ECE 340: Semiconductor Electronics

Chapter 8: Optoelectronic devices

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Outline

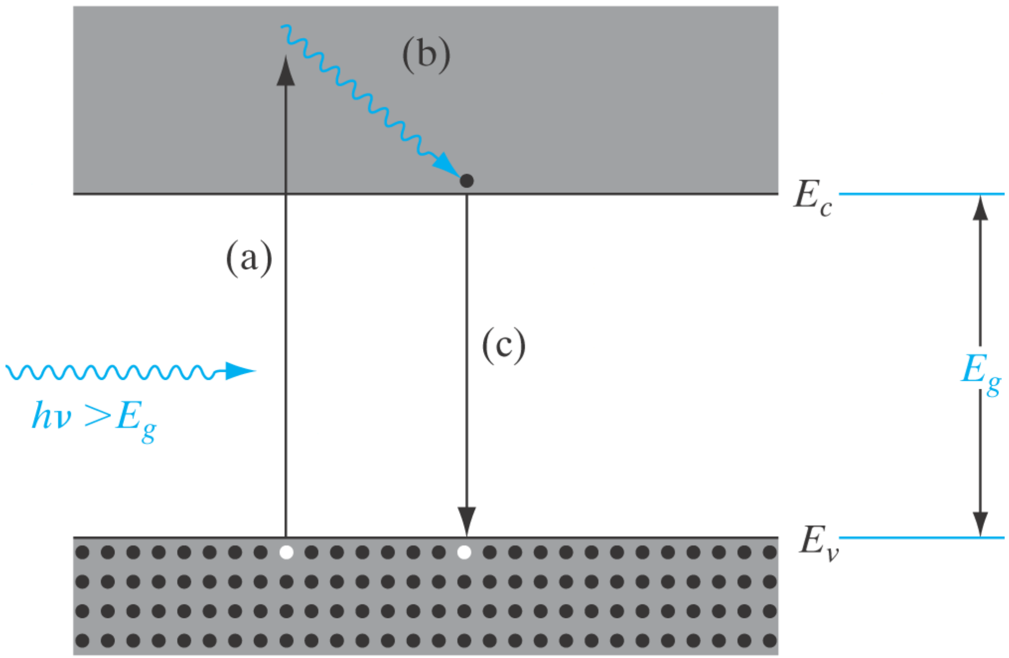
- Current and voltage in an illuminated junction
- Optoelectronic devices
  - Solar Cell
  - Photodetector
  - Light-Emitting Diodes
  - Semiconductor Lasers

Recap: Light Illumination

- If $\boldsymbol{h\nu \geq E_g}$,

photon can be absorbed, and EHP is generated

- Generation rate g_{op} is defined as the number of EHP generated per unit volume per unit time . (unit: EHPs/cm^3/s)

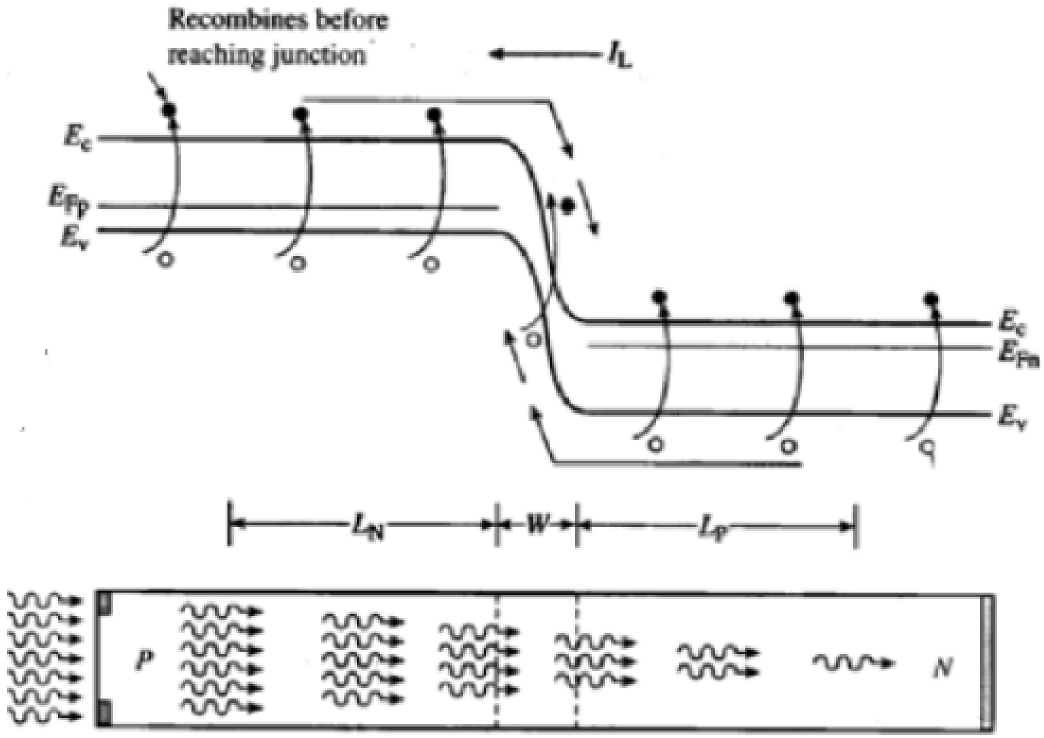


Light generated current

- Current due to optically generated carrier by the junction is

$$I_{op} = q \times g_{op} \times (generation\ volume)$$

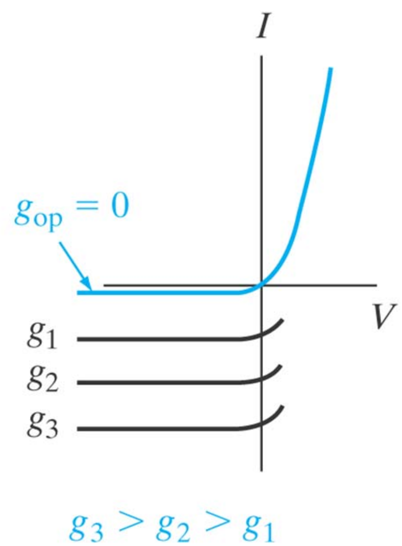
$$\boxed{I_{op} = qAg_{op}(L_p + L_n + W)}$$



Total current

- The total reverse current with illuminatior

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

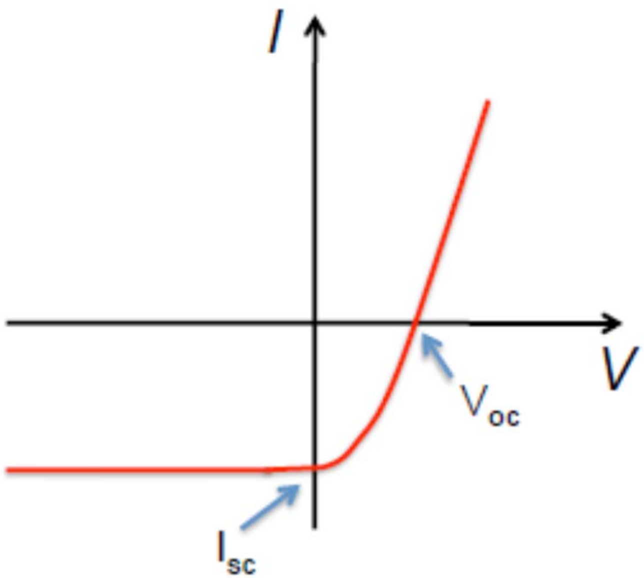


- Short-circuit current (V=0):

$$I_{sc} = -I_{op}$$

- Open circuit voltage (I=0):

$$V_{oc} = \frac{kT}{q} ln\left(\frac{I_{op}}{I_{th}} + 1\right)$$



More detail on open circuit voltage

$$V_{oc} = \frac{\boldsymbol{kT}}{\boldsymbol{q}} \boldsymbol{ln}\left(\frac{\boldsymbol{I_{op}}}{\boldsymbol{I_{th}}} + \mathbf{1}\right)$$

where $\boldsymbol{I_{th}} = \boldsymbol{I_0} = qA\left(\frac{D_p}{L_p}\boldsymbol{p_n} + \frac{D_n}{L_n}\boldsymbol{n_p}\right)$ $\quad I_{op} = qAg_{op}(L_p + L_n + W)$

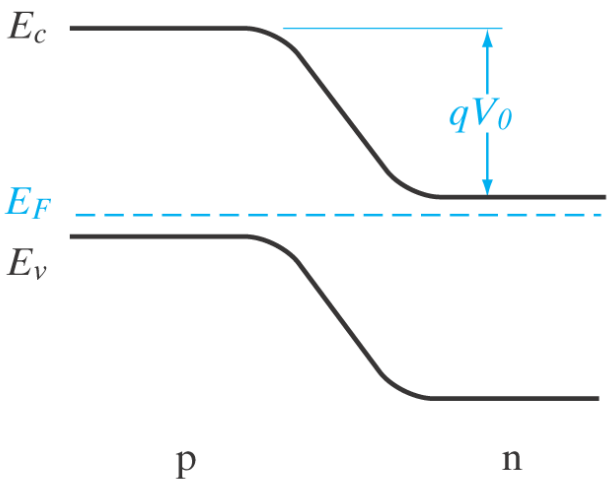
$$\Rightarrow \quad V_{oc} = \frac{\boldsymbol{kT}}{\boldsymbol{q}} \boldsymbol{ln}\left[\frac{L_p + L_n + W}{(L_p/\tau_p)\boldsymbol{p_n} + (L_n/\tau_n)\,\boldsymbol{n_p})} g_{op} + \mathbf{1}\right]$$

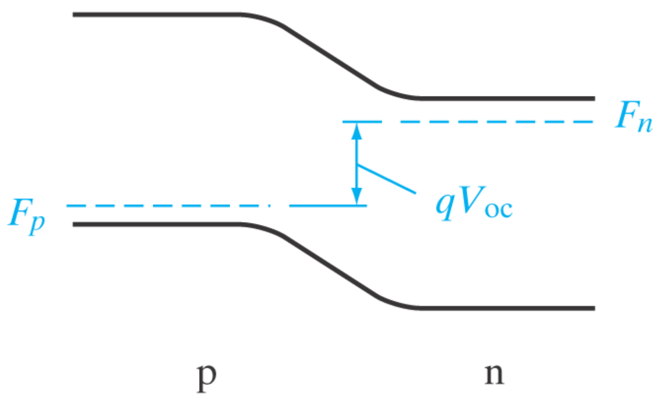
- For symmetric junction $p_n = n_p$, $\tau_p = \tau_n$. Define $g_{th} = p_n/\tau_n$, neglecting generation within W:

$$V_{oc} = \frac{\boldsymbol{kT}}{\boldsymbol{q}} \boldsymbol{ln}\frac{g_{op}}{g_{th}} \quad \text{for } g_{op} \gg g_{th}$$

Photovoltaic effect and open circuit voltage

- Photovoltaic effect: appearance of a forward voltage across an illuminated junction.
- Open circuit voltage V_{oc} must less than built-in potential V_0, since the contact potential is the maximum forward bias that can appear across a junction





Operation of an illuminated junction

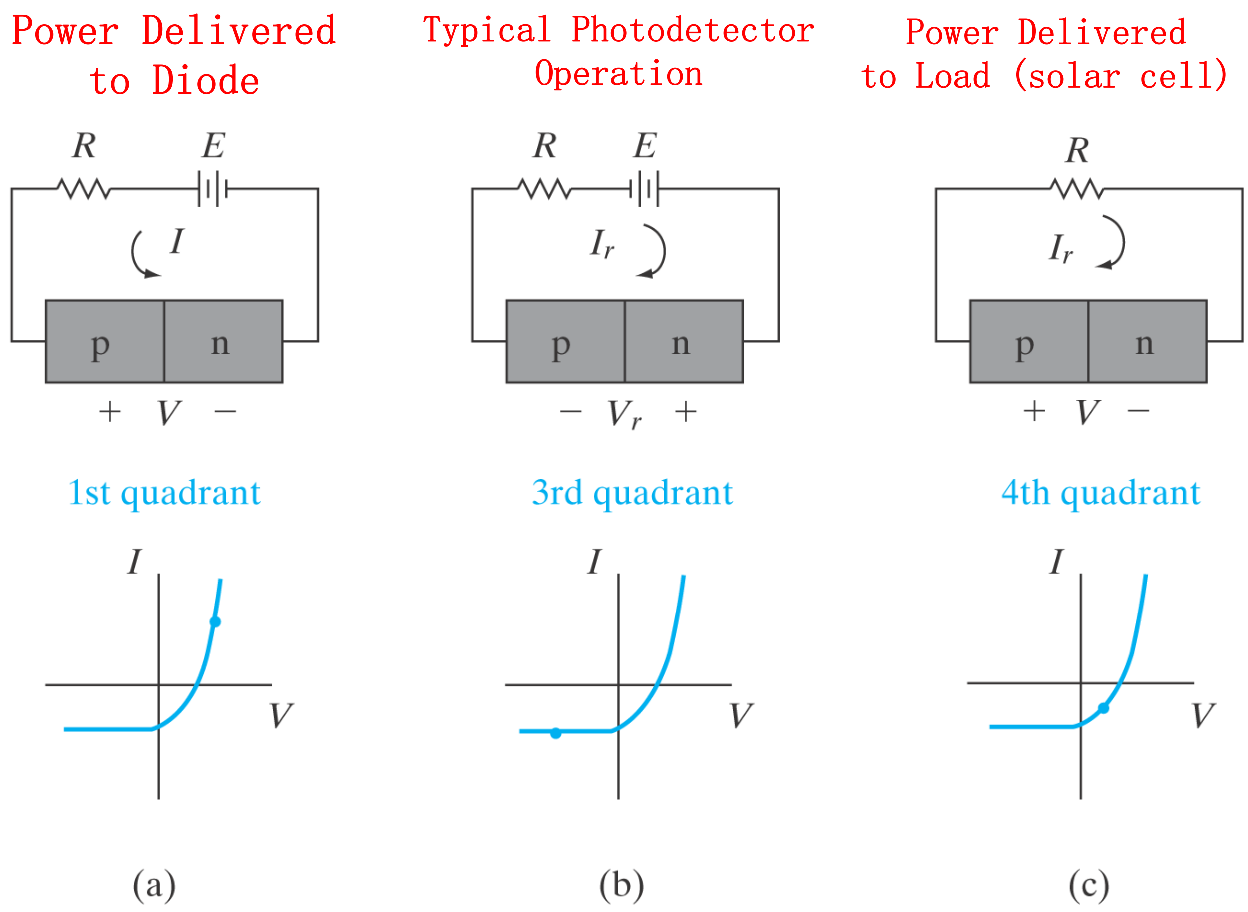


Figure 8.3

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.

Outline

- Current and voltage in an illuminated junction
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  - ⇨ Solar Cell
  - Photodetector
  - Light-Emitting Diodes
  - Semiconductor Lasers

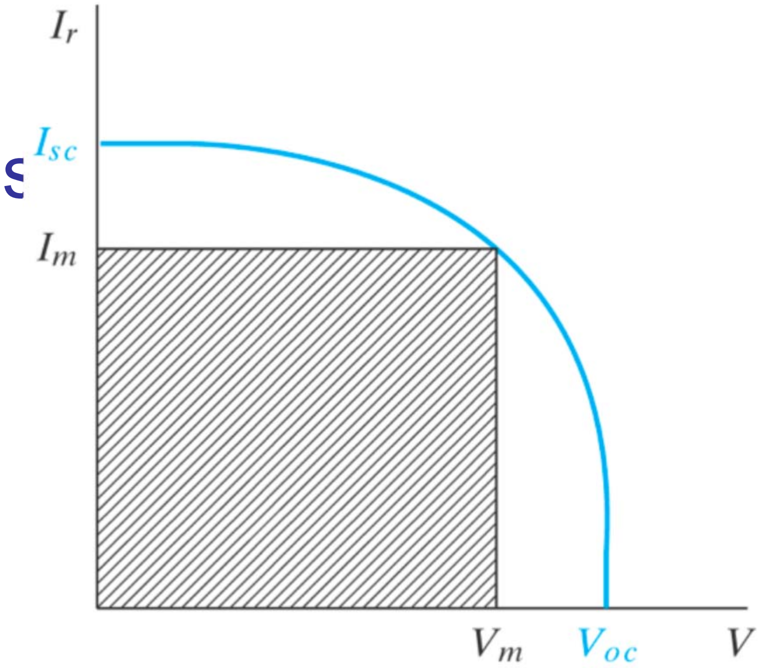
Solar Cell

- Convert solar energy to electric energy
- Operate in 4th quadrant

Solar cell figure-of-merit

- Maximum power delivered to a the solar cell occurs when VI_r is maximum:

$$P_m = I_m V_m$$



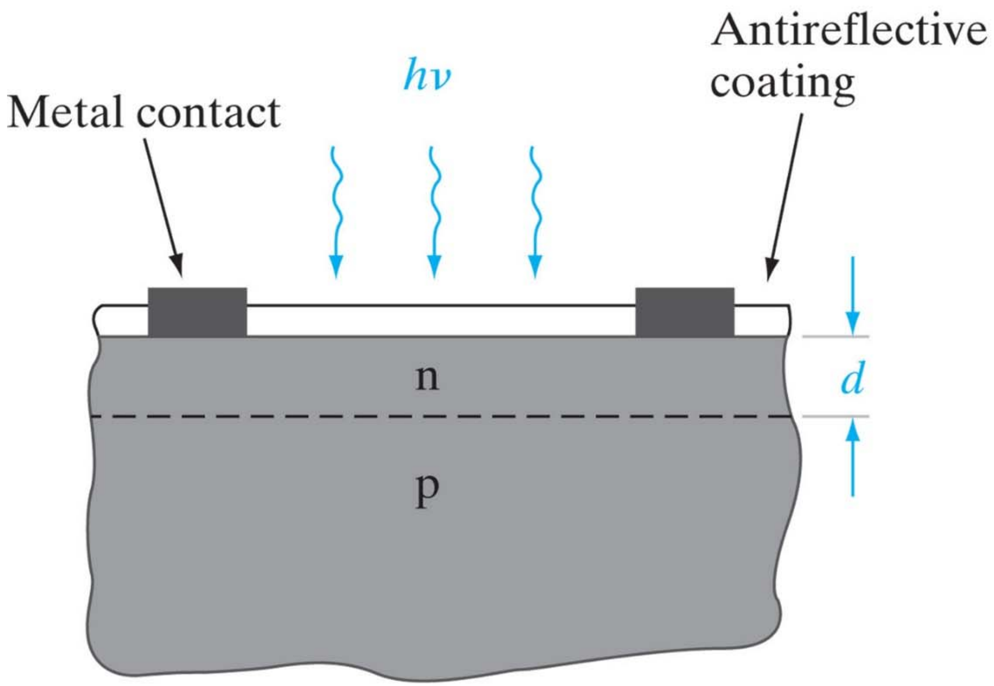
- Fill factor:

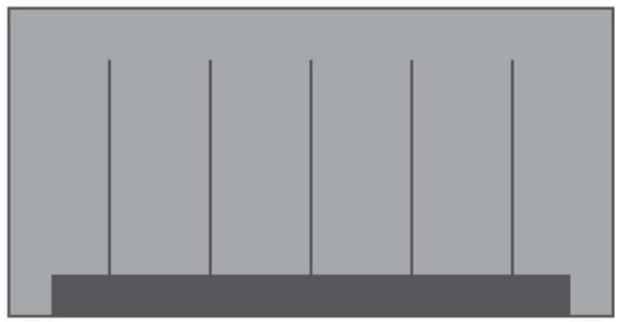
$$FF = \frac{I_m V_m}{I_{sc} V_{oc}}$$

- Efficiency: ratio of generated electrical energy to the incident solar energy on the solar cell

$$\eta = \frac{P_m}{P_{in}} = \frac{I_{sc} V_{oc} FF}{P_{in}}$$

Solar structure and design





- Heavy doping increase Voc but decrease carrier lifetime
- Series resistance must be small
- Anti-reflection coating to maximize light into semiconductor and minimize surface recombination
- Thin fingers distributed over surface to minimize shadowing while keeping series resistance small
- **Top layer need to be thin, so that junction is near the surface. (why?)**

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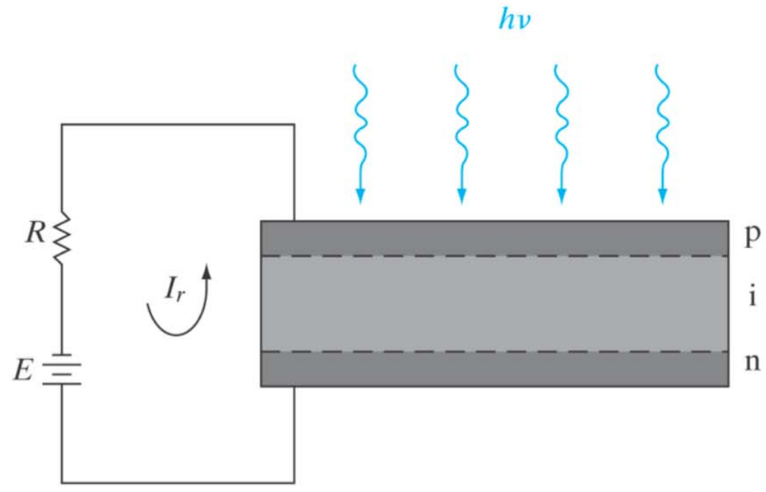
Photodetector

- Convert light to electric signal.
- Operate in reverse bias, 3rd quadrant.
- The current is Independent of voltage and proportional to the optical generation rate
- Carrier diffusion is slow, but drift is fast, absorption in the depletion region is preferred "depletion layer photodiode"
- There is also a design trade-off between sensitivity and speed –if the depletion width is very wide, sensitivity is better, but the bandwidth is reduced.



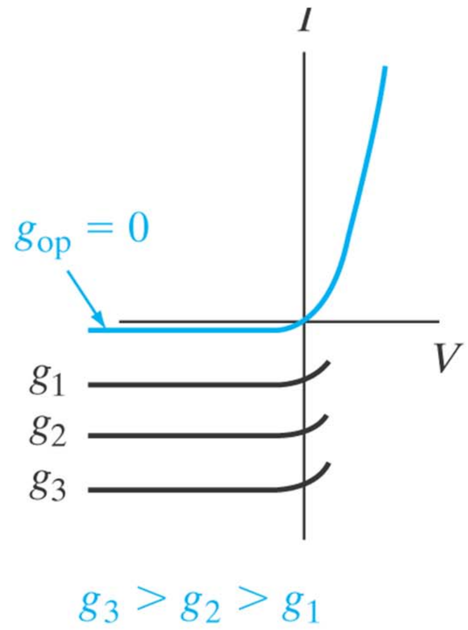


Figure of merit for photodetector

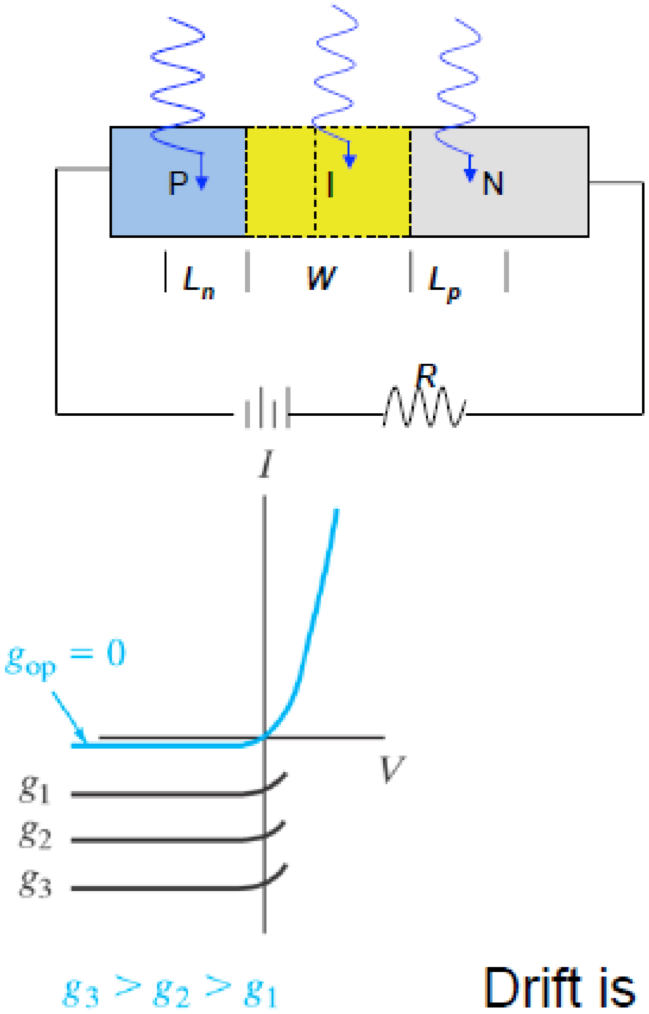
- External quantum efficiency: the ratio of number of carriers collected to number of photon impinging on the detector:

$$\boldsymbol{\eta = \frac{J_{op}/q}{P_{op}/h\nu}}$$

- Maximum response frequency

$$\boldsymbol{f_{max} \approx \frac{1}{transit\ time} \approx \frac{1}{W/V_{sat}} = \frac{V_{sat}}{W}}$$

p-i-n diode



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

$$I_{op} = qAg_{op}\left(L_p + L_n + W\right)$$

To improve PIN bandwidth,

we need to reduce the photogeneration in

the diffuson layers L_n and L_p and optimize W.

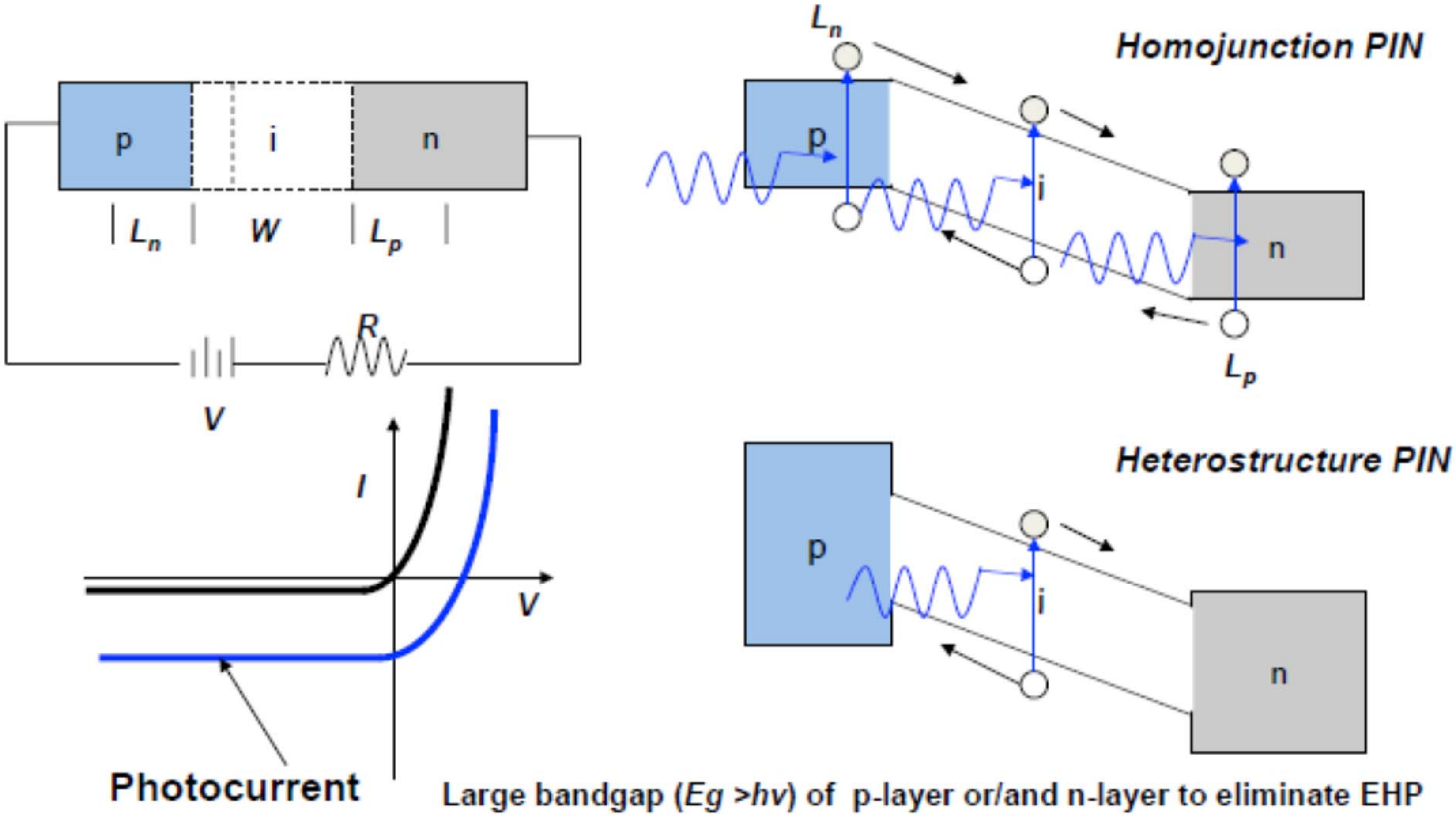
$$I_{op} = qAg_{op}(W) = qA\frac{\delta n}{\tau}W = q\eta\left(\frac{P_{abs}}{hv}\right)$$

$$\eta = \frac{I_{op}/q}{P_{abs}/hv} = \frac{I_{op}/q}{P_{inc}(1-e^{-\alpha\ell})/hv}$$

$$I_p = qA\delta nv_d = q\eta\left(\frac{P_{abs}}{hv}\right)\left(\frac{\tau v_d}{W}\right) = I_{op}\left(\frac{\tau}{t_r}\right)$$

Drift is fast, diffusion is slow

Homojunction and Heterostructure PINs



Large bandgap ($Eg > hv$) of p-layer or/and n-layer to eliminate EHP generation in any region except the "I" region

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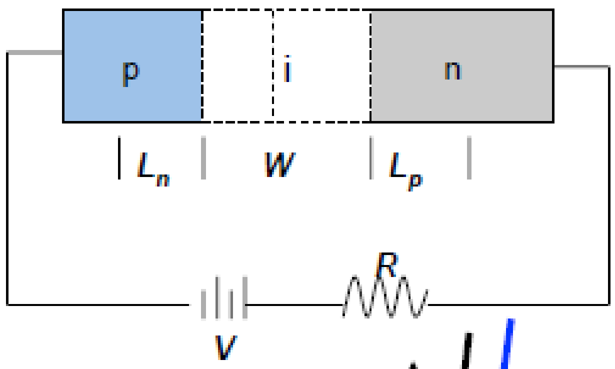
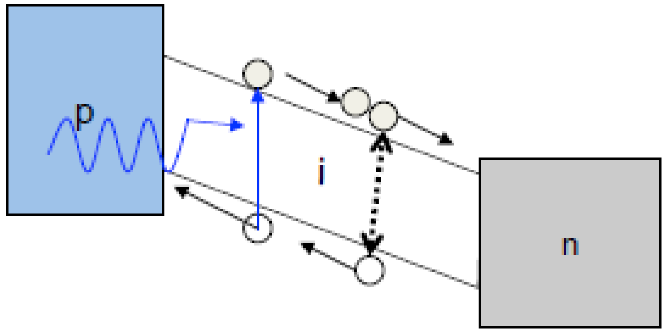
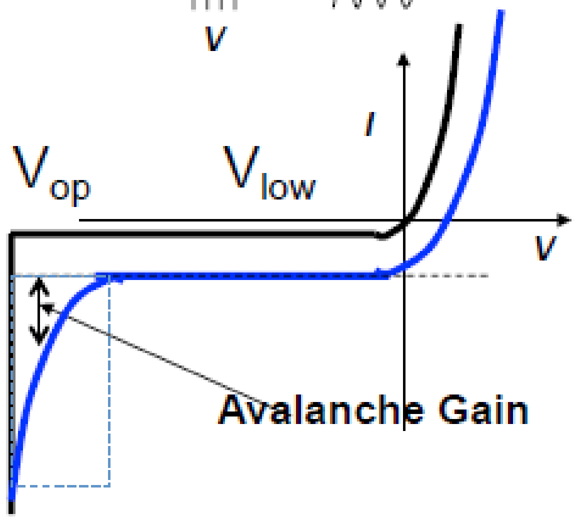
Avalanche Photodiodes

An electron or a hole with high energy in "I" layer can break chemical or ionic bonds in crystal to create an EHP





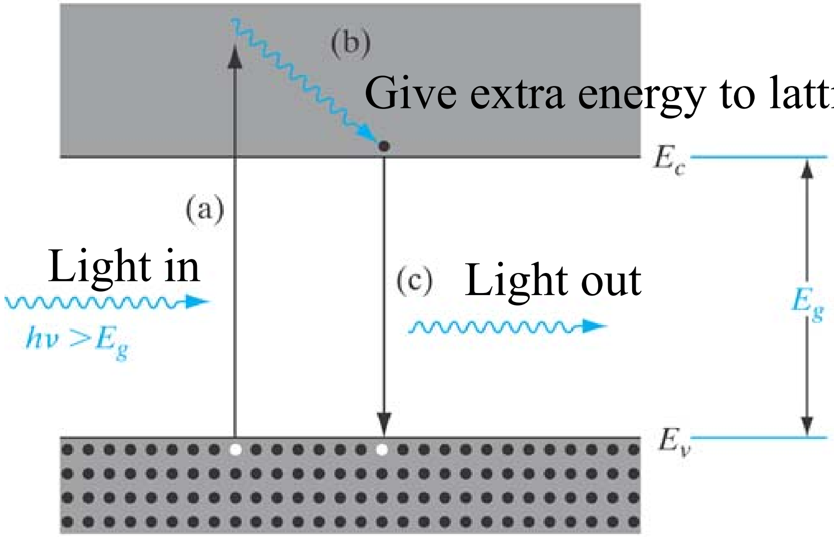


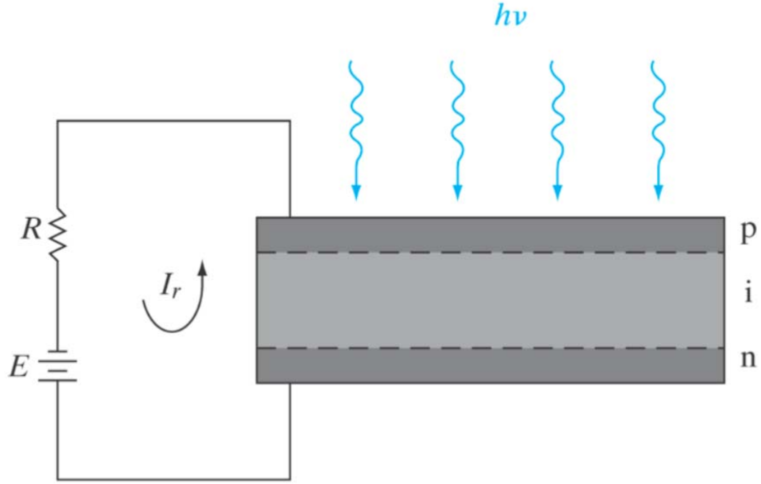
- An avalanche photodiode (APD) is operated under a reverse-bias voltage that is sufficient to enable avalanche multiplication
- An electron or a hole with high energy in the "i" layer can break chemical or ionic bonds in crystal to create an EHP
- The multiplication results in internal current gain

$$Gain \equiv \frac{(I_p - I_d)_{V_{op}}}{(I_p - I_d)_{V_{low}}}$$

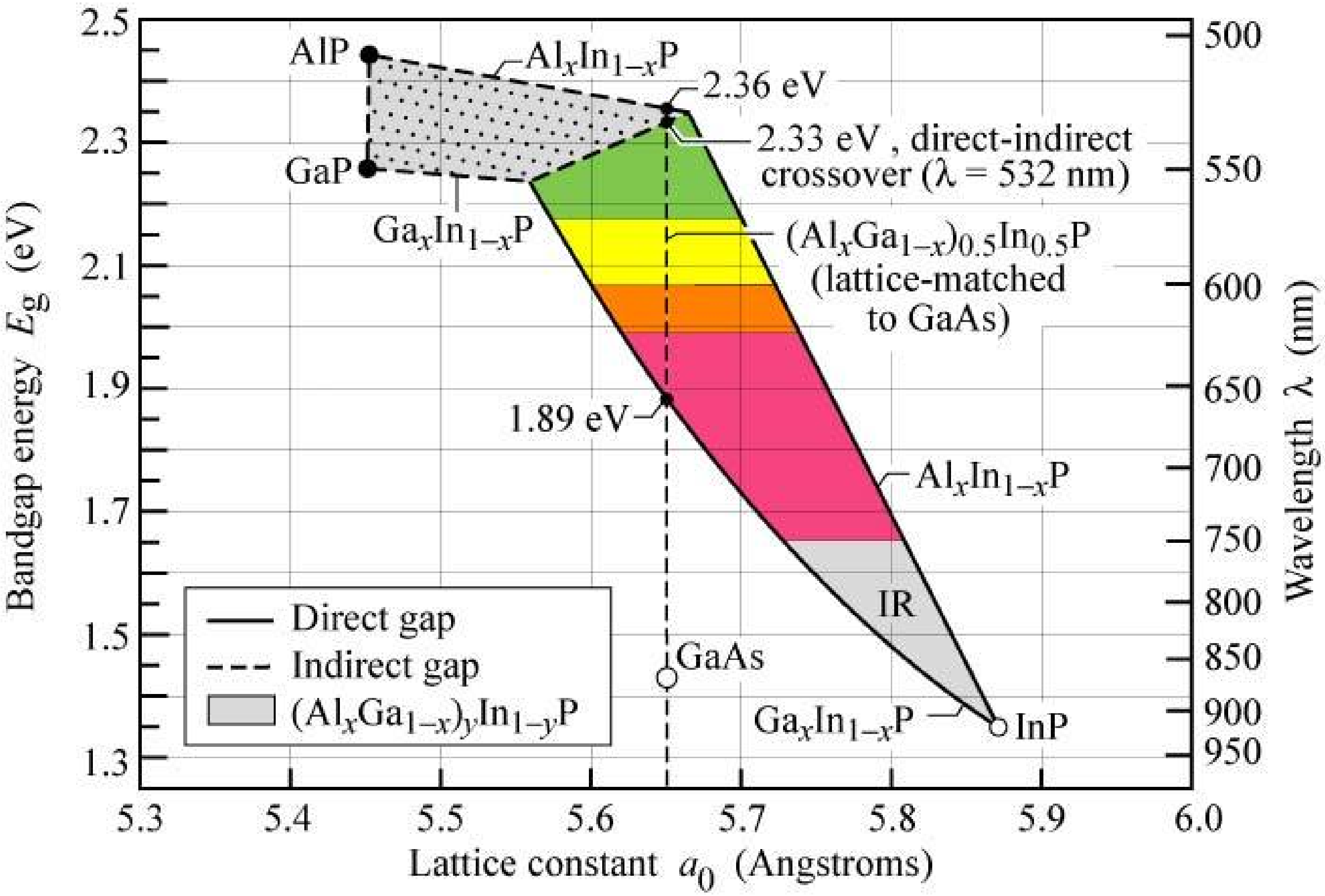
Bandgap match with incident light wavelength

- If $h\nu < E_g$ **no light absorption**
- If $h\nu \gg E_g$, light will be absorbed very near the surface. In addition, extra kinetic energy is wasted on heat, so it is most efficient, when $h\nu$ is slightly larger than E_g





Bandgap vs lattice constant



AlP
E_g = 2.45 eV
a_0 = 5.4510 Å

GaP
E_g = 2.26 eV
a_0 = 5.4512 Å

InP
E_g = 1.35 eV
a_0 = 5.8686 Å

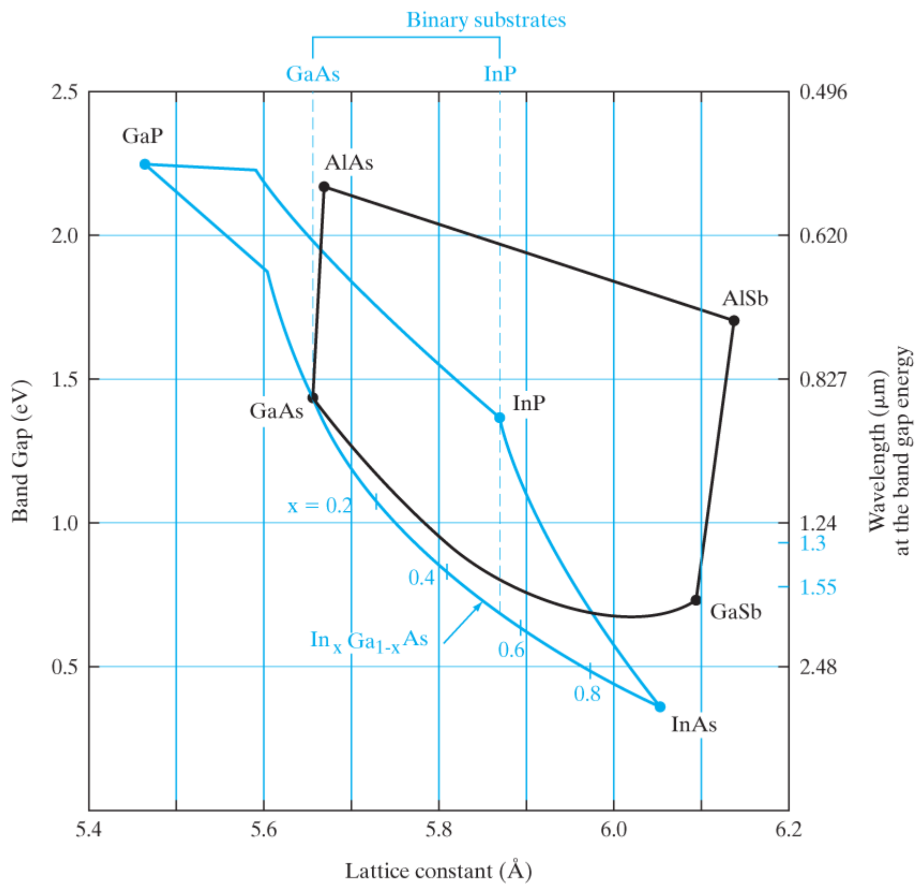
GaAs
E_g = 1.424 eV
a_0 = 5.6533 Å

Adjust bandgap by alloy composition

- Note, we can vary alloy composition (e.g. $In_xGa_{1-x}As$) and get different bandgap and lattice constants

- Getting same lattice constant as the substrate (GaAs or InP) is important to minimize lattice defects in a device.

- Generally, assume lattice constant (a) and band gap (E_G) vary linearly with alloy fraction (x)



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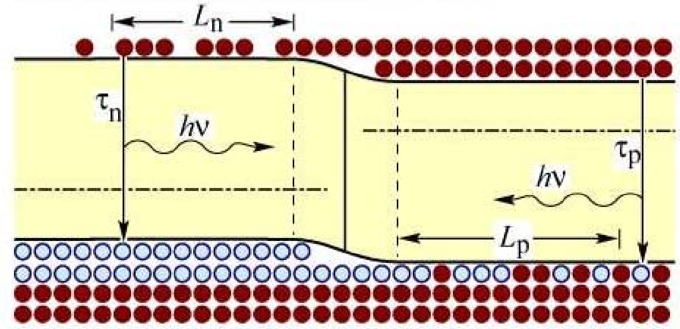
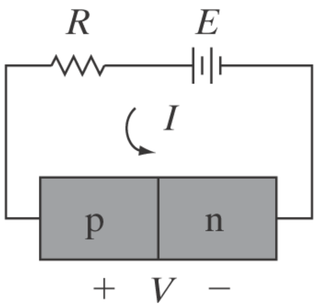
Light-emitting diode

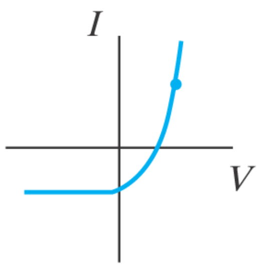
- Forward bias pn junction
- Minority & majority carriers recombine and emit light
- Operate in 1st quadrant
- Emitted light energy

$$h\nu_{out} = E_g$$





1st quadrant

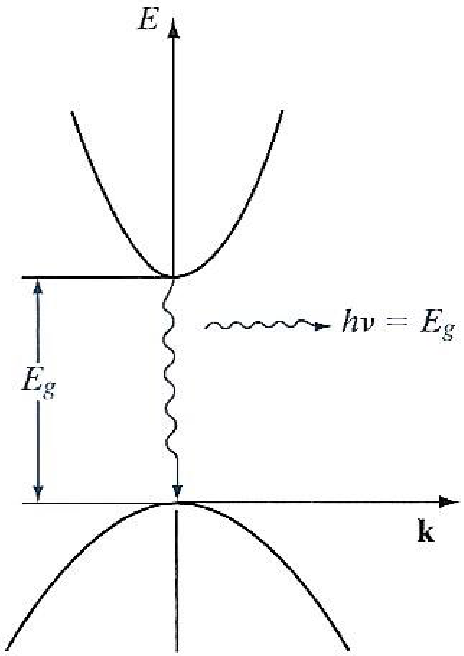


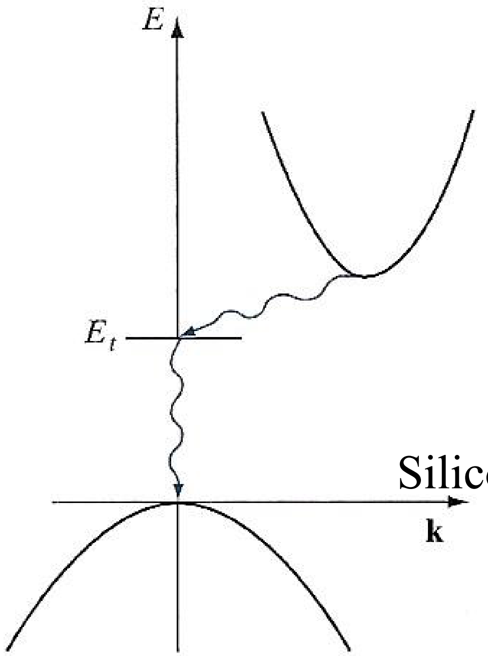
Direct and indirect band gap

Direct band gap

Indirect band gap

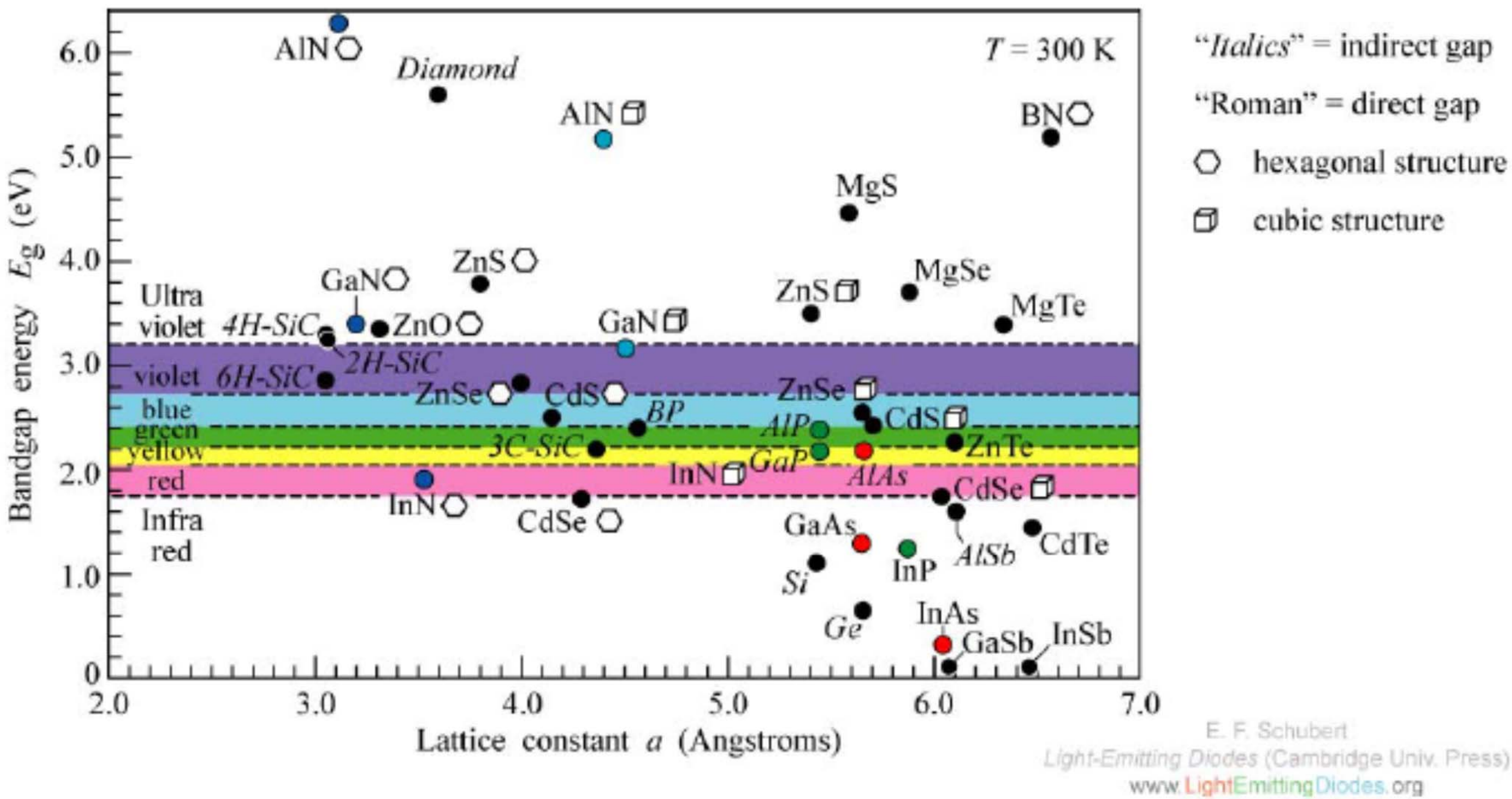
GaAs





Silicon

- Direct band gap: minimum in the conduction band and maximum of valence band occurs at the **same** k value. Indirect band gap: minimum in the conduction band and maximum of valence band occurs at the **different** k value
- For light emission, the material need to be direct band gap.


T = 300 K
"Italics" = indirect gap
"Roman" = direct gap
hexagonal structure
cubic structure
Bandgap energy E_g (eV)
Lattice constant a (Angstroms)
Ultra violet
violet
blue
green
yellow
red
Infra red
AlN
Diamond
BN
MgS
ZnS
GaN
ZnO
4H-SiC
2H-SiC
6H-SiC
MgSe
MgTe
ZnSe
CdS
BP
AlP
GaP
AlAs
3C-SiC
ZnTe
InN
CdSe
GaAs
AlSb
CdTe
Si
InP
Ge
InAs
GaSb
InSb
E. F. Schubert
Light-Emitting Diodes (Cambridge Univ. Press)
www.LightEmittingDiodes.org

Fiber communication

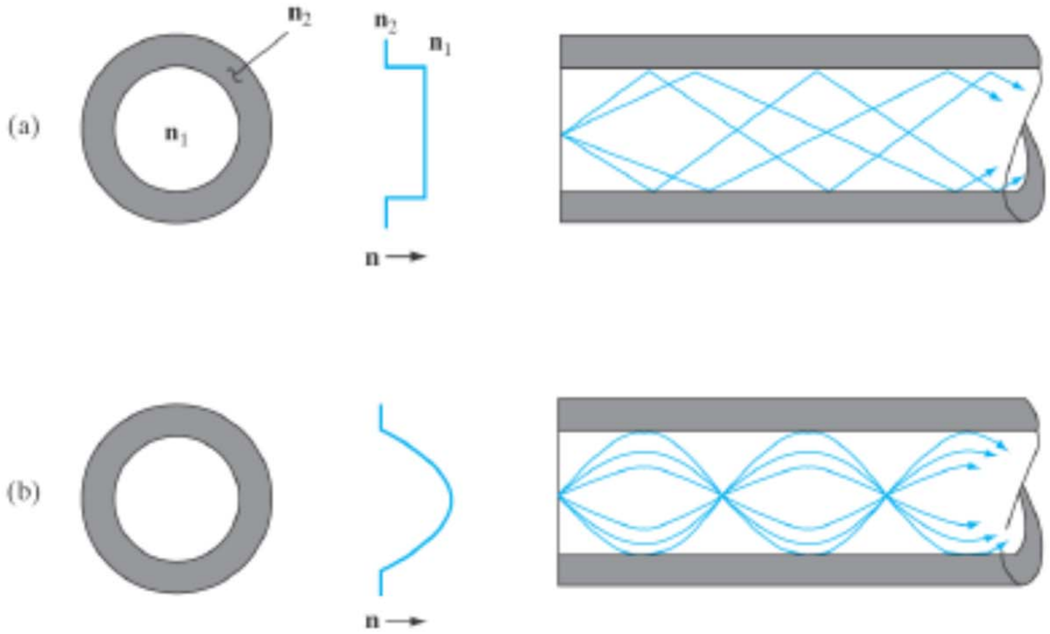


Figure 8.12

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).

Fiber communication wavelength

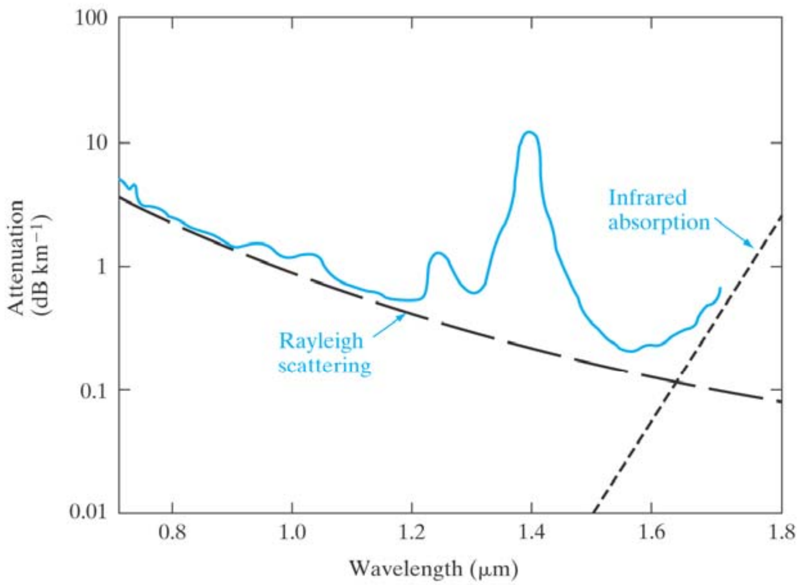
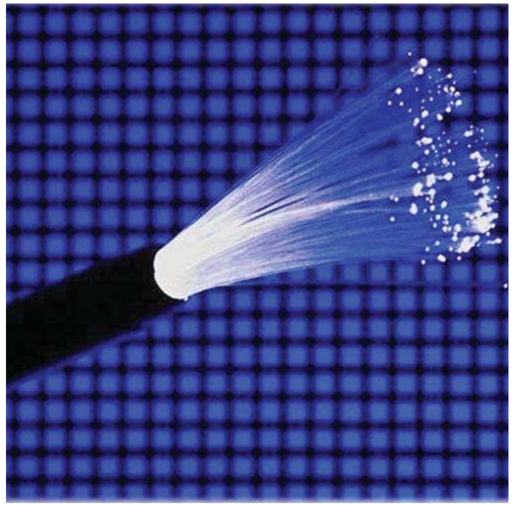


Figure 8.13

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



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

- Optical fiber communications → why use wavelengths of 1.3 or 1.55 μm? Minimum attenuation

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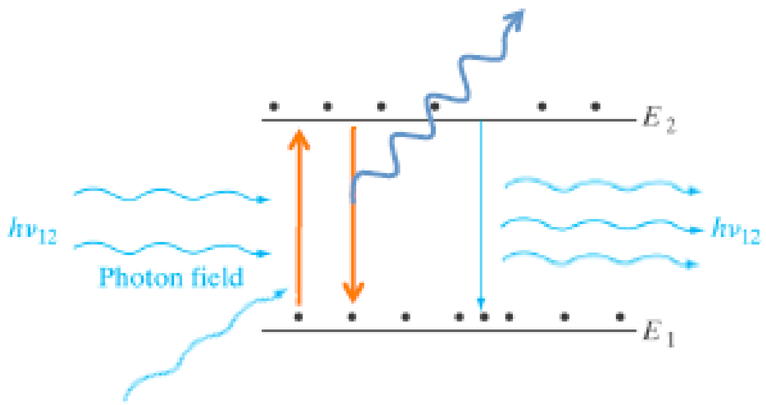
Laser

LASER: Light Amplification through Stimulated Emission of Radiation

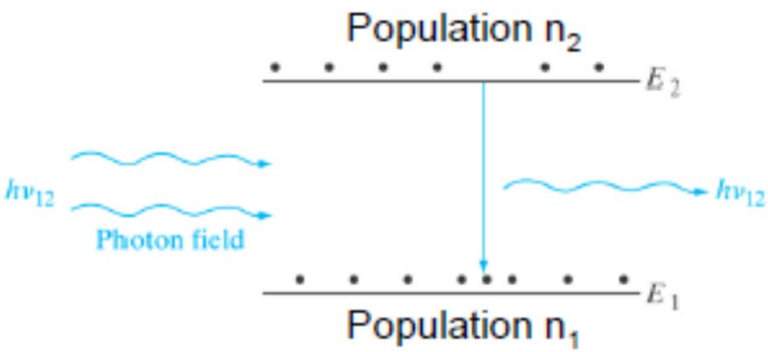
3 EHP-Photon Processes:

- ***Spontaneous Emission:*** Random transition from E_2 to E_1
- ***Absorption:*** Transition from E_1 to E_2 caused by interaction with and annihilation of a photon
- ***Stimulated Emission:*** Transition caused by presence of photon field
  - Stimulated photons have the same energy and phase as the stimulating photon field (monochromatic, coherent)



Two stage system

ng



ulation) n_2

lation) n_1

een the levels

From Boltzmann Statistics,

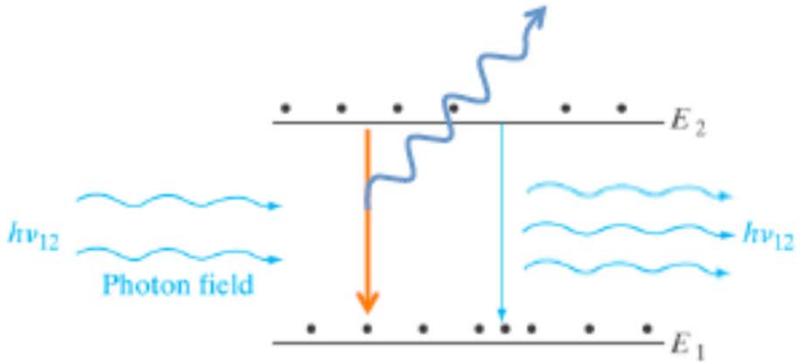
at **Thermal Equilibrium :**

$$\frac{n_2}{n_1} = e^{-(E_2-E_1)/kT} = e^{-h\nu_{12}/kT}$$

so in ***thermal equilibrium*** $n_2 \ll n_1$

Spontaneous Emission

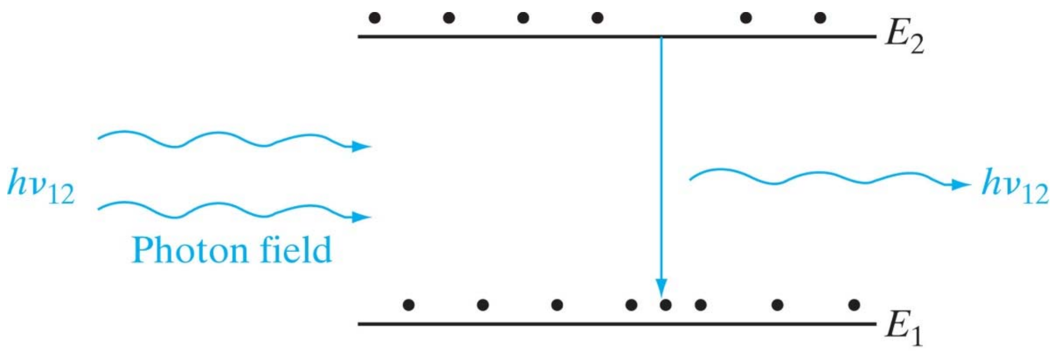
The rate of spontaneous emission is proportional only to the number of electrons in the upper state:



$$R_{spon} = -\left.\frac{dn_2}{dt}\right|_{spon} = A_{21} n_2$$

Spontaneous decay time constant: $\tau_{spon} = \left(A_{21}\right)^{-1}$

Stimulated emission



The rate of stimulated emission is proportional to the number of electrons in upper level and the energy density.

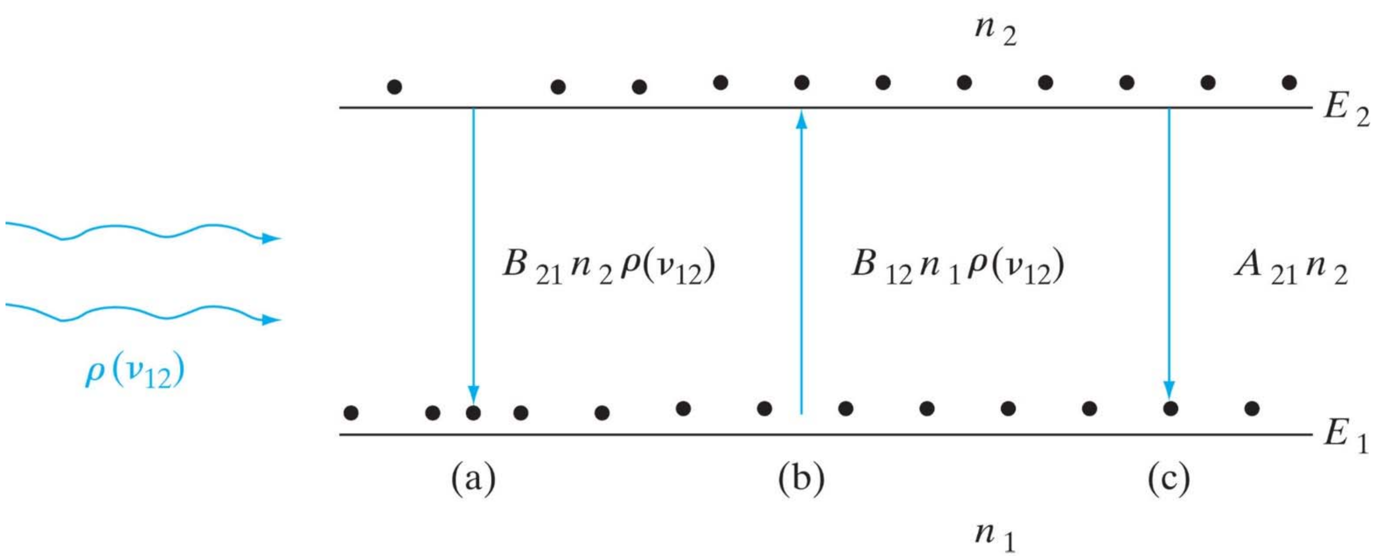
$$R_{stim} = \frac{dn_1}{dt} = -\frac{dn_2}{dt} = B_{21} n_2 \rho(\nu_{12})$$

Rate of stimulated emission

Electron population in the upper level

Energy density of the stimulating field

Steady state condition



In steady state, the emission rates must balance the absorption rate:

$$\left.\frac{dn_2}{dt}\right|_{abs} + \left.\frac{dn_2}{dt}\right|_{spon} + \left.\frac{dn_2}{dt}\right|_{stim} = 0 \qquad \text{or}$$

$$B_{12}n_1\rho(\nu_{12}) = A_{12}n_2 + B_{21}n_2\rho(\nu_{12})$$

Absorption | spontaneous emission | stimulated emission

Condition for lasing

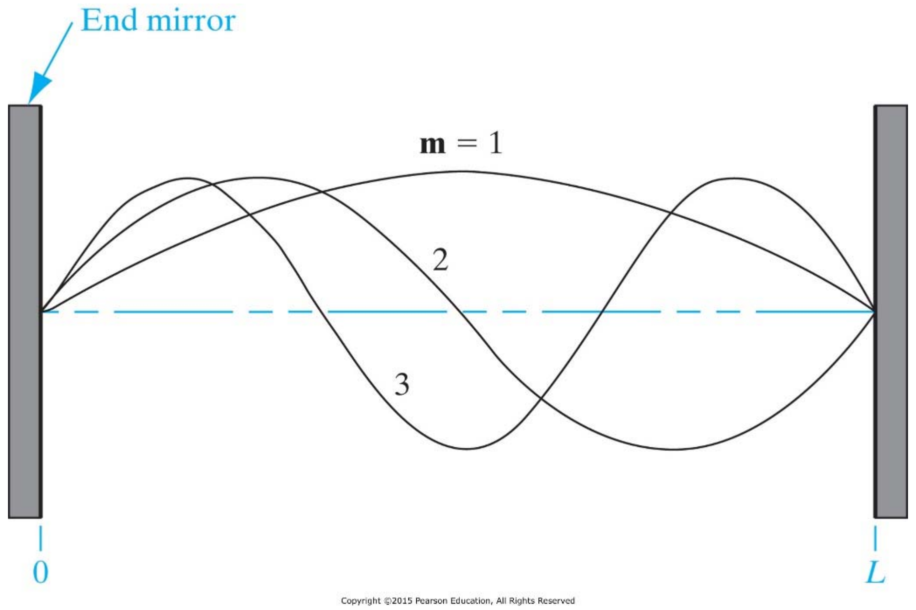
1. $$\frac{Stimulated\ emission\ rate}{Spontanous\ emission\ rate}=\frac{B_{21}n_2\rho(\nu_{12})}{A_{12}n_2}$$

A large photon field energy density enhances the stimulated emission rate →use optical resonant cavity

2. $$\frac{Stimulated\ emission\ rate}{absorption\ rate}=\frac{B_{21}n_2\rho(\nu_{12})}{B_{12}n_1\rho(\nu_{12})}=\frac{B_{21}n_2}{B_{12}n_1}$$

For stimulated emission to exceed absorption, n2>n1, --> need population inversion (negative temperature)

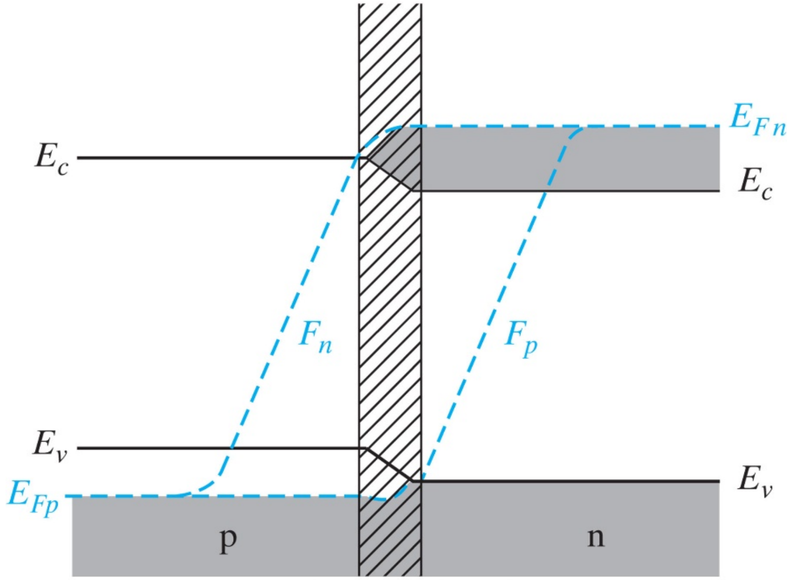
Resonance cavity



The length of the cavity for stimulated emission must be: $L = \frac{m\lambda}{2} = \frac{m\lambda_0}{2n}$

λ: Photon wavelength within the laser material
λ_0: output light wavelength in the atmosphere
n: index of refraction of the laser material

Population inversion in semiconductor laser



If p-n junction is formed between degenerate materials, when the forward bias is large enough, a condition of population inversion results.

$$n = N_c e^{-(E_c - F_n)/kT} = n_i e^{-(F_n - E_i)/kT}$$

$$p = N_v e^{-(F_p - E_v)/kT} = n_i e^{-(E_i - F_p)/kT}$$

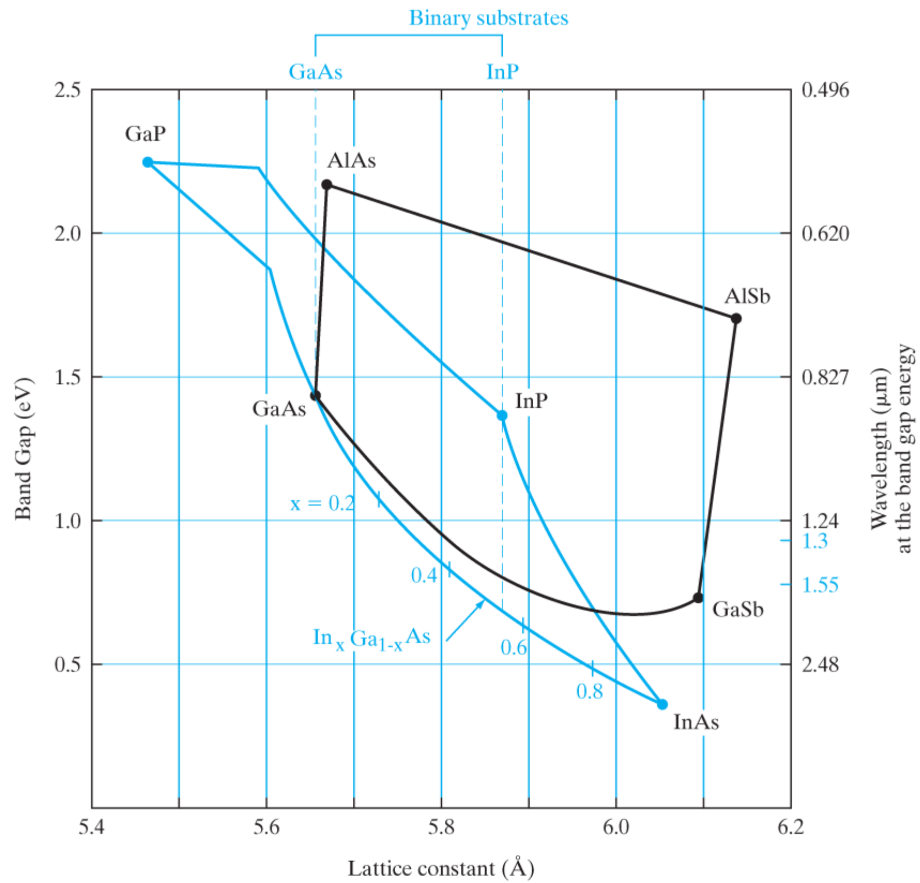
Lasing condition (population inversion):

$$F_n - F_p > h\nu$$

For band-edge transitions:

$$F_n - F_p > E_g$$

Ex: **Photodiode Design.** Consider a p-i-n photodiode (see Fig. 8-7), with "i" region made of $In_xGa_{1-x}As$ (see Fig. 1-13). Design stoichiometry "x" and thickness of the "i" region (W_i) to enable response at 1.3 μm wavelength, up to 20 GHz signals. Assume fields are sufficiently high to reach $v_{sat} \approx 10^7$ cm/s in the "i" region. Name at least one design constraint on the "p" and "n" regions of this photodiode. You may assume the lattice constant and band gap of $In_xGa_{1-x}As$ vary linearly with composition "x".



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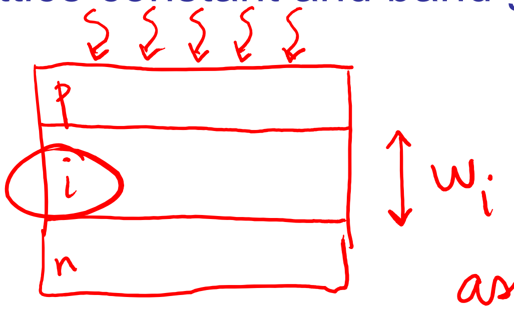

$\lambda = 1.3\ \mu m \longrightarrow E_G = \dfrac{1.24\ eV}{1.3\ \mu m} = 0.95\ eV$

actually need $E_G \leq 0.95\ eV$

assume linear variation with "x"

$$\underbrace{x(0.36)}_{InAs} + \underbrace{(1-x)(1.43)}_{GaAs} = 0.95\ eV \Longrightarrow \boxed{x \approx 0.45}$$

$$f = \frac{1}{\tau} \approx \frac{v_{sat}}{W_i} = 2 \times 10^{10}\ Hz$$

$$W_i = \frac{10^7\ cm/s}{2 \times 10^{10}\ 1/s} \leq 5 \times 10^{-4}\ cm$$

$$\boxed{\leq 5\ \mu m}$$