Quantitative Model of PV Cells – The Illuminated Diode

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Lecture Notes

WE FOUND WHAT WE SEEK: J=J(V)

Current Density vs Voltage Across Diode:

$$J_{total} = J_e + J_h = \left(\frac{qD_e n_{p_0}}{L_e} + \frac{qD_h p_{n_0}}{L_h} \right) \left(\exp(qV/kT) - 1 \right)$$

Total Current, I (Amps), Is Just Jtotal * Area of Diode…

$$I(V) = I_0 \left(\exp(qV/kT) - 1 \right)$$

$$I_0 = A \left(\frac{qD_e n_{p_0}}{L_e} + \frac{qD_h p_{n_0}}{L_h} \right)$$

I-V Characteristics of p-n diode

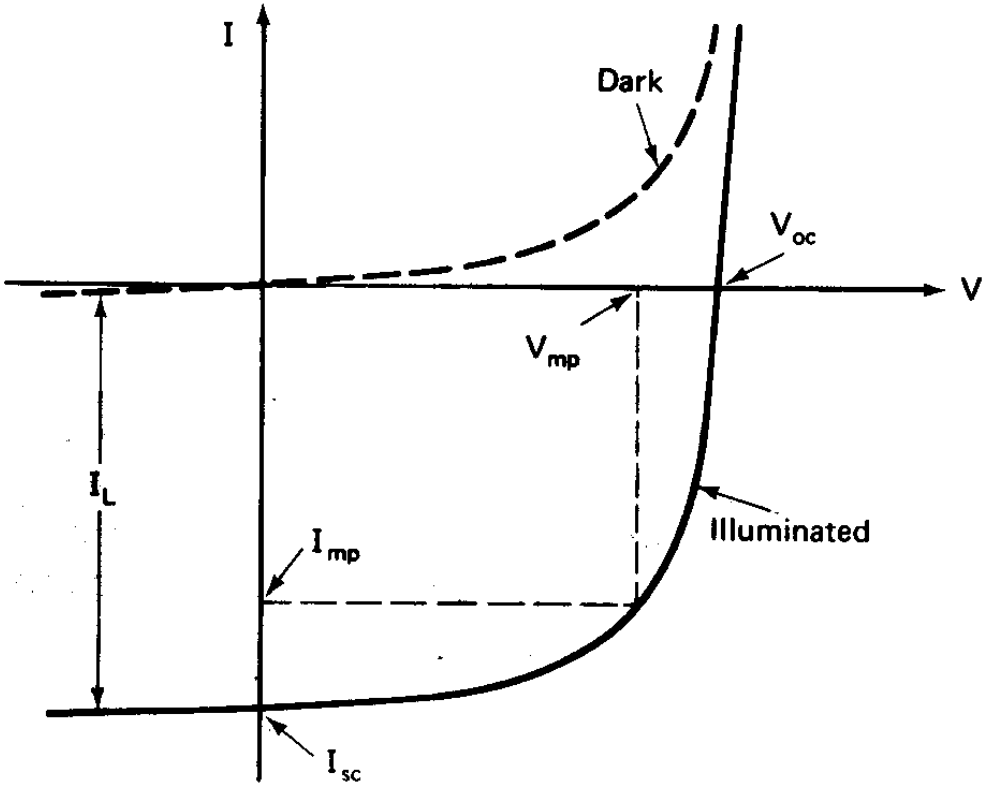


Figure 4.11. Terminal properties of a *p-n* junction diode in the dark and when illuminated.

Basics of Solar PV Cells

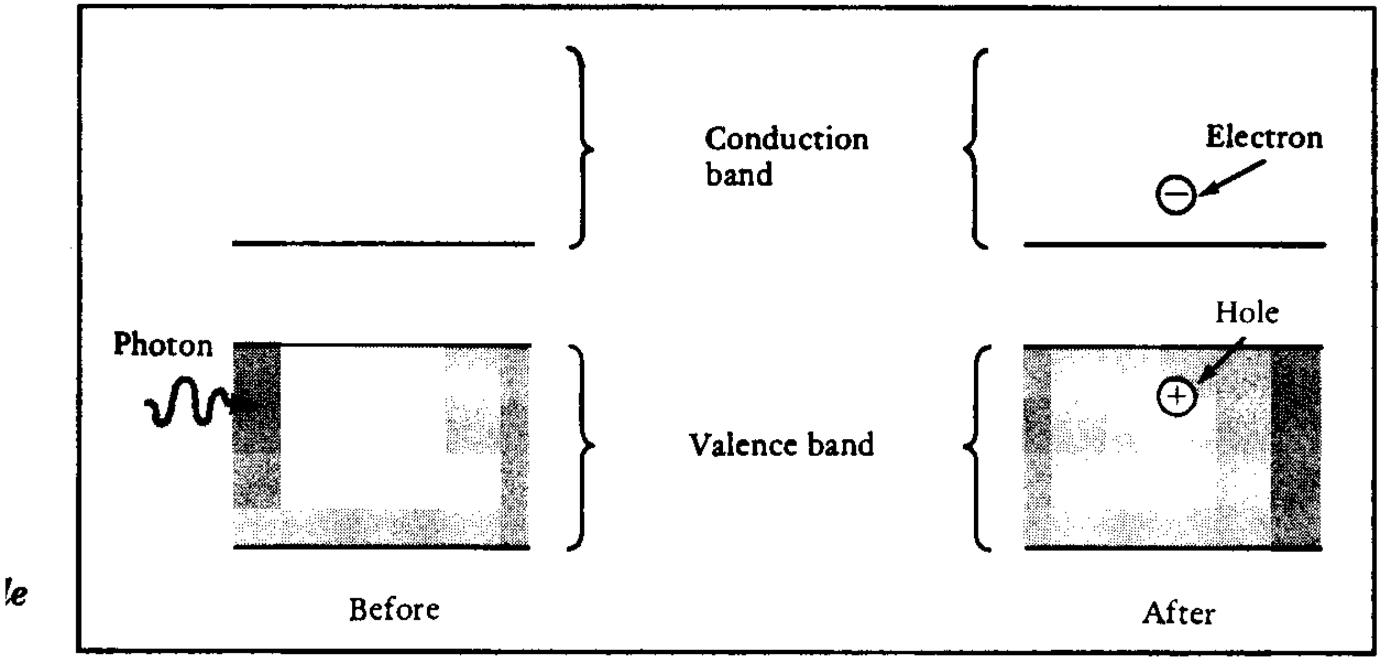
- Key Concepts
  - Photon Energy Spectrum
  - ***Charge Carrier Generation Via Photon Absorption***
  - Charge Carrier Loss Mechanisms
  - Un-illuminated p-n junction diode
  - Illuminated p-n junction diode: The Solar PV Cell
  - Solar PV Cell's as an Electricity Source

Calculating Effect of Illumination with E > Egap Photons

- Assume e-h generation rate G = constant
  - Corresponds to Ephoton ~ Egap Flux
- Earlier Assumptions Still Valid
  - Quasineutral Region, Depletion Region
  - Drift Current Density ~ Diffusive Density in Depletion Region
  - Small minority carrier population
  - Diffusive minority carrier transport in quasineutral region

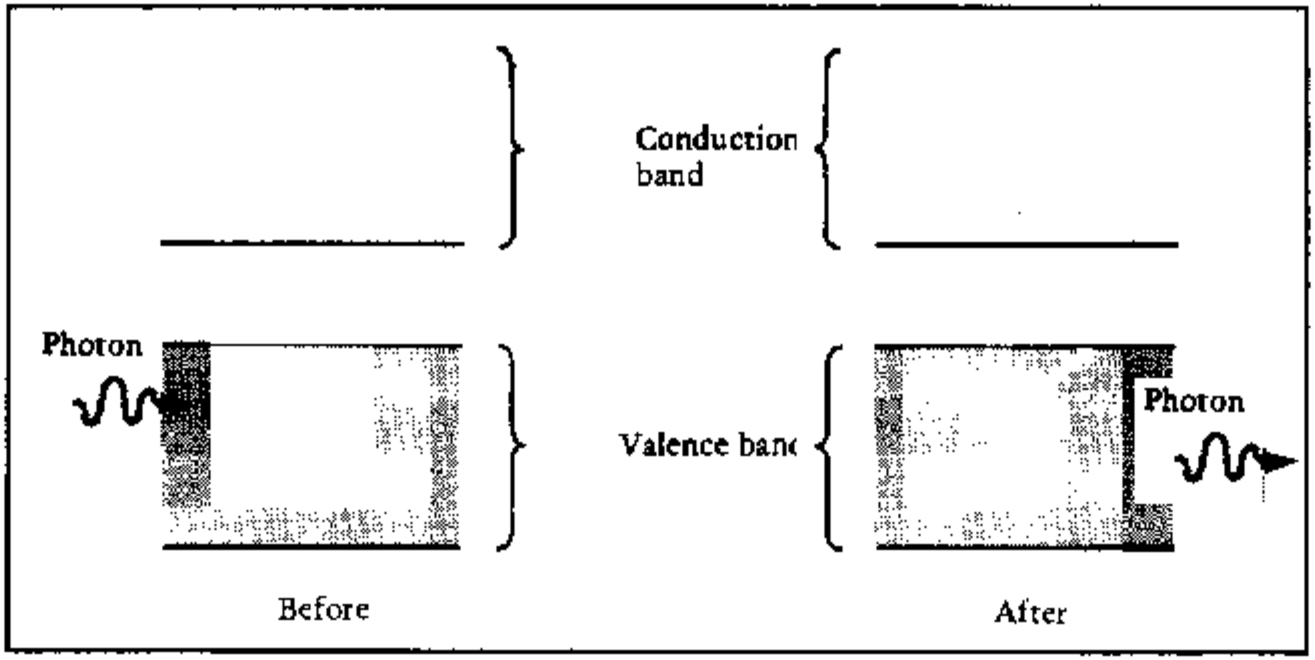
Photon absorption in semiconductor

For Photon Energy, $E_n > E_{gap}$ Photon Is Adsorbed & Creates e/hole pair At Adsorption Site:



Photon absorption in semiconductor

For Photon Energy, $E_n < E_{gap}$ Photon May be Adsorbed BUT DOES NOT CREATE e/hole pair… Or (more likely) it passes through material:



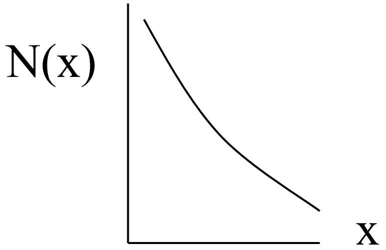
Approximate e/hole Generation Rate

- Assume All Photons Have Enough Energy to Create e/hole Pairs… Then G Is

$$G = \left(1 - R\right)\alpha N \exp(-x\alpha)$$

Number of Photons/Unit Area/Unit Time

Photon Flux vs Distance into PV Cell



PV Cell

Approximate e/hole Generation Rate

- For Weak Adsorption Approximate Generation Rate, G (units: e/hole pairs/unit volume/unit time)

$$G \sim (1-R)\alpha N$$

- R = fraction of light reflected from surface (R~0.05 with Anti-reflection coating)

  N = number photons/unit area/unit time
- a = photon intensity e-folding attenuation length
  - Typically few microns…

Typical Adsorption Coefficient

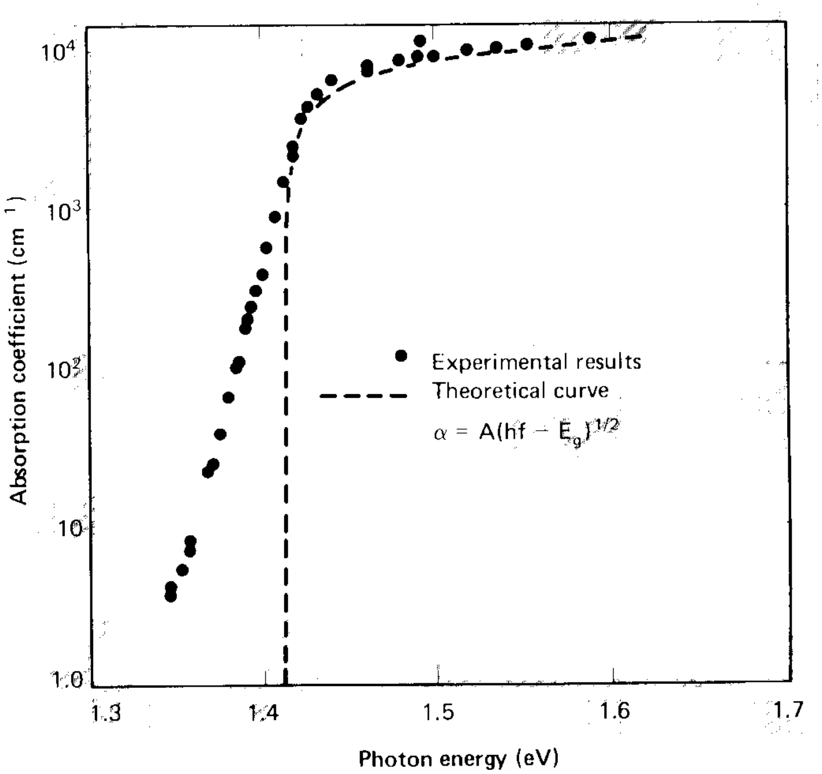


Figure 3.4. Absorption coefficient of GaAs as a function of photon energy. [After T. S. Moss and T. D. F. Hawkins, *Infrared Physics 1*, (1961), 111.]

- Data for Ga-As
- Typical Penentration Depth for E>Egap,L:
  - L=1/a~1 micron
- Data for Silicon Not Too Different

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Effect of Illumination on diode

MINORITY CHARGE CARRIER DISTRIBUTION:

Diffusion Eqn for hole population distribution

$$\frac{d^2\Delta p}{dx^2} = \frac{\Delta p}{L_h^2} - \frac{G}{D_h}$$

General Solution

$$\Delta p = G\tau_h + Ce^{x/L_h} + De^{-x/L_h}$$

Use Same Boundary Conditions to find Particular Solution

$$p_n(x) = p_{n_0} + G\tau_h + [p_{n_0}(e^{qV/kT} - 1]e^{-x/L_h}$$

Similar Result for Electrons Holds

Effect of Illumination on diode

MINORITY CHARGE CARRIER CURRENT:

Current is Diffusive, I.e. $J_h \sim dp/dx$, $J_e \sim dn/dx$ ➔

$$J_h(x) = \frac{qD_h p_{n_0}}{L_h}(e^{qV/kT} - 1)e^{-x/L_h} - qGL_h e^{-x/L_h}$$

$$J_e(x') = \frac{qD_e n_{p_0}}{L_e}(e^{qV/kT} - 1)e^{-x'/L_e} - qGL_e e^{-x'/L_e}$$

Next, need current across junction…

Need Current Flow in Depletion Region (aka Transition Region or Junction)

Current continuity equation gives

$$-\frac{1}{q}\frac{dJ_h}{dx} = (U - G) = \frac{1}{q}\frac{dJ_e}{dx}$$

Neglect Losses in Junction & Integrate across junction to find change in current:

$$\delta J_e = \left|\delta J_h\right| = -q\int_{-W}^{0} G\,dx \underset{\uparrow}{\sim} qGW$$

(since G ~ constant)

Distribution of carriers with Illumination

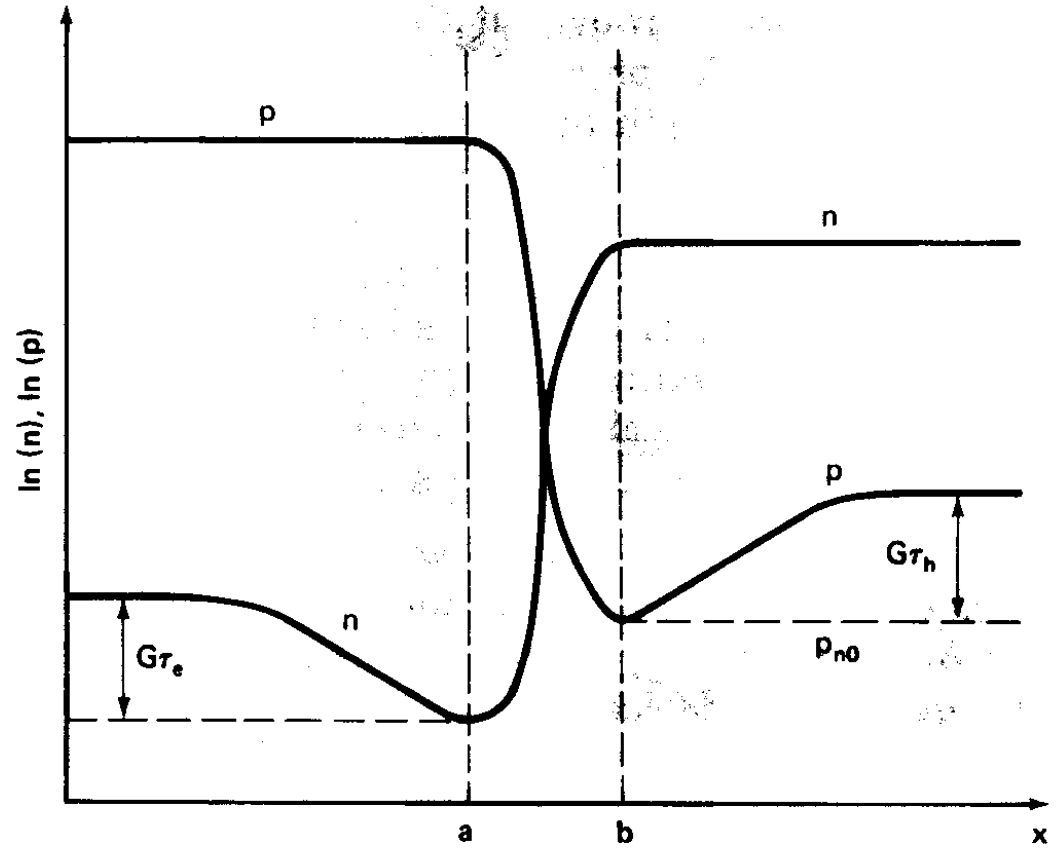


Figure 4.10. Distribution of carriers through a *p-n* junction when short-circuited under infrared illumination (generation rate assumed uniform through diode).

Diode Response w/ Illumination:

Current Density vs Voltage Across Diode:

$$J_{total} = J_e + J_h - dJ =$$

$$\left(\frac{qD_e n_{p_0}}{L_e} + \frac{qD_h p_{n_0}}{L_h} \right)\left(\exp(qV / kT) - 1\right) + qGW$$

Total Current, I (Amps), Is Just Jtotal * Area of Diode…

$$I = I_0 (e^{qV/kT} - 1) - I_L$$

$$I_L = qAG(L_e + W + L_h)$$

Illuminated p-n diode

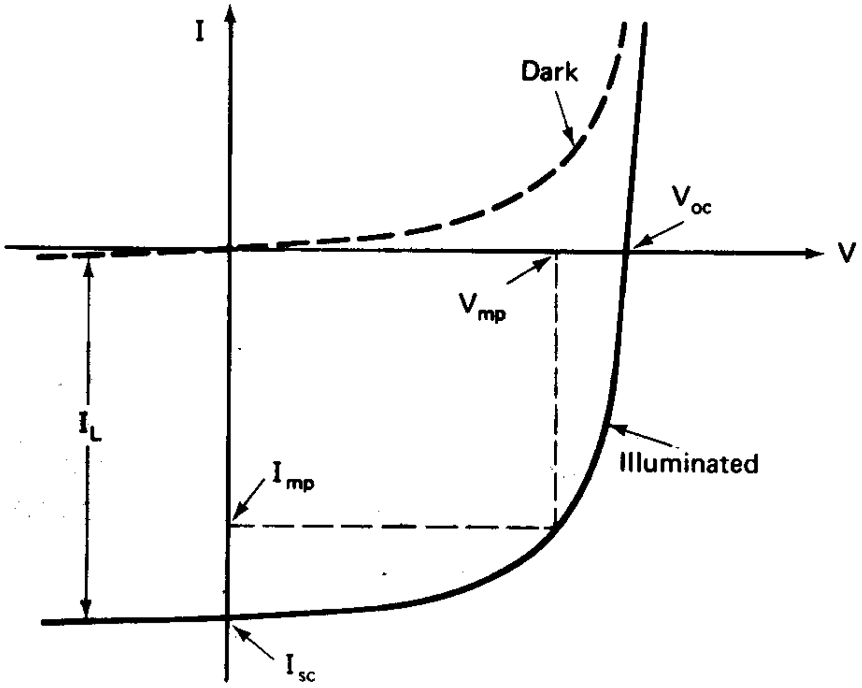
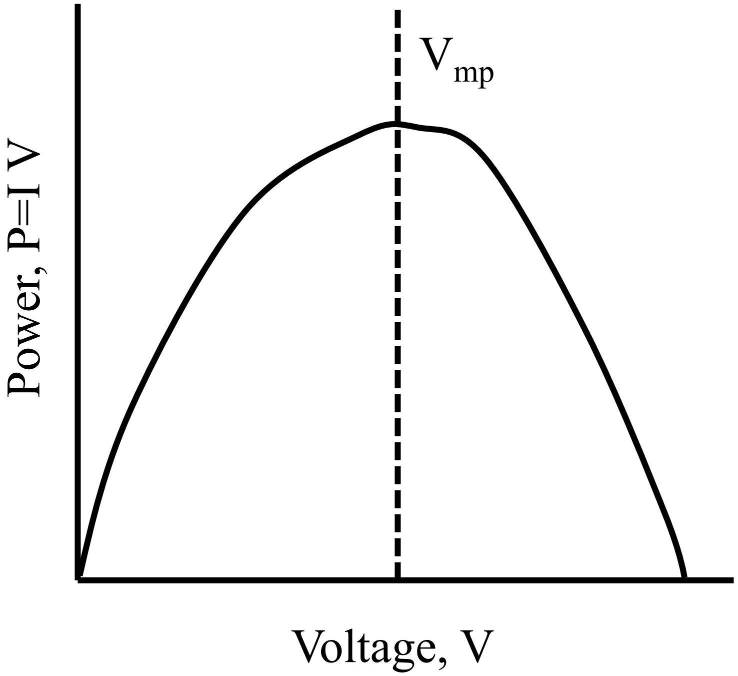


Figure 4.11. Terminal properties of a *p-n* junction diode in the dark and when illuminated.



Characterizing Solar PV Cell Performance

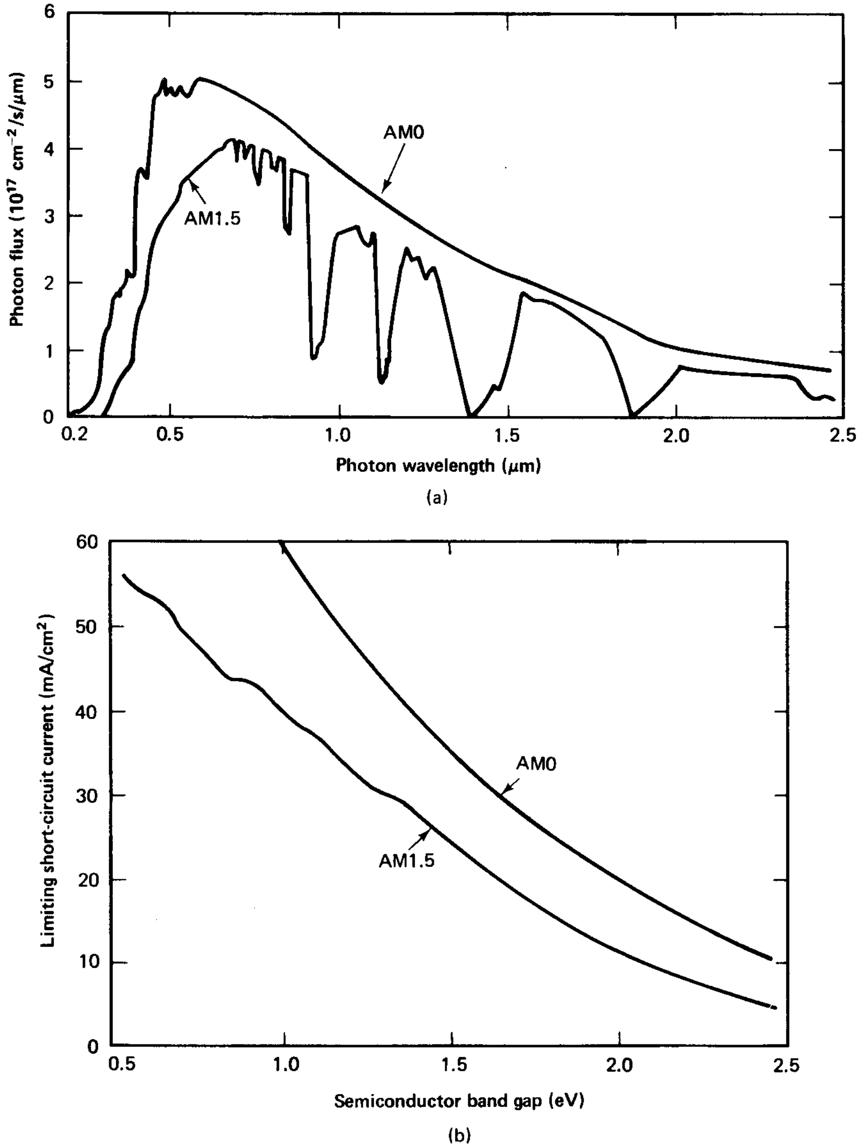
- Open Circuit Voltage, Voc $V_{oc} = \frac{kT}{q}\ln(\frac{I_L}{I_0}+1)$
- Short-circuit Current, $I_{SC} = I_L = qAG(L_e + W + L_h)$
- Maximum Power Point (Vmp,Imp)
- Fill Factor,

$$FF \equiv \frac{V_{MP}I_{MP}}{V_{OC}I_{SC}}$$

Typically FF~0.5-0.7

- Efficiency $\eta = \frac{V_{MP}I_{MP}}{P_{in}} = \frac{V_{OC}I_{SC}}{P_{in}} \sim 0.1 - 0.15$

Solar Photon Flux Spectrum & Maximum Short-Circuit Current

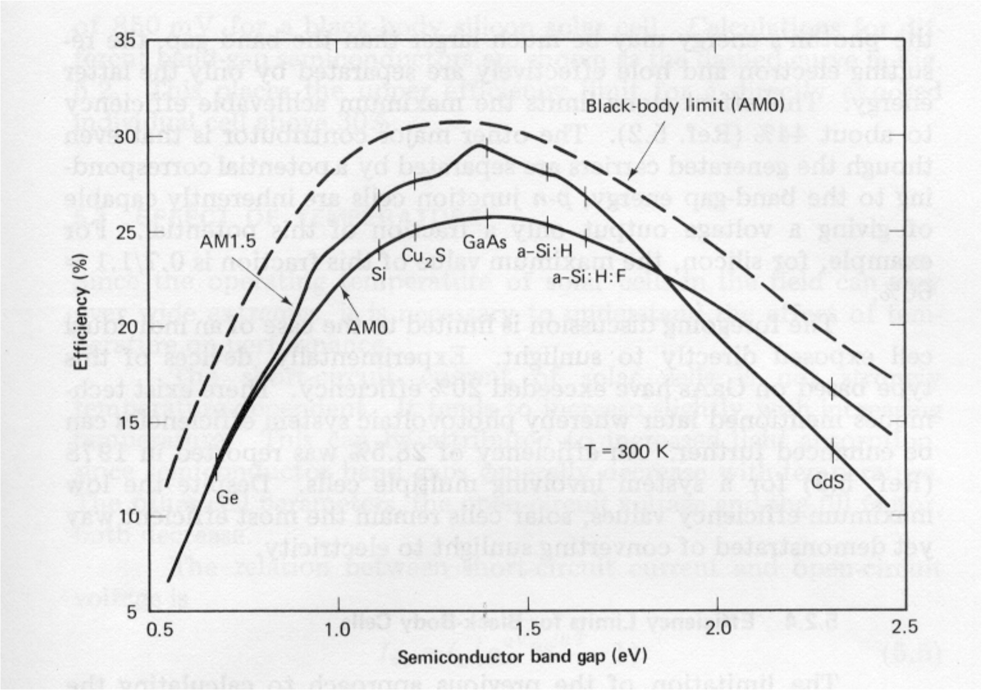


(a)

(b)

Figure 5.1. (a) Photon flux in sunlight corresponding to the AM0 and AM1.5 energy distributions given in Fig. 1.3. (b) Corresponding upper limits on the short-circuit current density as a function of the energy band gap of the solar cell material.

Solar Cell Efficiency Limits



One Photon =>
One e-hole pair +
Thermal Energy

Recombination Losses
(Surfaces, Defects,
Impurities)

Reflections & Scattering

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