A/cm}^2$ $J_{SCB} = 0.034 \text{ A/cm}^2$ For series, we pick $J_{sc} = 0.0034 \text{ A/cm}^2$	1.1989 V	0.0033 A cm^{-2}	1.0866 V	88.5

Tandem solar cell Amorphous Si/ Crystalline Si Voltage Vs Current



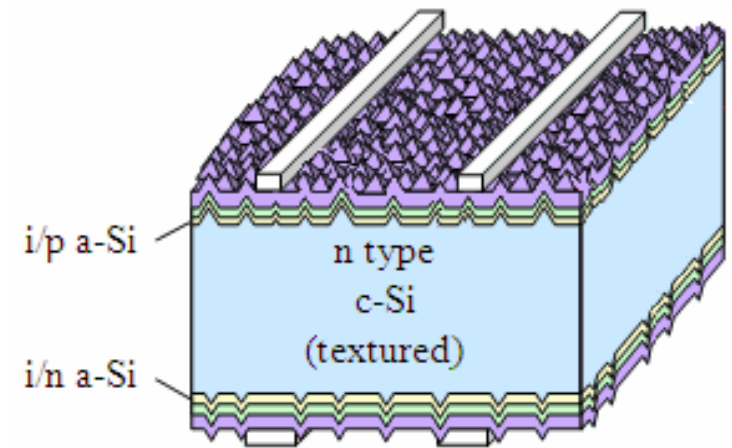
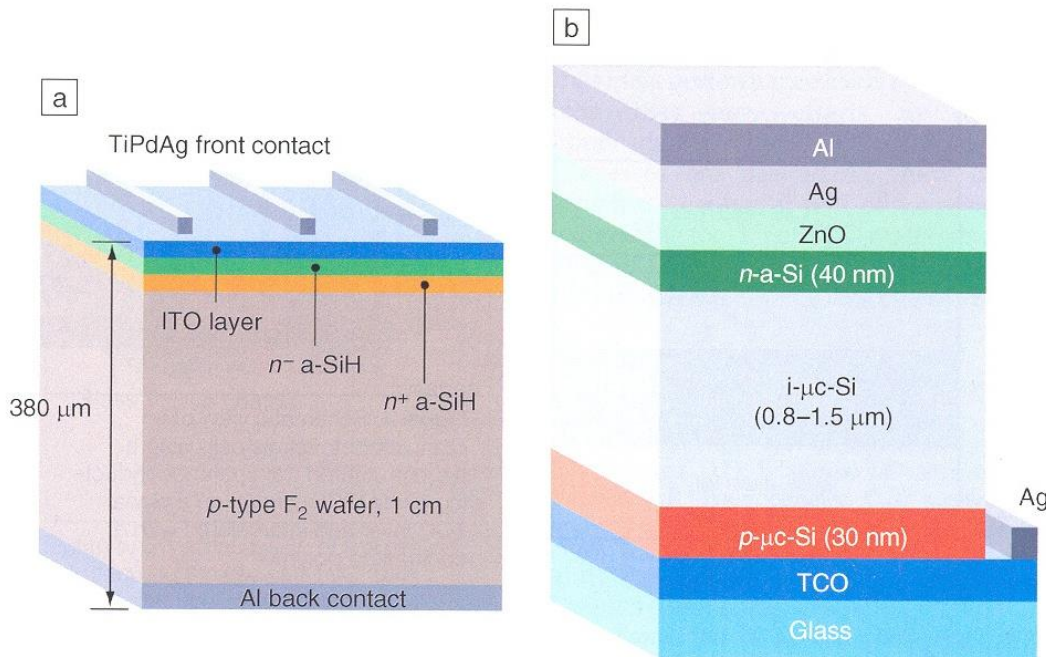
Solar cells-iii

Emerging new cell structures:

Next we describe cells which have emerged during last 10 years.
These include:

1. Sanyo's HIT (heterojunction with intrinsic thin film) cell and amorphous Si window and crystalline Si cell
2. CdTe-CdS First Solar Corp. Cell
3. 4-5 junction tandem cells
4. Multiple exciton generation (MEG) cells
5. Intermediate Band Cell
6. Organic and polymer cells
7. Quantum dot and quantum wire cells.
8. Dye sensitized cells

Sanyo's HIT Solar Cell using n-amorphous Si on p-crystalline Si and on glass substrates



The HIT cells are **surface textured** on both sides of the wafer to eliminate reflections.

Y. Tsunomura et al., Twenty two percent efficiency HIT solar cell", Solar Energy Materials and Solar Cells, 93, pp. 670-673, 2009.

Fig. 44 Sanyo's Heterojunction with intrinsic thin film (HIT) cell.
 (a) cSi-aSi-TCO-Metal grid contact HIT n-aSiH/a-n⁺Si/p-type Si wafer.
 (b) Glass/TCO(bottom contact)/p-mcSi (30nm)/i-mcSi(1mm)/n-aSi (40nm)/ZnO/Ag/Al. TCO= Transparent conducting oxides serving as contact. tin oxide, indium tin oxide, ZnO.

CdTe thin film cells

1. Glass is deposited with fluorine doped tin oxide (FTO) and tin oxide at 550C, R=20 Ohm/sq
2. CdS layer by chemical bath deposition (CBD) using cadmium acetate, thiourea, ammonium acetate, ammonium hydroxide in a water bath at 92C
3. Deposit 4 micron CdTe at 660C using closed space sublimation (CSS) with a source plate of CdTe held at 660C for 2min.
4. RF sputter thin film of Cu:doped ZnTe. Ion mill 100nm of top ZnTe.
5. DC sputter titanium Ti thin contact.
6. Light is incident from glass substrate side.

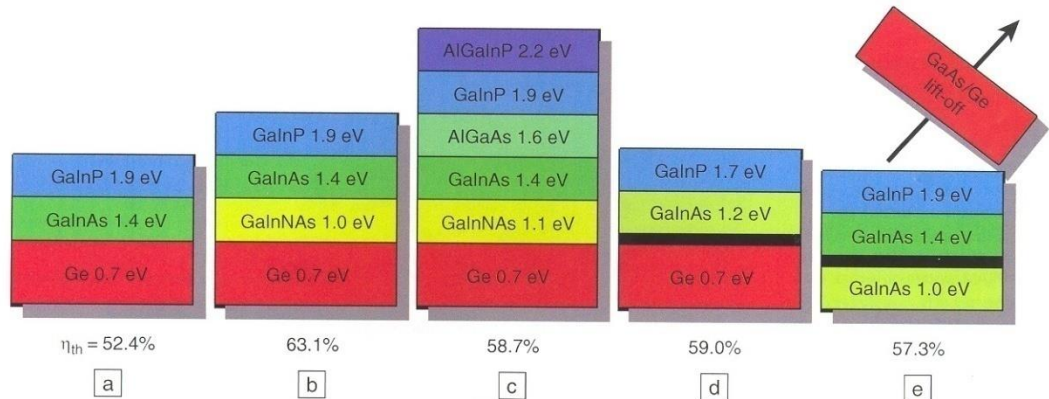
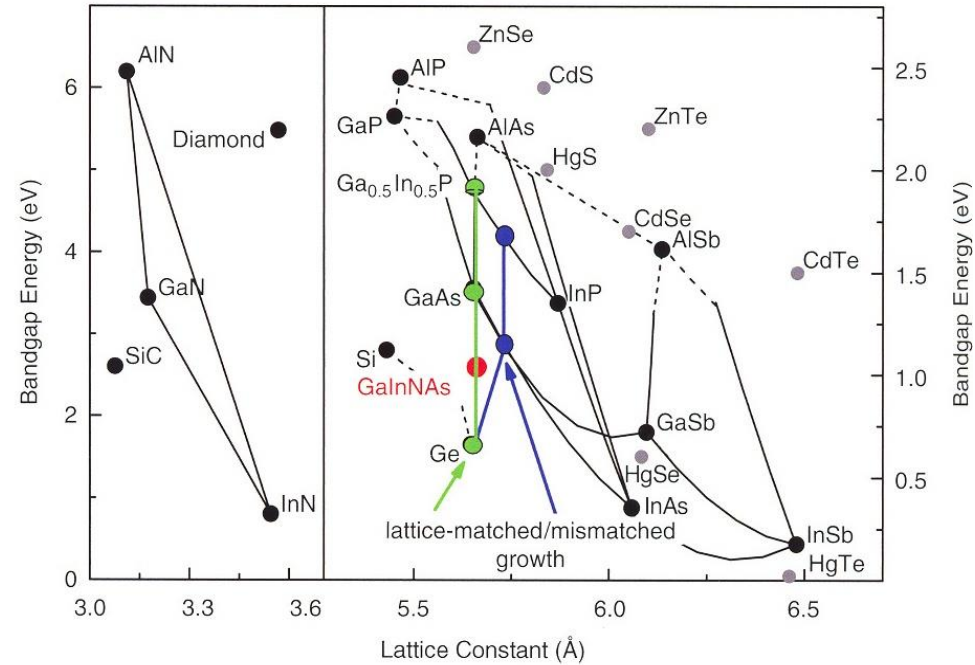
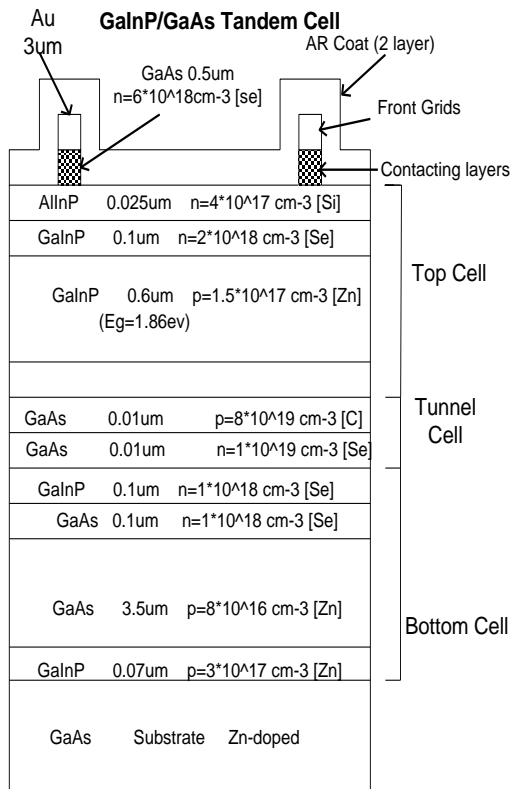
Ti	
Cu:p-ZnTe	
p-CdTe Absorber	
n-CdS	
Buffer	
TCO (Transparent Conducting Oxide)	SnO ₂ F doped :SnO ₂
Glass Substrate	

Rance et al , 14% efficient CdTe solar cells on ultra-thin glass substrates, Applied Physics Letter, 104, p. 143903, 2014.

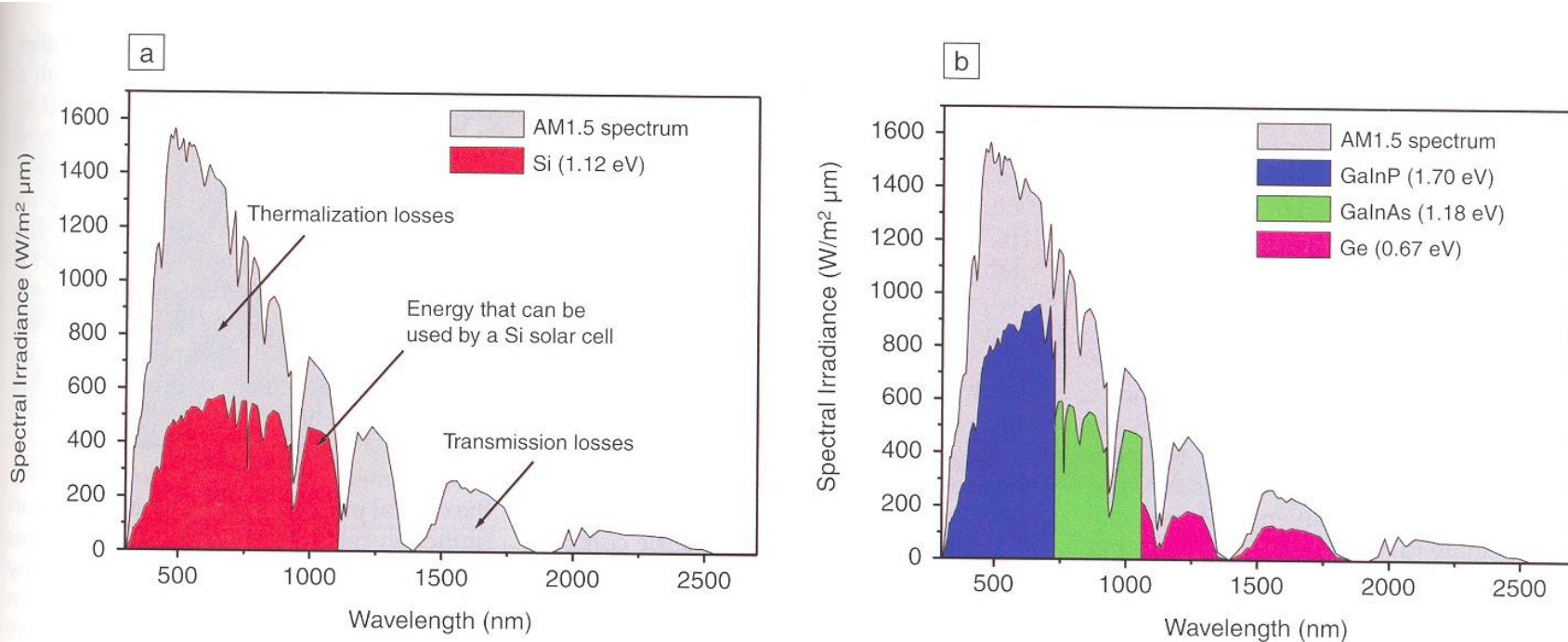
Multi-junction Tandem cells Design

Improve efficiency by:

1. Ge to absorb $h\nu > 0.67\text{eV}$,
--reduce long wavelength loss.
2. Multiple energy gap absorbers
--reduce excess energy loss



Excess energy loss: energy not utilized in electron-hole pair formation (Fig. 49)



Projected efficiencies

Projected conversion efficiencies are for various 3rd generation cells:

I. 66% Three-junction tandem cells

40-50% in some Multi-junction or Tandem Cells

II 66% Quantum Dot solar cells using Multi-Exciton generation (MEG)

III. Intermediate band (IB) devices.

IV. Si nanowire solar cells.

Multiple excitons generation MEG: Alternate to harnessing excess energy loss

Multiple exciton generation (MGE) phenomena and cells: Quantum Dot based solar cells

When the photon energy $h\nu$ is greater than the bandgap, the electron and hole generated have excess energy ($h\nu - E_g$) that is given up as phonons eventually heating up the lattice. That is, the energy of the hot carriers is lost.

Excess energy can be recovered in following ways: (a) recover hot carriers before they thermalize (ref 2-4), and (b) hot carriers producing 2-4 electron hole pair via impact ionization or via multiple exciton generation. Multiple exciton generation (MEG, this is shown in QDs of PbSe, CdSe etc.)

Impact Ionization

1 Photon creates 2 electron-hole pairs or exciton pairs. This is known as MEG.

A new possible mechanism for MEG involves simultaneous creation of multiple excitons.

No group has yet reported enhanced photo carriers in the external circuit.

Quantum Yield $\sim 300\%$ when 3 excitons are formed.

One photon forms 3 excitons or
3 electron-hole pairs

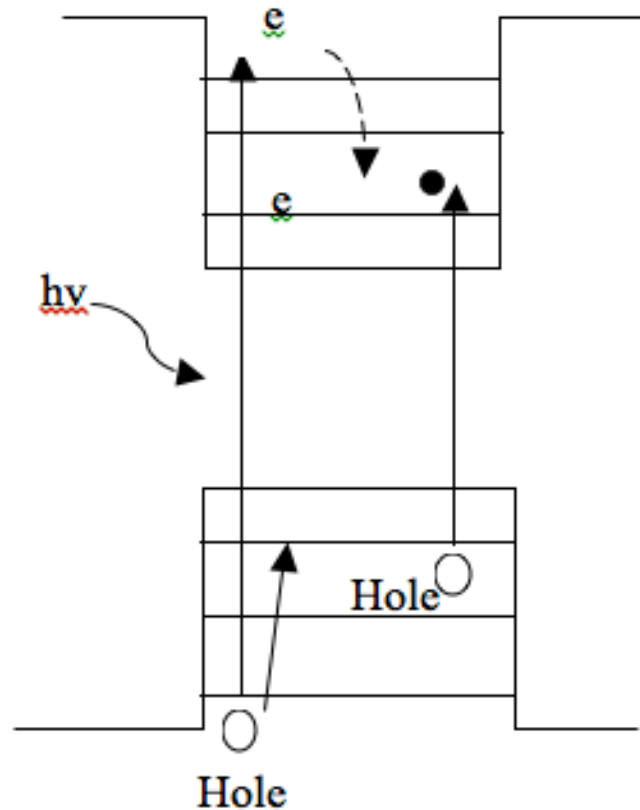


Fig. 51 Quantum yield is 300% if 3 excitons are formed 41

Intermediate band (IB) absorption to harness below gap photons

Loss of below band gap and sub-band gap photons. Here an intermediate level is introduced by introducing a deep impurity level in the band gap.

This is shown theoretically to be useful for single junction as well as tandem cells.

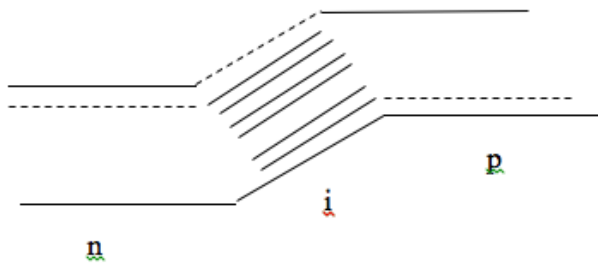


Fig. 53. 3-D Analog of mini-bands found in superlattices

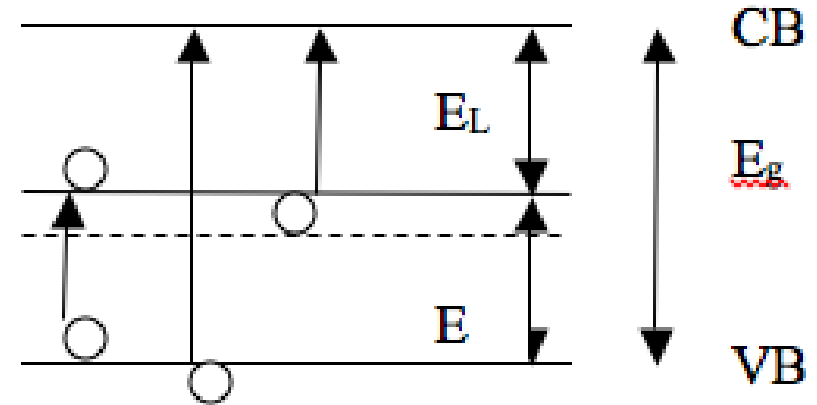


Fig. 52 shows Intermediate band (due to impurity level or levels; superlattice mini-bands, lone pair bands) in the middle of Conduction Band and Valence Band.

Types of QDot based Cells

1. Photoelectrodes composed of QD arrays. QDs such as InP (3-5nm dia) used to sensitize a TiO_2 nanocrystalline film.
2. QDs dispersed in Organic/polymeric Semiconductors [i.e. in blend of electron and hole transporting polymers].
3. Dye sensitized cells.

QD cells

2) TCO (transparent conducting oxide) deposited with InP-sensitized TiO_2 (30nm)

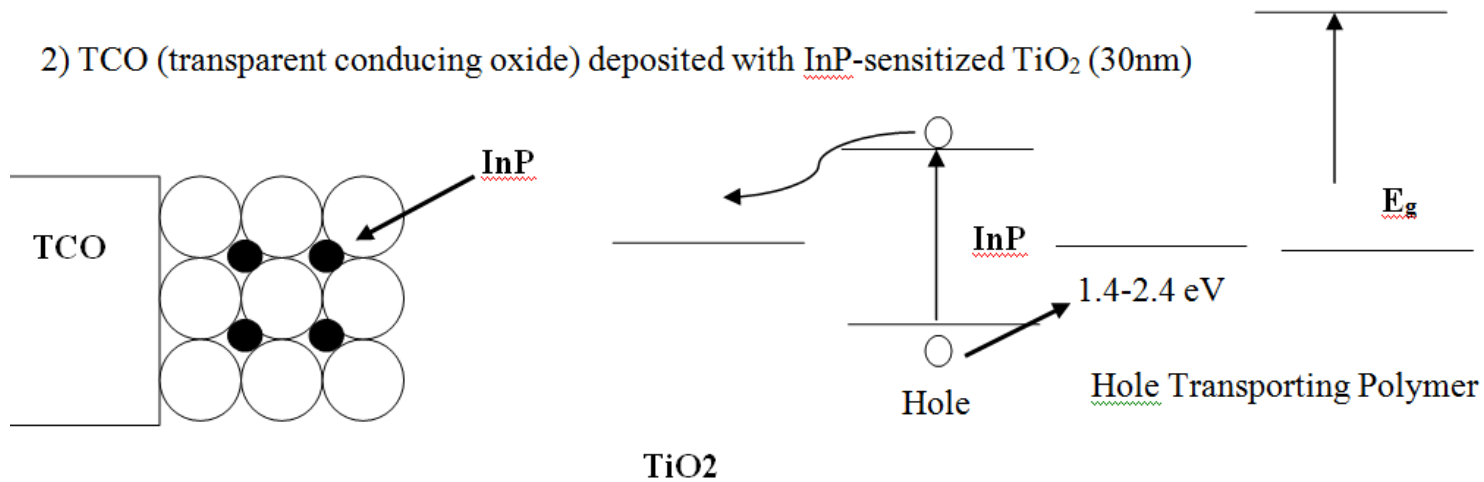


Fig. 54 InP QDs with TiO_2 spheres in a polymer blend.

QDot cells

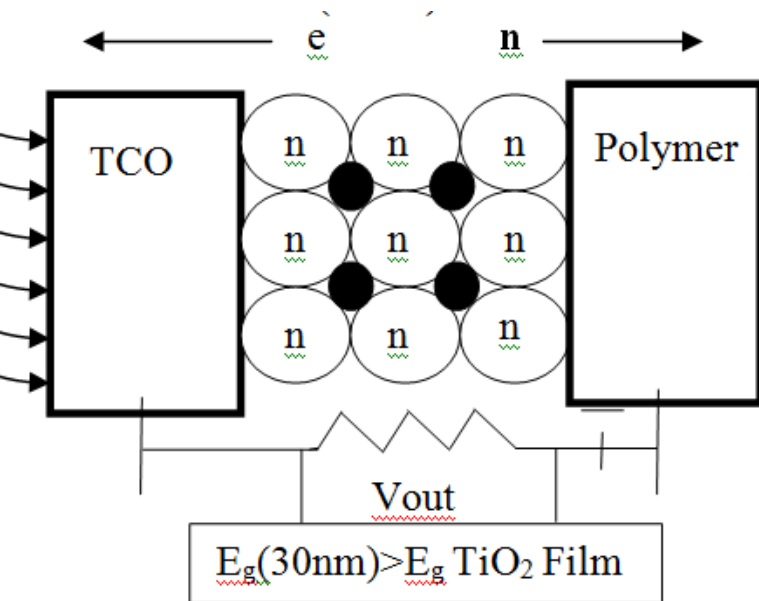
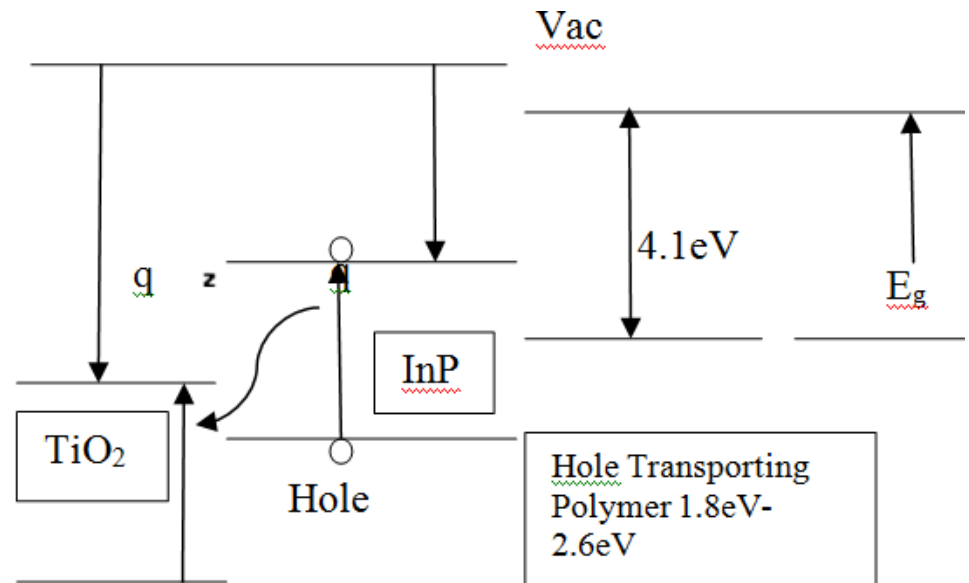


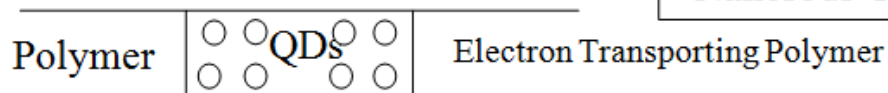
Fig .60



QDs in Organic Photovoltaics

3. Quantum Dots dispersed in Organic/polymeric Semiconductors. [i.e. in blend of electron and hole transporting polymers].

QD's CdSe
Nanorods CdSe



CdSe Low η in CdSe Qd's

-Nano dots must be cladded.

High η in CdSe nanowires

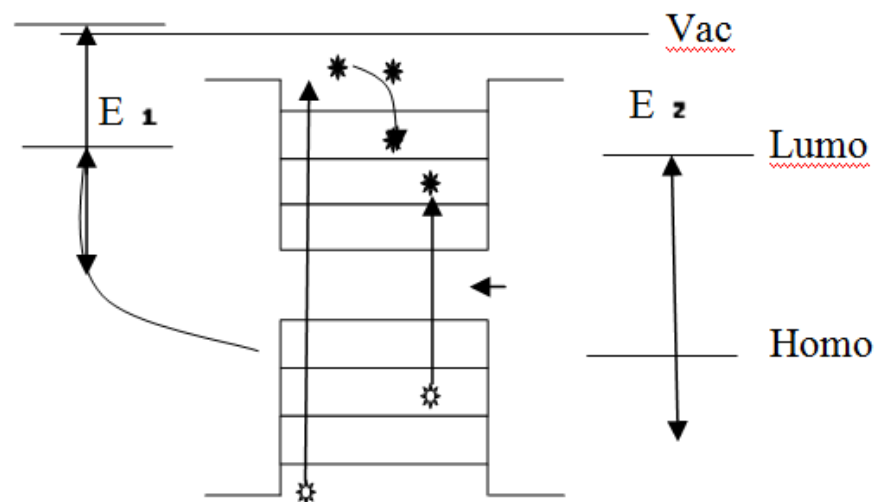


Fig .61

Dye sensitized solar cells.

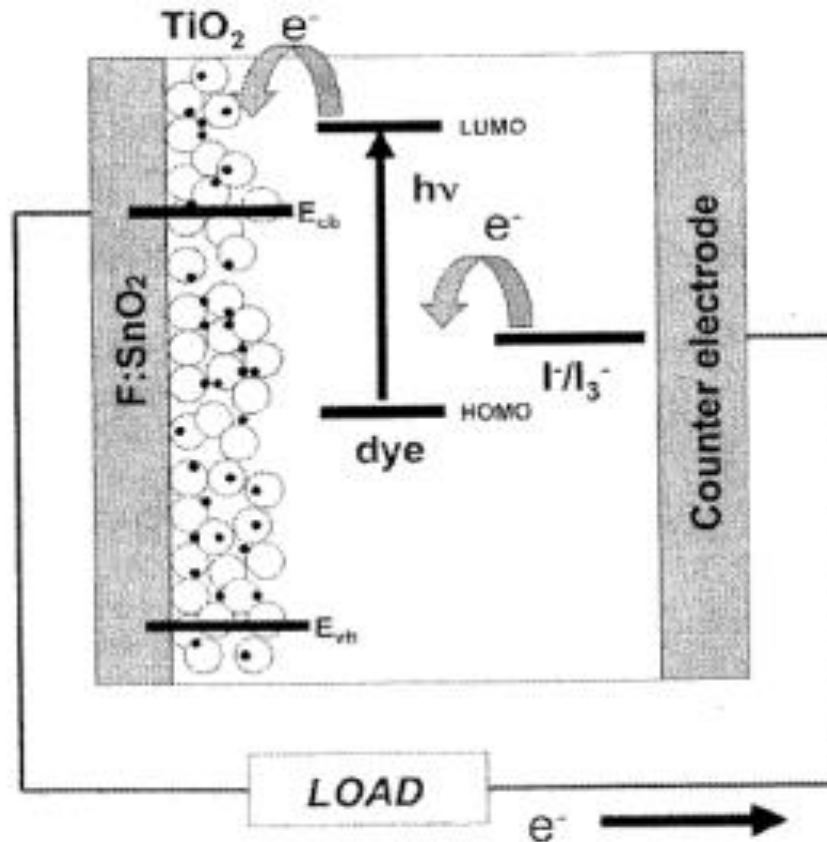
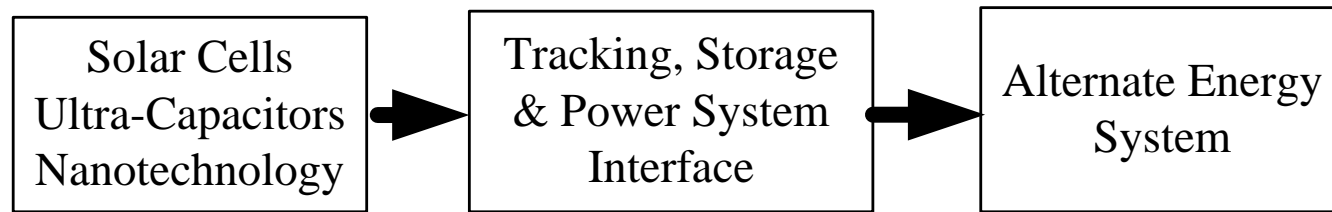


Figure shows dye-sensitized solar cell⁵⁷ using hybrid nanomaterials.

Solar modules



The flowchart of Fig. 10(a) shows how energy conversion (solar cells) and storage (e.g. ultra-capacitors⁴⁷⁻⁵⁰) devices are used to implement alternate energy systems for various applications. Here, the middle block shows the interface circuits (such as micro-inverters²⁷, solar tracking, and capacitor switching) depending on the application. Figure

Solar module cost

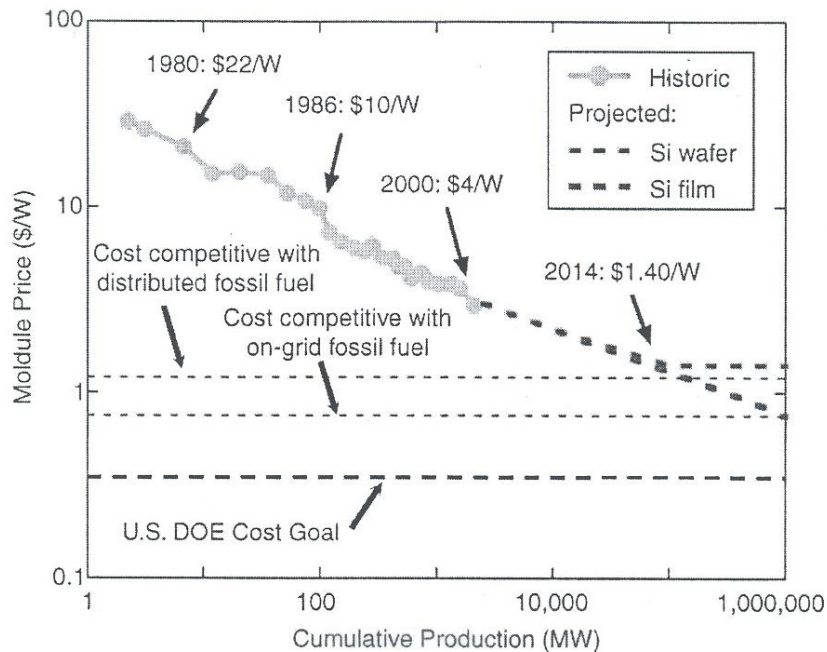


Fig. 43. Module price as a function of power production.

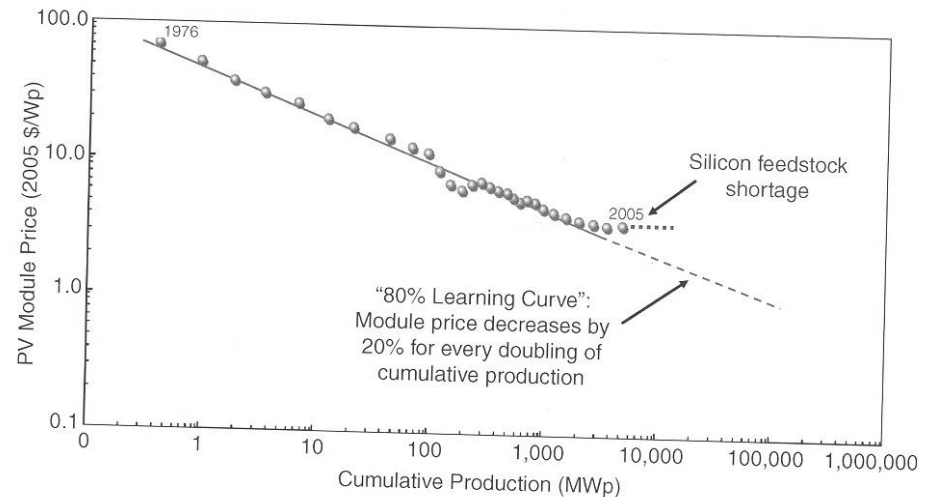


Fig. 45. Module cost /Wp in 2005. [Ref: A. Slaoui and R. Collins, p. 211, MRS Bull, March 07] *The goal here is to obtain \$1.82 to \$1.2/Wp in 2010 and 2015, respectively.*

Comparison of various technologies

Table 1. Confirmed terrestrial cell and submodule efficiencies measured under the global AM1.5 spectrum (1000 W/m²) at 25°C (IEC 60904-3: 2008, ASTM G-173-03 global).

Classification ^a	Effic. ^b (%)	Area ^c (cm ²)	V _{oc} (V)	J _{sc} (mA/cm ²)	FF ^d (%)	Test centre ^e (and date)	Description
Silicon							
Si (crystalline)	25.0 ± 0.5	4.00 (da)	0.706	42.7 ^f	82.8	Sandia (3/99) ^g	UNSW PERL [18]
Si (multicrystalline)	20.4 ± 0.5	1.002 (ap)	0.664	38.0	80.9	NREL (5/04) ^g	FhG-ISE [19]
Si (thin film transfer)	19.1 ± 0.4	3.983 (ap)	0.650	37.8 ^h	77.6	FhG-ISE (2/11)	ISFH (43-μm thick) [20]
Si (thin film submodule)	10.5 ± 0.3	94.0 (ap)	0.492 ⁱ	29.7 ⁱ	72.1	FhG-ISE (8/07) ^g	CSG Solar (1–2 μm on glass; 20 cells) [21]
III-V cells							
GaAs (thin film)	28.3 ± 0.8	0.9944 (ap)	1.107	29.47 ^j	86.7	NREL (8/11)	Alta devices [3]
GaAs (multicrystalline)	18.4 ± 0.5	4.011 (t)	0.994	23.2	79.7	NREL (11/95) ^g	RTI, Ge substrate [22]
InP (crystalline)	22.1 ± 0.7	4.02 (t)	0.878	29.5	85.4	NREL (4/90) ^g	Spire, epitaxial [23]
Thin film chalcogenide							
CIGS (cell)	19.6 ± 0.6 ^k	0.996 (ap)	0.713	34.8 ^l	79.2	NREL (4/09)	NREL, CIGS on glass [24]
CIGS (submodule)	17.4 ± 0.5	15.993 (da)	0.6815 ^l	33.84 ^l	75.5	FhG-ISE (10/11)	Solibro, four serial cells [4]
CdTe (cell)	16.7 ± 0.5 ^k	1.032 (ap)	0.845	26.1	75.5	NREL (9/01) ^g	NREL, mesa on glass [25]
Amorphous/nanocrystalline Si							
Si (amorphous)	10.1 ± 0.3 ^m	1.036 (ap)	0.886	16.75 ^d	67.0	NREL (7/09)	Oerlikon Solar Lab, Neuchatel [26]
Si (nanocrystalline)	10.1 ± 0.2 ⁿ	1.199 (ap)	0.539	24.4	76.6	JQA (12/97)	Kaneka (2 μm on glass) [27]
Photochemical							
Dye sensitised	11.0 ± 0.3 ^o	1.007 (da)	0.714	21.93 ^h	70.3	AIST (9/11)	Sharp [5]
Dye sensitised (submodule)	9.9 ± 0.4 ^o	17.11 (ap)	0.719 ⁱ	19.4 ^l	71.4	AIST (8/10)	Sony, eight parallel cells [28]
Organic							
Organic thin film	10.0 ± 0.3 ^o	1.021 (ap)	0.899	16.75 ^l	66.1	AIST (10/11)	Mitsubishi Chemical [6]
Organic (submodule)	4.2 ± 0.2 ^o	294.5 (da)	0.714	12.26 ^l	47.7	AIST (9/11)	Sumitomo Chemical (10 series cells) [7]
Multijunction devices							
GaInP/GaInAs/Ge	34.1 ± 1.2	30.17 (t)	2.691	14.7 ^l	86.0	FhG-ISE (9/09)	AZUR (monolithic) [8]
a-Si/no-Si/no-Si (thin film)	12.4 ± 0.7 ^p	1.050 (ap)	1.936	8.96 ^h	71.5	NREL (3/11)	United Solar [29]
a-Si/no-Si (thin film cell)	12.3 ± 0.3 ^q	0.962 (ap)	1.365	12.93 ^l	69.4	AIST (7/11)	Kaneka [9]
a-Si/no-Si (thin film submodule) ^r	11.7 ± 0.4 ^{q,r}	14.23 (ap)	5.462	2.99	71.3	AIST (9/04)	Kaneka [30]

^aCIGS: CuInGaSe; a-Si: amorphous silicon/hydrogen alloy.

Summary

1. Thin film cells: CdTe-CdS or CIGS (First Solar),
2. Multi-junction cells: Concentrated solar
3. Poly-Si cells:
4. cSi-aSi-TCO-Metal grid contact HIT n-aSi:H /a-n+Si/p-type Si wafer. Sanyo's (HIT) cell.
5. Organic cells
6. Dye sensitized cells
7. Emerging quantum dot / quantum wire cells.

Excess energy loss is the primary cause in poor efficiency

It is the photon energy not used in electron-hole pair generation which results in loss and reduction in current.

Let us look at DEFG trapezoid segment of solar spectrum

Number of photons per second N_{PH} whose power is represented by trapezoid DFEG.

$N_{PH} = \text{Area of trapezoid} / h\nu_{av}$, $h\nu_{av} = (\text{energy at G} + \text{D})/2$,

The photon energy is $= 1.24/0.95\mu\text{m} = 1.3 \text{ eV}$ at Point G or EG

The photon energy is $= 1.24/1.1\mu\text{m} = 1.1 \text{ eV}$ at Line FD.

Average photon energy $h\nu_{av}$ in trapezoid $= (1.3 + 1.1)/2 = 1.2 \text{ eV}$.

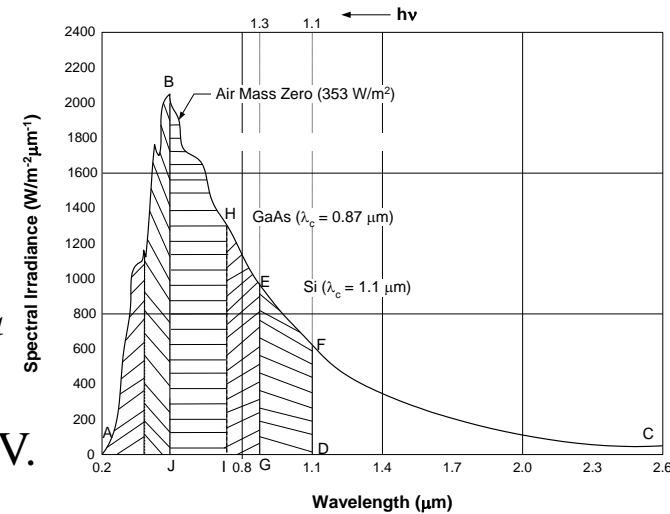


Fig. 37. Solar spectrum at air mass 0, p.446

Excess energy per photon in DFEG $= 1.2 - 1.1 = 0.1 \text{ eV}$.

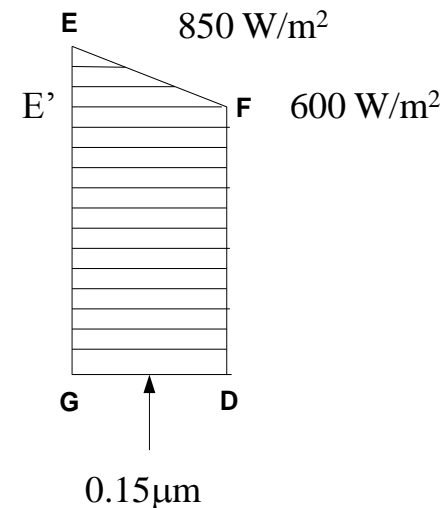
Number of photons/s N_{PH} in the trapezoid DFEG $= \text{Shaded Area} / 1.2 \text{ eV}$.

DFEG Shaded Area $= \text{Rectangle} + \text{Triangle}$

$$\begin{aligned} &= 600(1.1 - 0.95) + (EE' \times E'F)/2 \\ &= 90 + 0.15(850 - 600)/2 = 90 + 19.75 \\ &= 108.75 \text{ W/m}^2 \end{aligned}$$

Excess Photon Energy Loss in DFEG $= 0.1(108.75/1.2) = 9.06 \text{ W/m}^2$

$$\text{Excess energy lost per sec} = N_{PH}|_{DFEG} * (h\nu|_{average} - E_g)$$



Sample Quiz Questions:

1. Finding open circuit voltage V_{oc} if I_{sc} and I_s are given; finding output voltage V_m or V_{mp} resulting in the maximum power output; finding I_m or I_{mp} the current at maximum power to the load; computing fill factor FF.

$$V_{oc} = \frac{kT}{q} \ln \left(\frac{I_L + I_s}{I_s} \right) \quad V_m = V_{oc} - \frac{kT}{q} \ln \left[1 + \frac{qV_m}{kT} \right] \quad I_m = I_s \left[e^{\frac{qV_m}{kT}} - 1 \right] - I_L$$

$$I = I_s \left(e^{\frac{qV}{kT}} - 1 \right) - I_L \text{ (or } I_{sc} \text{)} \quad FF = \frac{V_m I_m}{V_{oc} I_L} = \frac{P_m}{V_{oc} I_L} = \frac{\text{Area of inner rectangle}}{\text{Area of outer rectangle}} \quad I_s = \frac{qAD_p P_{no}}{L_p} + \frac{qAD_n N_{po}}{L_n}$$

(Here, I_{sc} or I_L is the light generated short circuit current.

I_s is reverse saturation current and it depends on minority doping concentrations p_{no} or n_{po} , diffusion coefficients D_p or D_n , and diffusion lengths L_p or L_n .)

2. Finding excess energy losses in a solar cell with given energy gap E_g .

Excess energy lost/sec in spectral range DEFG (slide 23) =
photons/sec (N_{PH}) * excess energy per photon ($h\nu_{av} - E_g$)

$$N_{PH} |_{DEFG} * (h\nu|_{average} - E_g)$$

3. Familiarity with currently pursued competing technologies:

- a. CdS-CdTe and CdS-CuInGaSe (CIGS) cells
- b. Poly-Si cells: polycrystalline Si wafers are cheaper than single crystalline.
- c. Amorphous Si on glass and amorphous Si/crystalline Si cells (HIT cells): improved conversion efficiency over poly-Si wafer cells.
- d. Multi-junction tandem cells: Ge substrates for concentrated solar
- e. Organic solar cells and dye-sensitized photochemical cells.

Sample Quiz Questions (Cont.):

4. Familiarity with quantum dot based solar cells
 - a. Absorption is high in a quantum dot layer, so thinner QD films absorb higher power. The energy gap in QDs is size dependent.
 - b. Multiple exciton generation (MEG) and intra-band (IB) cells.
5. Is the short circuit current I_{sc} **higher** for lower energy gap semiconductors? **True**
6. Is the open circuit voltage V_{oc} **lower** for lower energy gap semiconductors? **True**
7. How does multi-junction/tandem cells improve efficiency? Different cells absorb different spectral energy photons. This reduces over all Excess Energy not used in creating electron-hole pairs when photons are absorbed.
8. Why do CdTe cell panels cost less? **Higher conversion efficiency** is achieved as p-doped thin CdTe absorber layers have less defect density when grown on glass.
9. Effect of doping concentrations on V_{oc} via I_s (Use equations from Q.1).
 - a. Will the V_{oc} increase if **doping concentrations increase**? **True**
 - b. Will the V_{oc} increase if the **temperature is reduced**? **True.**