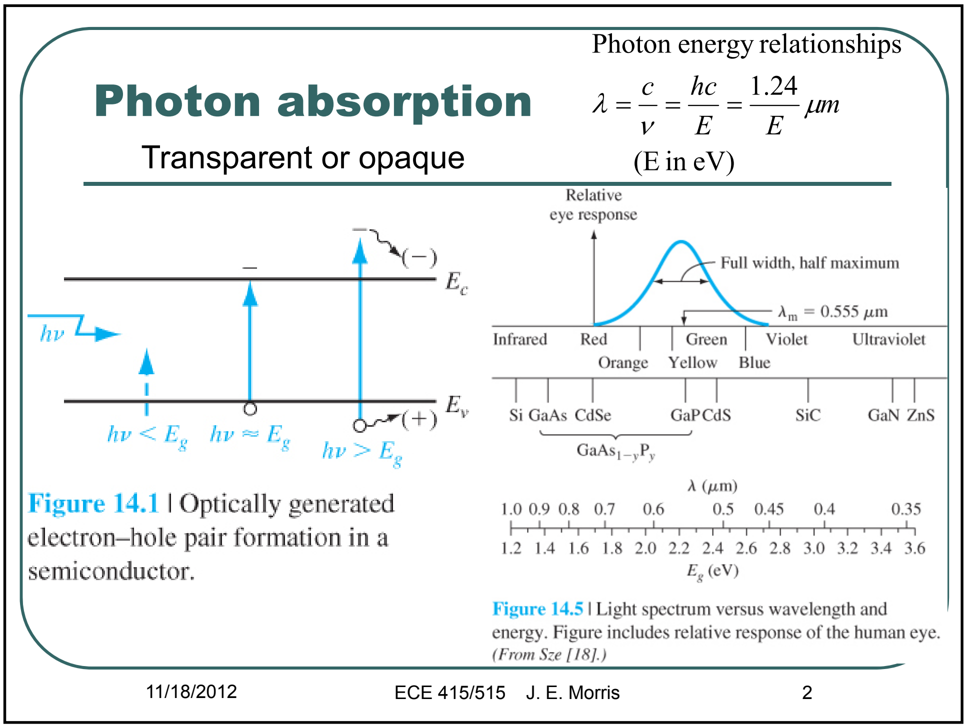
EE415/515 Fundamentals of Semiconductor Devices Fall 2012

Lecture 16:
PVs, PDs, & LEDs
(Chapter 14.1-14.6)



Photon absorption

Transparent or opaque

Photon energy relationships

$$\lambda = \frac{c}{\nu} = \frac{hc}{E} = \frac{1.24}{E}\ \mu m$$

(E in eV)

Figure 14.1 | Optically generated electron–hole pair formation in a semiconductor.

Figure 14.5 | Light spectrum versus wavelength and energy. Figure includes relative response of the human eye. *(From Sze [18].)*

Photon absorption

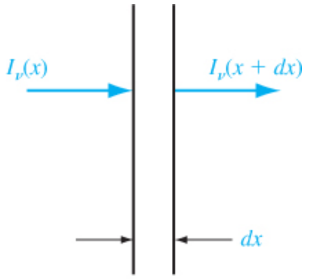


Figure 14.2 | Optical absorption in a differential length.

$$\text{Energy absorbed in element dx} = \alpha I_\nu(x)dx$$

$$I_\nu(x+dx) - I_\nu(x) = \frac{dI_\nu(x)}{dx}.dx = -\alpha I_\nu(x)dx$$

$$\text{Hence } \frac{dI_\nu(x)}{dx} = -\alpha I_\nu(x)$$

$$\frac{dI_\nu(x)}{I_\nu(x)} = -\alpha dx$$

$$\left[\ln(I_\nu(x))\right]_0^x = -\alpha\left[x\right]_0^x$$

$$\ln I_\nu(x) - \ln I_{\nu 0} = -\alpha x = \ln\frac{I_\nu(x)}{I_{\nu 0}}$$

$$I_\nu(x) = I_{\nu 0}\exp{-\alpha x}$$

Photon absorption coefficient α

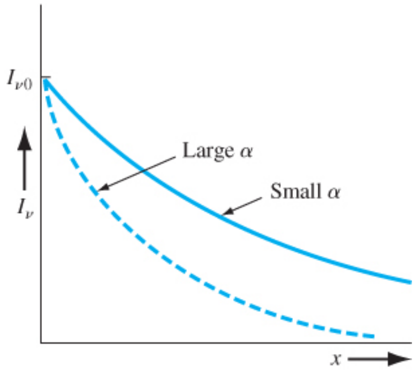


Figure 14.3 | Photon intensity versus distance for two absorption coefficients.

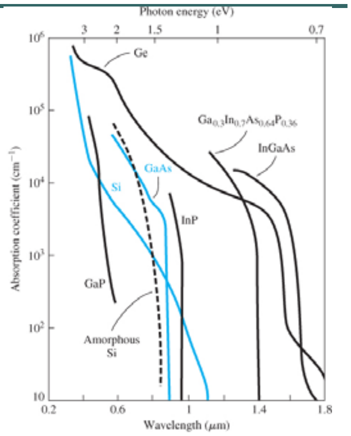


Figure 14.4 | Absorption coefficient as a function of wavelength for several semiconductors.
(From Shur [13].)

Ex 14.1 For 5µm thick Si, determine the % of photon energy which will pass through for photon wavelengths λ (a) 0.8µm & (b) 0.6µm.

For silicon, $\lambda = 0.8\,\mu\text{m} \Rightarrow \alpha \cong 10^3\ \text{cm}^{-1}$

$\lambda = 0.6\,\mu\text{m} \Rightarrow \alpha \cong 4.5\times10^3\ \text{cm}^{-1}$

Let $d = 5\,\mu\text{m} = 5\times10^{-4}\ \text{cm}$

(a) For $\lambda = 0.8\,\mu\text{m}$,

$$\frac{I_\nu(d)}{I_{\nu0}} = \exp(-\alpha d)$$

$$= \exp\left[-\left(10^3\right)\left(5\times10^{-4}\right)\right]$$

$$= 0.607 = 60.7\%$$

(b) For $\lambda = 0.6\,\mu\text{m}$,

$$\frac{I_\nu(d)}{I_{\nu0}} = \exp(-\alpha d)$$

$$= \exp\left[-\left(4.5\times10^3\right)\left(5\times10^{-4}\right)\right]$$

$$= 0.105 = 10.5\%$$

Ex 14.2 A photon flux of intensity $I_{\nu0}$=0.10W/cm² at wavelength λ=1µm is incident on a Si surface. Neglecting any reflection from the surface, determine the EHP generation rate at depths of (a) x=5µm and (b) x=20µm below the surface.

Electron - hole pair generation rate

$$g' = \frac{\alpha I_\nu(x)}{h\nu}$$

For $\lambda = 1\,\mu\text{m}$ in silicon, $\alpha \cong 10^2\ \text{cm}^{-1}$

Now

$$E = h\nu = \frac{1.24}{\lambda} = \frac{1.24}{1.0} = 1.24\,\text{eV}$$

(a) $I_\nu(d) = I_{\nu0}\exp(-\alpha d)$

$$= (0.10)\exp\left[-\left(10^2\right)\left(5\times10^{-4}\right)\right]$$

$$= 0.0951\ \text{W/cm}^2$$

$$g' = \frac{\alpha I_\nu(d)}{h\nu} = \frac{\left(10^2\right)(0.0951)}{\left(1.6\times10^{-19}\right)(1.24)}$$

$$= 4.79\times10^{19}\ \text{cm}^{-3}\,\text{s}^{-1}$$

(b) $I_\nu(d) = I_{\nu0}\exp(-\alpha d)$

$$= (0.10)\exp\left[-\left(10^2\right)\left(20\times10^{-4}\right)\right]$$

$$= 0.0819\ \text{W/cm}^2$$

$$g' = \frac{\alpha I_\nu(d)}{h\nu} = \frac{\left(10^2\right)(0.0819)}{\left(1.6\times10^{-19}\right)(1.24)}$$

$$= 4.13\times10^{19}\ \text{cm}^{-3}\,\text{s}^{-1}$$

Solar Cells

At zero bias : Built - in field

EHPs generated by incident light ⇒ reverse current

Reverse current I_L ⇒ a forward bias $I_L R$ in load R

Total current $I = I_L - I_F = I_L - I_S\left[\exp\frac{eV}{kT} - 1\right]$

Short circuit current : $V = 0$

$$I = I_L = I_{sc}$$

Open circuit current : $I = 0 = I_L - I_S\left[\exp\frac{eV_{oc}}{kT} - 1\right]$

$$V_{oc} = \frac{kT}{e}\ln\left(1 + \frac{I_L}{I_S}\right)$$

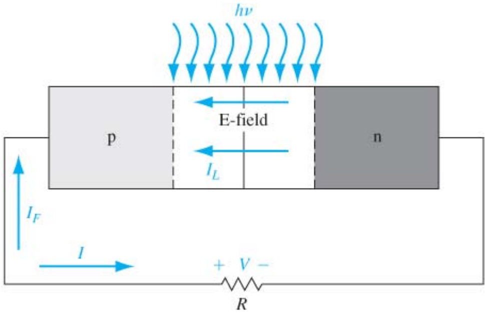


Figure 14.6 | A pn junction solar cell with resistive load.

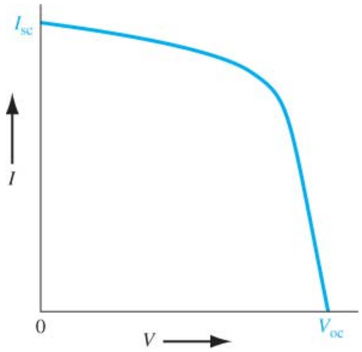


Figure 14.7 | *I–V* characteristics of a pn junction solar cell.

Ex 14.3 A GaAs pn junction solar cell has $N_a = 10^{17}$/cc, $N_d = 2\times10^{16}$/cc, $D_n = 190\,\text{cm}^2/\text{s}$, $D_p = 10\,\text{cm}^2/\text{s}$, $\tau_{n0} = 10^{-7}\,\text{s}$, $\tau_{p0} = 10^{-8}\,\text{s}$. Assume a photocurrent density $J_L = 20\,\text{mA/cm}^2$ is generated in the solar cell. Calculate (a) V_{OC} and (b) V_{OC}/V_{bi}.

(a) We find

$$L_n = \sqrt{D_n \tau_{n0}} = \sqrt{(190)(10^{-7})}$$
$$= 4.36\times10^{-3}\,\text{cm}$$
$$L_p = \sqrt{D_p \tau_{p0}} = \sqrt{(10)(10^{-8})}$$
$$= 3.16\times10^{-4}\,\text{cm}$$

Now

$$J_S = en_i^2\left(\frac{D_n}{L_n N_a} + \frac{D_p}{L_p N_d}\right)$$
$$= (1.6\times10^{-19})(1.8\times10^{6})^2$$
$$\times\left[\frac{190}{(4.36\times10^{-3})(10^{17})} + \frac{10}{(3.16\times10^{-4})(2\times10^{16})}\right]$$
$$J_S = 1.046\times10^{-18}\,\text{A/cm}^2$$

We find

$$V_{oc} = V_t \ln\left(1 + \frac{J_L}{J_S}\right)$$
$$= (0.0259)\ln\left(1 + \frac{20\times10^{-3}}{1.046\times10^{-18}}\right)$$
$$= 0.971\,\text{V}$$

$$\text{(b) } V_{bi} = V_t \ln\left(\frac{N_a N_d}{n_i^2}\right)$$
$$= (0.0259)\ln\left[\frac{(10^{17})(2\times10^{16})}{(1.8\times10^{6})^2}\right]$$
$$= 1.24\,\text{V}$$

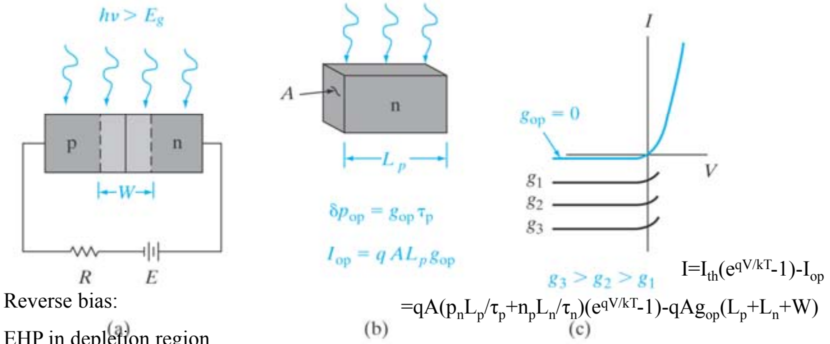
So

$$\frac{V_{oc}}{V_{bi}} = \frac{0.971}{1.240} = 0.783$$

Zero bias: -ve acceptor ions in P, +ve donor ions in N: elec field N→P in depletion region

Reverse bias: Field increased

$I_{op}=qAg_{op}(L_p+L_n+W)$ ….. EHP generation: W, electrons <u>within L_n of depletion edge </u>in P



Reverse bias:

EHP in depletion region
→ holes to P, e-s to N
→incr reverse current

$I=I_{th}(e^{qV/kT}-1)-I_{op}$

$=qA(p_nL_p/\tau_p+n_pL_n/\tau_n)(e^{qV/kT}-1)-qAg_{op}(L_p+L_n+W)$

$V=0$, $I_{sc} = - I_{op}$, & $I=0$, $V_{oc} = (kT/q)\ln(1+I_{op}/I_{th})$
>0

Figure 8.1

Optical generation of carriers in a p-n junction: (a) absorption of light by the device; (b) current I_{op} resulting from EHP generation within a diffusion length of the junction on the n side; (c) I–V characteristics of an illuminated junction.

Photovoltaic Effect

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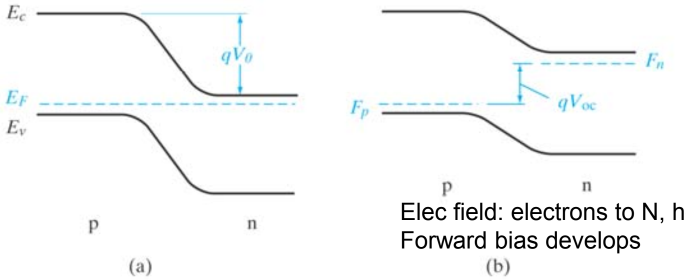
$V_{oc} = (kT/q)\ln(1+I_{op}/I_{th}) > 0$

Photovoltaic Effect

Max $qV_{oc} = qV_0$



Elec field: electrons to N, holes to P
Forward bias develops

Figure 8.2

Effects of illumination on the open circuit voltage of a junction: (a) junction at equilibrium; (b) appearance of a voltage V_{oc} with illumination.

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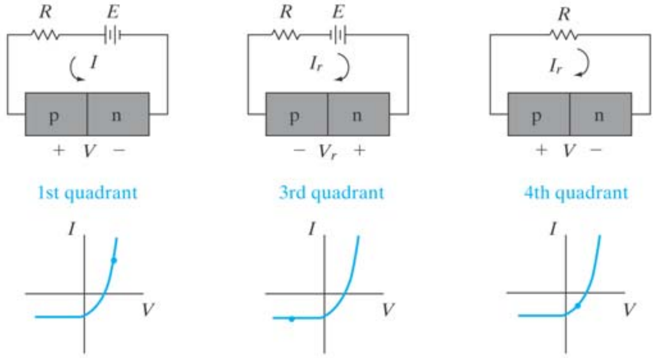
Operating conditions



(a) Conventional diode operation

(b) Photodiode

(c) Solar cell (c.f. battery)

Figure 8.3

Operation of an illuminated junction in the various quadrants of its I–V characteristic; in (a) and (b), power is delivered to the device by the external circuit; in (c) the device delivers power to the load.

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Solar cell power

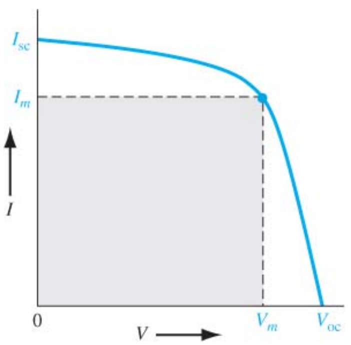

Figure 14.8 | Maximum power rectangle of the solar cell *I*–*V* characteristics.

Load power $P = IV = I_L V - I_S\left[\exp\frac{eV}{kT} - 1\right]V$

For max load power set $\frac{\mathrm{dP}}{\mathrm{dV}} = 0$

$$= I_L - I_S\left[\exp\frac{eV}{kT} - 1\right] - I_S V\left[\exp\frac{eV}{kT}\right]\frac{e}{kT}$$

at $\mathrm{V_m}$ where

$$I_L + I_S = I_S\left[\exp\frac{eV_m}{kT}\right]\left[1 + \frac{eV_m}{kT}\right]$$

$$\left[\exp\frac{eV_m}{kT}\right]\left[1 + \frac{eV_m}{kT}\right] = 1 + \frac{I_L}{I_S}$$

Conversion efficiency $\eta = \frac{\mathrm{P_m}}{\mathrm{P_{in}}}100\% = \frac{\mathrm{I_m V_m}}{\mathrm{P_{in}}}100\%$

where $\mathrm{P_{in}}$ is the incident optical power

4th quadrant (inverted)

Maximum power operating point I_m,V_m

Fill factor $=I_m V_m / I_{SC} V_{OC}$

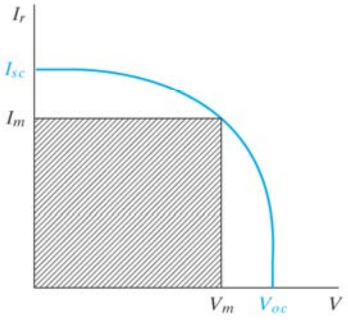

Figure 8.6

I–*V* characteristics of an illuminated solar cell. The maximum power rectangle is shaded.

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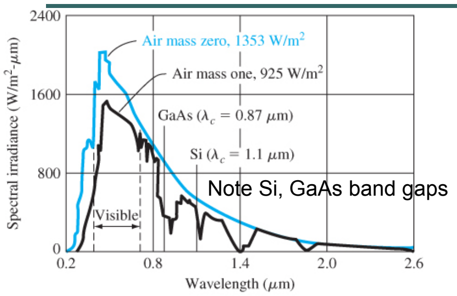
Solar spectrum

If $hc/\lambda < E_g \rightarrow$ no absorption
If $hc/\lambda > E_g \rightarrow$ energy $> E_g$ dissipates as heat



Note Si, GaAs band gaps

Figure 14.9 | Solar spectral irradiance.
(From Sze [18].)

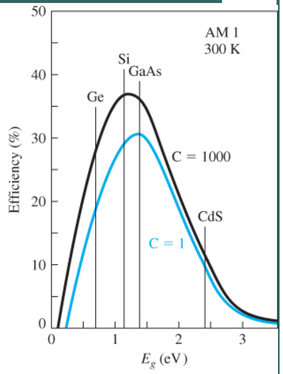


Figure 14.10 | Ideal solar cell efficiency at $T = 300$ K for C = 1 sun and for a C = 1000 sun concentrations as a function of bandgap energy.
(From Sze [18].)

Air mass zero → spectrum outside earth atmosphere
Air mass one → spectrum at earth surface at noon

Concentration: I_{sc} incr linearly with C, V_{oc} incr little

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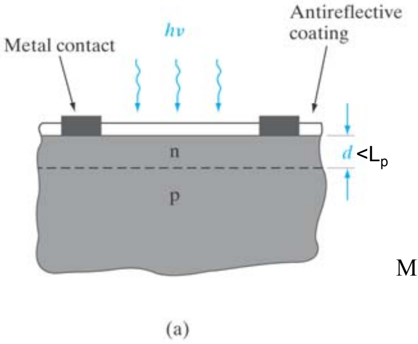
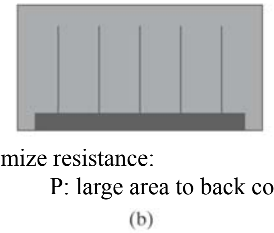
Solar cell design:

N region: Junction near surface ($d<L_p$)
Minimizes hole loss by recombination before reaching junction.
P region: Need optical absorption depth ($1/\alpha$) $< d+L_n$





Minimize resistance:
P: large area to back contact
N: Contact fingers for short paths

Large $V_0 \rightarrow$ heavy doping
Limited by long lifetimes requirement

Figure 8.5
Configuration of a solar cell: (a) enlarged view of the planar junction; (b) top view, showing metal contact "fingers."

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Non-uniform absorption

Photon absorption rate at depth x $= \alpha \, \Phi_0 \exp - \alpha x$

where Φ_0 is the incident optical flux at the surface

Also include surface reflection coefficient R, so :

EHP generation rate (assuming one EHP/photon) is

$$G_L = \alpha(\lambda).\Phi(\lambda).[1 - R(\lambda)].\exp - \alpha(\lambda)x$$

where all parameters vary with λ.

EHP generation depth varies with α, i.e. λ

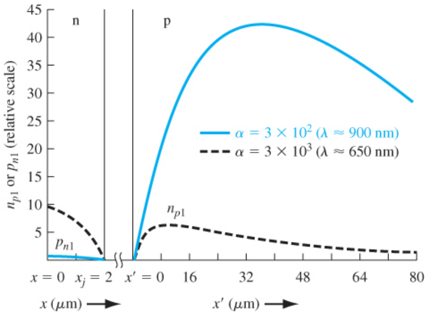


Figure 14.11 | Steady-state, photon-induced normalized minority carrier concentration in the pn junction solar cell for two values of incident photon wavelength ($x_j = 2\ \mu$m, $W = 1\ \mu$m, $L_p = L_n = 40\ \mu$m).

Heterojunctions expand the absorption energy range

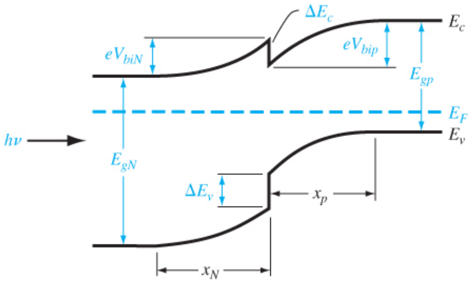


Figure 14.12 | The energy-band diagram of a pN heterojunction in thermal equilibrium.

N region absorbs hν>E_{gN}
p region absorbs E_{gN}>hν>E_{gp}

Similarly ⟶

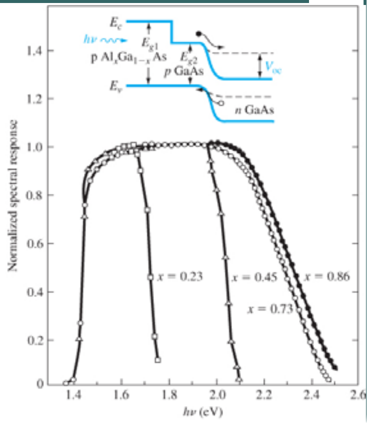


Figure 14.13 | The normalized spectral response of several AlGaAs/GaAs solar cells with different compositions. *(From Sze [17].)*

Amorphous Si solar cells

(more economic than single crystal)

Short range order; CVD at 600°C; hydrogenated dangling bonds; low mobility in band gap, high $>E_c$ & $<E_v$; high optical absorption→ ~1µm thk film

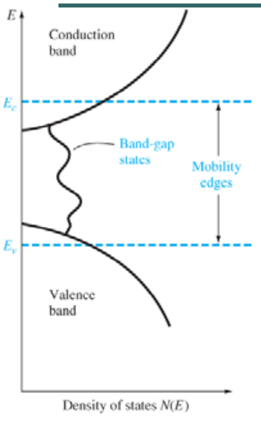
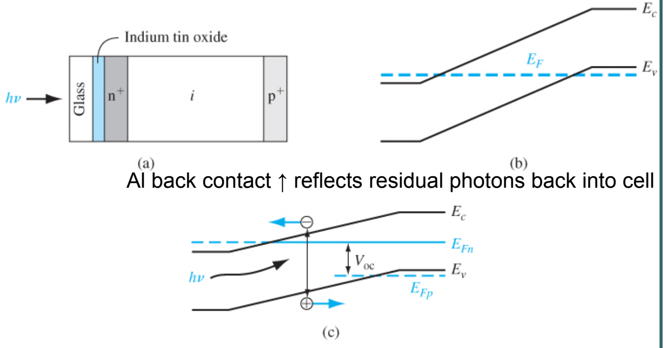


Figure 14.14 | Density of states versus energy of amorphous silicon.
(From Yang [22].)



Al back contact ↑ reflects residual photons back into cell

Figure 14.15 | The (a) cross section, (b) energy-band diagram at thermal equilibrium, and (c) energy-band diagram under photon illumination of an amorphous silicon PIN solar cell. *(From Yang [22].)*

Photoconductor

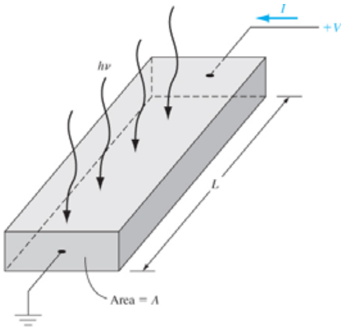


Figure 14.16 | A photoconductor.

At thermal equilibrium $\sigma_0 = e(\mu_n n_0 + \mu_p p_0)$

With (optical) excess carriers $\sigma = e[\mu_n(n_0 + \delta n) + \mu_p(p_0 + \delta p)]$

For EHP generation in n - type, $\delta n = \delta p \equiv \delta p$, & $\delta \mathrm{n} << \mathrm{n}_0$

$$\sigma = e[\mu_n(n_0 + \delta p) + \mu_p(p_0 + \delta p)] = e(\mu_n n_0 + \mu_p p_0) + e(\mu_n + \mu_p)\delta p$$

and photoconductivity $\Delta\sigma = e(\mu_n + \mu_p)\delta p$

so current density $J = J_0 + J_L = (\sigma_0 + \Delta\sigma)E$

and photocurrent $I_L = J_L A = A(\Delta\sigma)E = eG_L\tau_p(\mu_n + \mu_p)AE$

or, with transit time $t_n = \dfrac{L}{\mu_n E}$, $I_L = eG_L\tau_p(\mu_n + \mu_p)A\dfrac{L}{\mu_n t_n}$

$$= eG_L\left(\frac{\tau_p}{t_n}\right)(1 + \frac{\mu_p}{\mu_n})AL$$

Photoconductor gain $\Gamma_{\mathrm{ph}} = \dfrac{\text{Rate of charge collection at contacts}}{\text{Rate of optical charge generation}}$

$$= \frac{I_L}{eG_L AL} = \left(\frac{\tau_p}{t_n}\right)(1 + \frac{\mu_p}{\mu_n}) \approx \frac{\tau_p}{t_n} \approx \frac{\mu s}{ns}$$

(number of times photoelectron flows around circuit before recombination)

Ex 14.4 For an N-type Si photoconductor of length L=100μm, c/s area A=10^{-7}cm^2, & minority carrier lifetime τ_p=10^{-6}s. Determine the photocurrent if G_L=10^{21}/cc-s and E=10V/cm. Assume μ_n=1000cm^2/v-s & μ_p=400cm^2/v-s.

The photocurrent is given by

$$I_L = eG_L\tau_p(\mu_n + \mu_p)AE$$
$$= (1.6\times10^{-19})(10^{21})(10^{-6})$$
$$\times(1000+400)(10^{-7})(10)$$
$$I_L = 2.24\times10^{-7}\text{ A} = 0.224\,\mu\text{ A}$$

Photodiode (reverse bias)

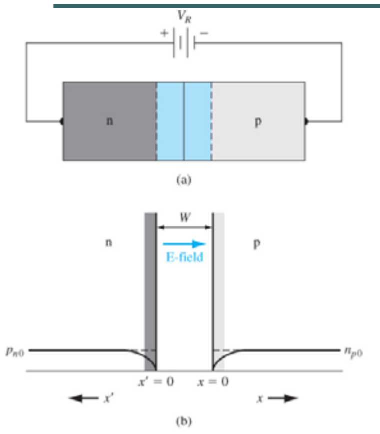


Figure 14.17 | (a) A reverse-biased pn junction. (b) Minority carrier concentration in the reverse-biased pn junction.

Photocurrent from EHP generation in rev - bias depletion region

$J_{L1} = e\int G_L dx = eG_L W$ if $\mathrm{G_L}$ constant over depletion width W

(Responds quickly to illumination $\Rightarrow$ "prompt" current)

Ambipolar transport equation : $\mathrm{D_n}\dfrac{\partial^2(\delta n_p)}{\partial x^2} + G_L - \dfrac{\delta n_p}{\tau_{n0}} = \dfrac{\partial(\delta n_p)}{\partial t}$

For steady state : $\dfrac{\partial^2(\delta n_p)}{\partial x^2} - \dfrac{\delta n_p}{L_n^2} = -\dfrac{G_L}{\mathrm{D_n}}$

Homogeneous solution : $\dfrac{\partial^2(\delta n_{ph})}{\partial x^2} - \dfrac{\delta n_{ph}}{L_n^2} = 0$

$\delta n_{ph} = Ae^{-x/L_n} + Be^{x/L_n} \Rightarrow Ae^{-x/L_n}$ (x > 0) for finite as x → ∞

Particular solution : $-\dfrac{\delta n_{pp}}{L_n^2} = -\dfrac{G_L}{\mathrm{D_n}} \Rightarrow \delta n_{pp} = \dfrac{G_L L_n^2}{\mathrm{D_n}} = G_L\tau_{n0}$

$\therefore\ \delta n_p = Ae^{-x/L_n} + G_L\tau_{n0}$ and $\delta n_p(0) = -n_{p0}$ since $\mathrm{n_p}(0) = 0$

Hence $A = -G_L\tau_{n0} - n_{p0}$ and $\delta n_p(x) = G_L\tau_{n0} - (G_L\tau_{n0} + n_{p0})e^{-x/L_n}$

and similarly $\delta p_n(x') = G_L\tau_{p0} - (G_L\tau_{p0} + p_{n0})e^{-x'/L_p}$

Photodiode (cont'd)

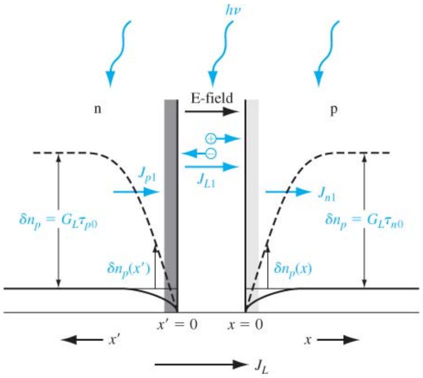


Figure 14.18 | Steady-state, photoinduced minority carrier concentrations and photocurrents in a "long" reverse-biased pn junction.

Diffusion current due to minority electrons at x = 0 :

$$J_{n1} = eD_n \left.\frac{d(\delta n_p)}{dx}\right|_{x=0}$$

$$= eD_n \frac{d}{dx}\left.\left[G_L\tau_{n0} - (G_L\tau_{n0} + n_{p0})e^{-x/L_n}\right]\right|_{x=0}$$

$$= \frac{eD_n}{L_n}(G_L\tau_{n0} + n_{p0}) = eG_L L_n + \frac{eD_n n_{p0}}{L_n}$$

$$= \text{photocurrent} + \text{reverse saturation current}$$

Similarly $\mathrm{J}_{\mathrm{p1}} = eG_L L_p + \dfrac{eD_p p_{n0}}{L_p}$

so steady state photocurrent $\mathrm{J}_{\mathrm{L}} = J_{L1} + J_{n1} + J_{p1}$

$$= e(W + L_n + L_p)G_L$$

where $e(L_n + L_p)G_L$ is the "delayed" photocurrent

Ex 14.5 Calculate (a) the steady photocurrent density and (b) the ratio of prompt photocurrent to steady-state photocurrent in a reverse-biased long Si pn diode with V_R=5V and G_L=10^{21}/cc-s, assuming N_a=N_d=10^{15}/cc, D_n=25cm²/s, D_p=10cm²/s, τ_{n0}=5x10^{-7}s, τ_{p0}=10^{-7}s.

We find

$$V_{bi} = V_t \ln\left(\frac{N_a N_d}{n_i^2}\right)$$

$$= (0.0259)\ln\left[\frac{(10^{15})(10^{15})}{(1.5\times10^{10})^2}\right]$$

$$= 0.575\ \mathrm{V}$$

$$W = \left[\frac{2\in_s(V_{bi}+V_R)}{e}\left(\frac{N_a+N_d}{N_aN_d}\right)\right]^{1/2}$$

$$= \left\{\frac{2(11.7)(8.85\times10^{-14})(0.575+5)}{1.6\times10^{-19}} \times\left[\frac{10^{15}+10^{15}}{(10^{15})(10^{15})}\right]\right\}^{1/2}$$

$$= 3.80\times10^{-4}\ \mathrm{cm}$$

Then

$$J_L = e(W + L_n + L_p)G_L$$

From Example 14.5, $L_n = 35.4\ \mu\mathrm{m}$

$L_p = 10.0\ \mu\mathrm{m}$

$$J_L = (1.6\times10^{-19})(3.80+35.4+10.0)(10^{-4})(10^{21})$$

$$J_L = 0.787\ \mathrm{A/cm}^2$$

Now

$$J_{L1} = eWG_L$$

$$= (1.6\times10^{-19})(3.80\times10^{-4})(10^{21})$$

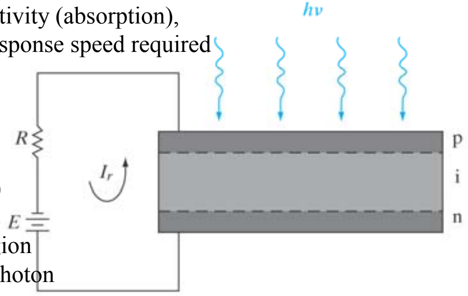
$$= 0.0608\ \mathrm{A/cm}^2$$

Then

$$\frac{J_{L1}}{J_L} = \frac{0.0608}{0.787} = 0.0773$$

Photodiode/Photodetector (3^{rd} quadrant)
I_{OP} proportional to g_{OP}, ~independent of V

Carriers generated in neutral regions within L of depletion region: Diffusion process slow
Hence large depletion region width W; electric field drift response fast
Large W for max sensitivity (absorption),
limited by response speed required
(Wide W, low C)



p-i-n detector :
("i" intrinsic or high ρ)
Large W:
rev bias all across i region
If τ's>>τ_t, then 1 ehp/photon

Figure 8.7
Schematic representation of a p-i-n photodiode.

External quantum efficiency :
η_Q =carriers/photon
$=(J_{OP}/q)/(P_{OP}/h\upsilon) \leq 1$

Increase η_Q (gain)
Operate at avalanche
Avalanche photodiode

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PIN photodiode

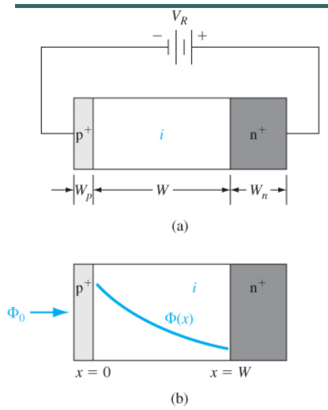

Figure 14.19 | (a) A reverse-biased PIN photodiode. (b) Geometry showing nonuniform photon absorption.

Only the fast "prompt" current is of interest
∴ increase the depletion region width W
⇒ PIN diode with intrinsic "i" region

For photon flux Φ_0 and small W_p, then

$$\Phi(x) = \Phi_0 \exp-\alpha x$$

$$\& \; J_L = e\int_0^W G_L dx$$

$$= e\int_0^W \alpha\Phi_0 \exp-\alpha x.dx$$

$$= e\Phi_0(1-\exp-\alpha W)$$

neglecting recombination

Ex 14.6 Calculate the photocurrent density for a Si PIN diode with an intrinsic region width of W=20μm at a photon flux of 10^{17}/cm^2-s for photon absorption coefficients (a) α=10^2/cm and (b) α=10^4/cm.

(a) For $\alpha = 10^2\,\text{cm}^{-1}$

$$J_L = e\Phi_o\left[1-\exp(-\alpha W)\right]$$

$$= \left(1.6\times10^{-19}\right)\left(10^{17}\right)$$

$$\times\left\{1-\exp\left[-\left(10^2\right)\left(20\times10^{-4}\right)\right]\right\}$$

$$J_L = 2.90\times10^{-3}\,\text{A/cm}^2 = 2.90\,\text{mA/cm}^2$$

(b) For $\alpha = 10^4\,\text{cm}^{-1}$

$$J_L = \left(1.6\times10^{-19}\right)\left(10^{17}\right)$$

$$\times\left\{1-\exp\left[-\left(10^4\right)\left(20\times10^{-4}\right)\right]\right\}$$

$$J_L = 1.6\times10^{-2}\,\text{A/cm}^2 = 16.0\,\text{mA/cm}^2$$

Avalanche photodiode

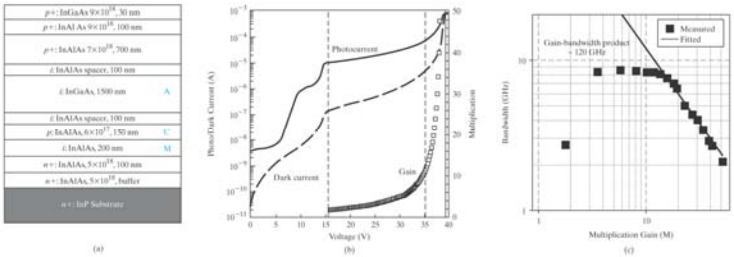

Figure 8.8

Use of multilayer heterojunctions to enhance the photodiode operation: (a) an avalanche photodiode in which light near 1.55 μm is absorbed in a narrow-band-gap material (InGaAs, $E_g = 0.75$ eV) after passing through a wider-gap material (InP and InAlAs); holes are swept to an InAlAs junction, where avalanche multiplication takes place. The *i* regions are lightly doped; (b) photocurrent, dark current, and gain increasing as a function of bias because of avalanche multiplication; (c) typical gain–bandwidth characteristics of such a SACM APD. [After X. Zheng, J. Hsu, J. Hurst, X. Li, S. Wang, X. Sun, A. Holmes, J. Campbell, A. Huntington, and L. Coldren, *IEEE J. Quant. Elec.*, 40(8), pp. 1068–1073, Aug. 2004.]

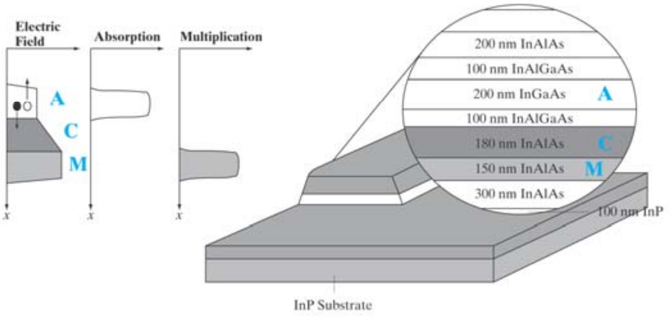

Figure 8.9

Schematic of a waveguide photodiode. The photons are strongly absorbed in the narrow-band-gap InGaAs region A, and carriers are multiplied by the avalanche process in region M. The charge region C helps optimize the electric field profile between A and M.

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Phototransistor

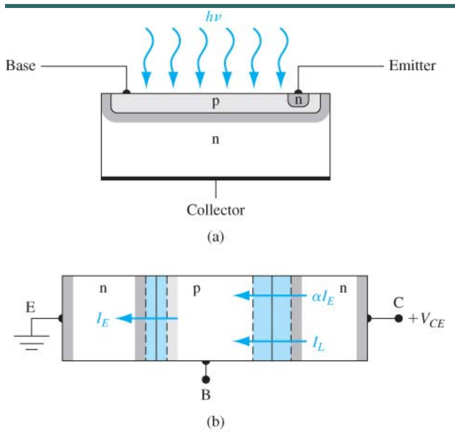

Figure 14.20 | (a) A bipolar phototransistor. (b) Block diagram of the open-base phototransistor.

High gain by transistor action

EHP generation in large C - B junction

Photocurrent $I_E = \alpha I_E + I_L$

$$I_C = I_E = \frac{I_L}{1-\alpha} = (1+\beta)I_L$$

Photoluminescence & electroluminescence

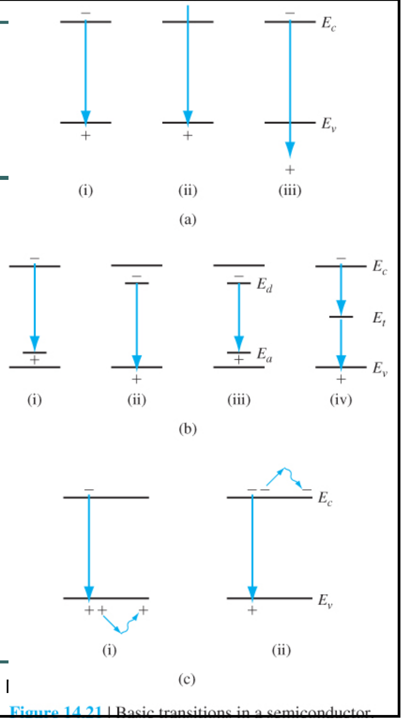

Figure 14.21 | Basic transitions in a semiconductor.

Luminescence when recombination → light

Photoluminescence when excess carriers generated by photo-absorption

Electroluminescence when excess carriers due to electrical current (applied field)

(a) Basic interband transitions:
(ii) and (iii) cause emission spectrum/bandwidth
(b) Impurity/defect states
[(iv) → deep trap recombination]
(c) Auger (non-radiative) transitions

Spontaneous emission rate:-

$$I(\nu) \propto \nu^2 \sqrt{h\nu - E_g}\, \exp-\left[\frac{h\nu - E_g}{kT}\right]$$

GaAs emission spectra & luminescent efficiency

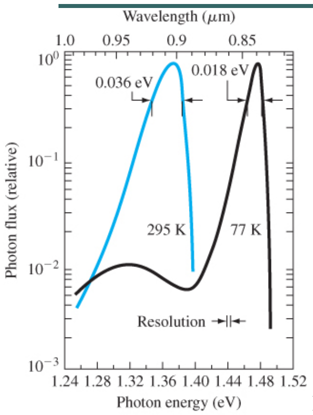

Figure 14.22 | GaAs diode emission spectra at T = 300 K and T = 77 K. *(From Sze and Ng [17].)*

$$\text{Quantum efficiency } \eta_q = \frac{R_r}{R} = \frac{\text{Radiative recombination rate}}{\text{Total recombination rate}} = \frac{\tau_{nr}}{\tau_r + \tau_{nr}}$$

$$\text{where } \tau_r \ \& \ \tau_{nr} = \text{radiative \& non-radiative lifetimes}$$

$$\rightarrow 1 \text{ for } \tau_{nr} \text{ very large}$$

$$\text{Interband recombination rate } R_r = Bnp$$

$$B(direct\ bandgap) \sim 10^6\, xB(indirect \text{ bandgap})$$

Typically emitted photons have $hv > E_g$ so reabsorption possible

Direct and indirect band gap materials

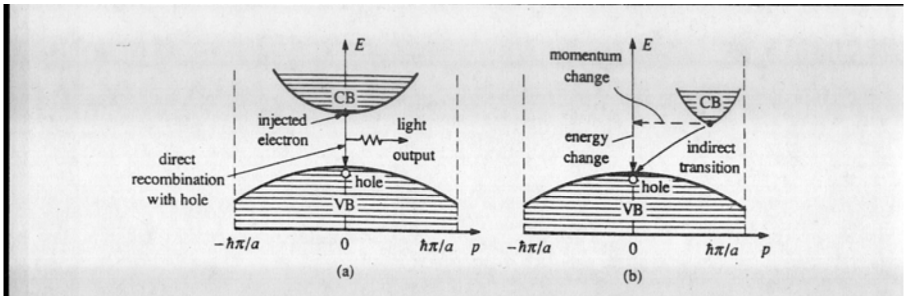

FIGURE 5.2 (a) Interband recombination in a direct-bandgap semiconductor; (b) recombination in an indirect-gap semiconductor also involves a momentum change. (*Source:* J. Allison, *Electronic Engineering Semiconductors and Devices*, 2nd ed., London: McGraw-Hill, 1990, p. 303. With permission.)

Direct band-gap $Al_xGa_{1-x}As$ for optical devices: 0<x<0.45

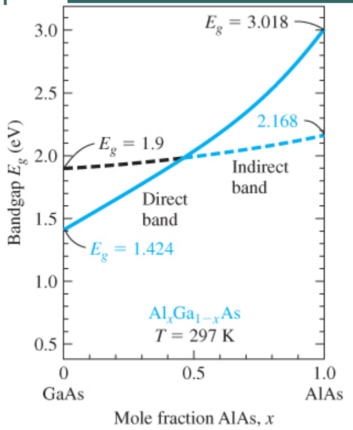

Figure 14.23 | Bandgap energy of $Al_xGa_{1-x}As$ as a function of the mole fraction x.
(From Sze [18].)

$E_g = 1.424+1.247x$ eV for $0 < x < 0.35$

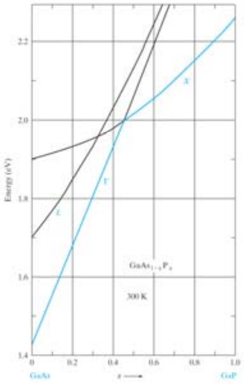

Figure 8.11

Conduction band energies as a function of alloy composition for $GaAs_{1-x}P_x$.

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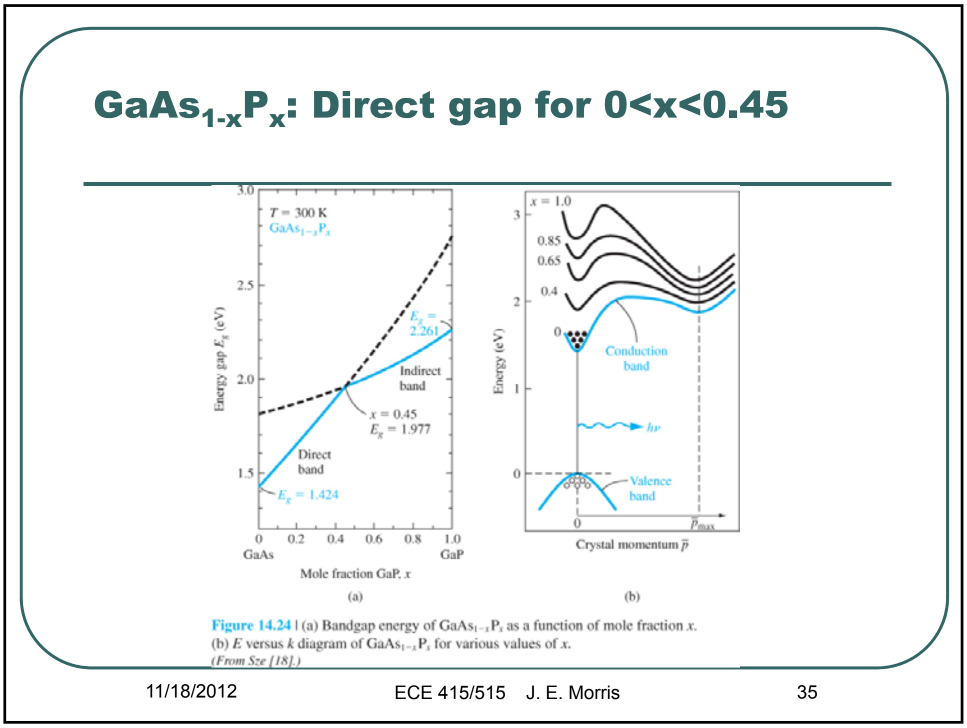
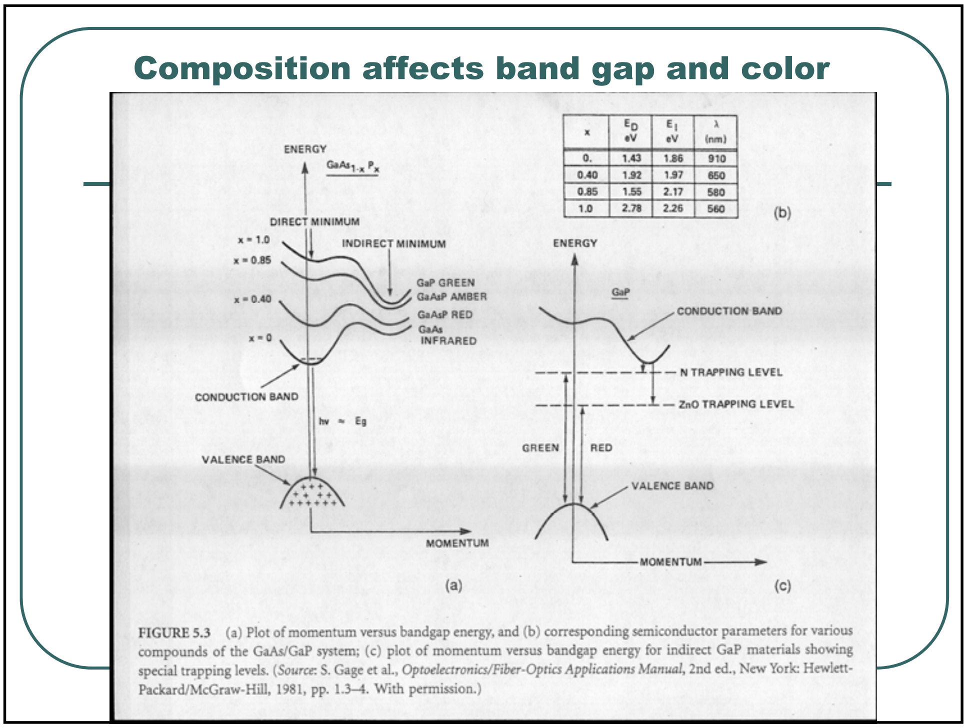


$GaAs_{1-x}P_x$: Direct gap for 0<x<0.45

Figure 14.24 | (a) Bandgap energy of $GaAs_{1-x}P_x$ as a function of mole fraction x. (b) E versus k diagram of $GaAs_{1-x}P_x$ for various values of x. *(From Sze [18].)*



Composition affects band gap and color

x	E_D eV	E_I eV	λ (nm)
0.	1.43	1.86	910
0.40	1.92	1.97	650
0.85	1.55	2.17	580
1.0	2.78	2.26	560

FIGURE 5.3 (a) Plot of momentum versus bandgap energy, and (b) corresponding semiconductor parameters for various compounds of the GaAs/GaP system; (c) plot of momentum versus bandgap energy for indirect GaP materials showing special trapping levels. (*Source*: S. Gage et al., *Optoelectronics/Fiber-Optics Applications Manual*, 2nd ed., New York: Hewlett-Packard/McGraw-Hill, 1981, pp. 1.3–4. With permission.)

Ex 14.7 Determine the output wavelengths of $GaAs_{1-x}P_x$ materials for mole fractions (a) x=0.15 and (b) x=0.30.

(a) For $x = 0.15$, $E_g \cong 1.60\,\text{eV}$

$$\lambda = \frac{1.24}{1.60} = 0.775\,\mu\text{m}$$

(b) For $x = 0.30$, $E_g \cong 1.76\,\text{eV}$

$$\lambda = \frac{1.24}{1.76} = 0.705\,\mu\text{m}$$

Light-emitting diode (LED): Light emission from forward biased junction

$\lambda = hc/E_g = 1.24/E_g$ µm with E_g in eV

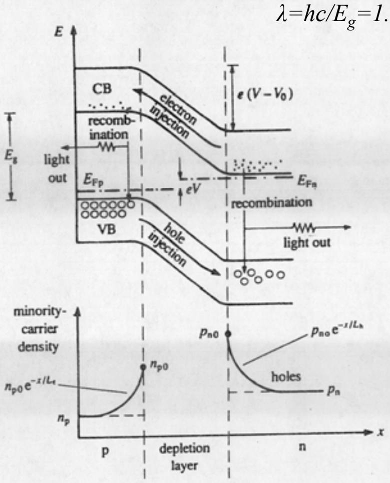


FIGURE 5.1 Light emission due to radiative recombination of injected carriers in a forward-biased pn junction. (*Source:* J. Allison, *Electronic Engineering Semiconductors and Devices*, 2nd ed., London: McGraw-Hill, 1990, p. 302. With permission.)

Internal quantum efficiency

$\gamma = \frac{J_n}{J_n + J_p + J_R}$ is fraction of diode current that produces luminescence

where $J_R = \frac{en_iW}{2\tau_0}\left[\exp\frac{eV}{kT} - 1\right]$ is non-radiative (mid-gap traps)

For n^+p: $J_n >> J_p$ and make J_R small at sufficient forward bias, so $\gamma \to 1$

$R_r = \frac{\delta n}{\tau_r}$ and $R_{nr} = \frac{\delta n}{\tau_{nr}}$ for electrons injected into p-region,

so total recombination rate $R = R_r + R_{nr} = \frac{\delta n}{\tau} = \frac{\delta n}{\tau_r} + \frac{\delta n}{\tau_{nr}}$

Radiative efficiency $\eta = \frac{R_r}{R_r + R_{nr}} = \frac{\frac{1}{\tau_r}}{\frac{1}{\tau_r} + \frac{1}{\tau_{nr}}} = \frac{\tau}{\tau_r}$ ($R_{nr} \propto N_t$ trap site density)

Internal quantum efficiency $\eta_i = \gamma\eta$

External quantum efficiency:
Fraction of generated photons actually emitted

1. Geometry and re-absorption

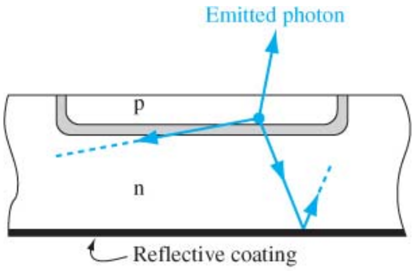
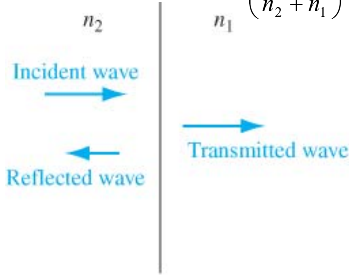


Figure 14.25 | Schematic of photon emission at the pn junction of an LED.

2. Fresnel loss at the air interface

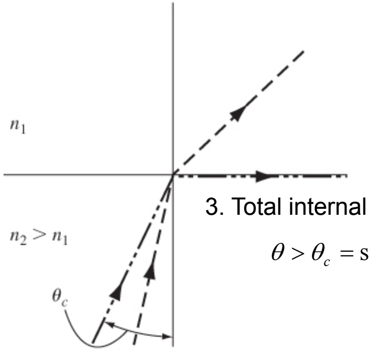
Reflection coefficient $\Gamma = \left(\frac{n_2 - n_1}{n_2 + n_1}\right)^2$



n_1, n_2 refractive indices

Figure 14.26 | Schematic of incident, reflected, and transmitted photons at a dielectric interface.

External quantum efficiency



3. Total internal reflection for

$$\theta > \theta_c = \sin^{-1}\frac{n_1}{n_2}$$

Figure 14.27 | Schematic showing refraction and total internal reflection at the critical angle at a dielectric interface.

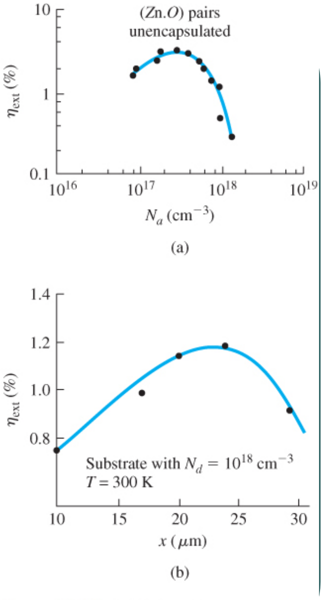


Figure 14.28 | (a) External quantum efficiency of a GaP LED versus acceptor doping. (b) External quantum efficiency of a GaAs LED versus junction depth. *(From Yang [22].)*

Ex 14.8 At wavelength λ=0.70μm, the index of refraction for GaAs is n_2=3.8 and for GaP is n_2=3.2. Consider a $GaAs_{1-x}P_x$ material with x=0.40. Assuming the index of refraction is a linear function of x, determine the reflection coefficient, Γ, at the $GaAs_{0.6}P_{0.4}$-air interface.

For GaAs, $\bar{n}_2 = 3.8$

For GaP, $\bar{n}_2 = 3.2$

Then for $GaAs_{0.6}P_{0.4}$,

$$\bar{n}_2 = (3.8-3.2)(0.6)+3.2 = 3.56$$

Then

$$\Gamma = \left(\frac{\bar{n}_2-\bar{n}_1}{\bar{n}_2+\bar{n}_1}\right)^2 = \left(\frac{3.56-1.0}{3.56+1.0}\right)^2 = 0.315$$

Ex 14.9 Calculate the critical angle between $GaAs_{0.6}P_{0.4}$ and air.

For $GaAs_{0.6}P_{0.4}$, $\bar{n}_2 = 3.56$ (See Exercise Ex 14.8)

Then

$$\theta_c = \sin^{-1}\left(\frac{\bar{n}_1}{\bar{n}_2}\right) = \sin^{-1}\left(\frac{1.0}{3.56}\right) = 16.3^\circ$$

Physical construction for efficiency

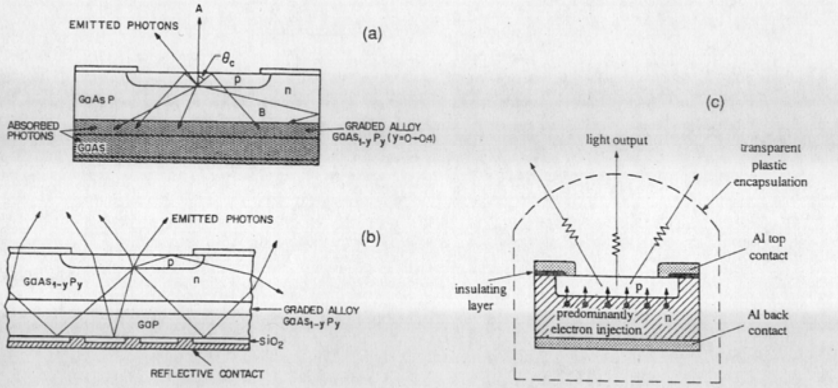


FIGURE 5.4 Effect of (a) opaque substrate, (b) transparent substrate, and (c) encapsulation on photons emitted at the *pn* junction. (*Source*: (a and b) S.M. Sze, *Semiconductor Devices: Physics and Technology*, New York: Wiley, 1985, p. 262. Reprinted by permission of John Wiley & Sons, Inc. (c) J. Allison, *Electronic Engineering Semiconductors and Devices*, 2nd ed., London: McGraw-Hill, 1990, p. 307. With permission.)

LED brightness & heterostructures

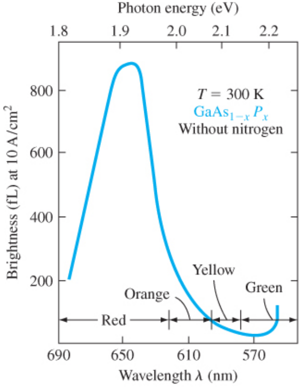


Figure 14.29 | Brightness of GaAsP diodes versus wavelength (or versus bandgap energy). (i.e. as a function of x)
(From Yang [22].)

Photons emitted by electrons injected into narrow-gap p-type not absorbed by wide-gap n-type

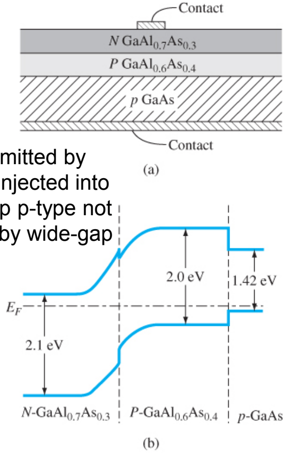


Figure 14.30 | The (a) cross section and (b) thermal equilibrium energy-band diagram of a GaAlAs heterojunction LED. *(From Yang [22].)*

LED materials and development

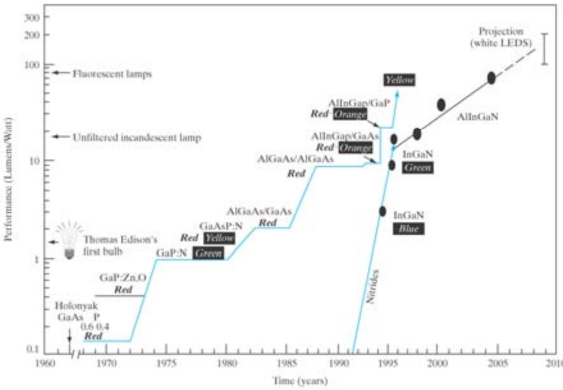


Figure 8.10

Improvement of luminous intensity of LEDs over time. [Modified from M. G. Craford, *IEEE Circuits and Devices*, p. 24, Sept. 1992.]

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Fiber-Optic transmission

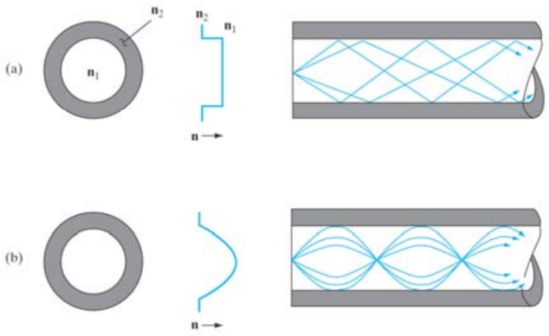

Figure 8.12

Two examples of multimode fibers: (a) *a step index* having a core with a slightly larger refractive index **n**; (b) *a graded index* having, in this case, a parabolic grading of **n** in the core. The figure illustrates the cross section (left) of the fiber, its index-of-refraction profile (center), and typical mode patterns (right).

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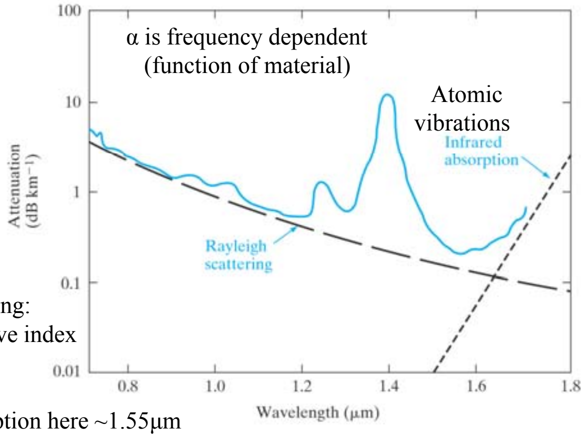
Attenuation $I(x)=I_0e^{-\alpha x}$



α is frequency dependent
(function of material)

Atomic
vibrations

Rayleigh scattering:
Random refractive index
variations ~λ

Minimum absorption here ~1.55μm
(IR laser)

Figure 8.13

Typical plot of attenuation coefficient **α** vs. wavelength λ for a fused silica optical fiber. Peaks are due primarily to OH$^-$ impurities.

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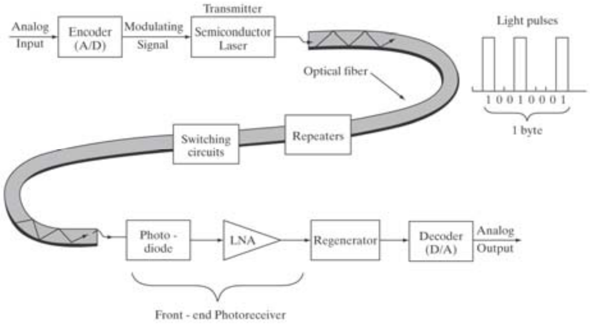

Figure 8.14a

Schematic of a fiber-optic communication system illustrating the transmission of analog signals, such as those in telephony or TV. After the signal is converted to a digital electrical signal, it is used to modulate the laser light output as light pulses that are transmitted down the fiber, with periodic amplification of the signal with repeaters to compensate for fiber loss. Switching circuits route signals appropriately. After the optical signal is transformed to an electrical output by a photodetector and a low-noise preamplifier (LNA), it is converted to an analog signal, once distortions of the digital signals due to propagation through the fiber have been corrected with the use of a "regenerator."

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Assignment 8(b)

14.4
14.11
14.16
14.19