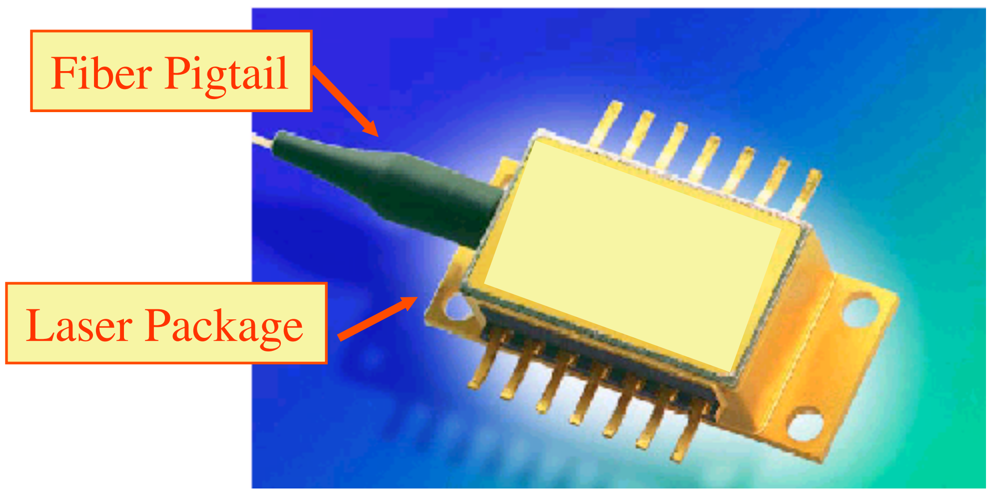
Lecture 10 -Transmitters

Semiconductor Optical Sources

- The optical sources practically used in optical communications are based on semiconductor devices
- The generated optical signal is to be efficiently coupled to the output optical fiber
  - Other kinds of sources (non-semiconductor) and/or free space coupling is sometimes done in R&D labs, but only for advanced and prototypal research
  - All commercial sources comes in very compact packages, and are fiber pigtailed in the factory
  - Pigtailing and packaging is one of the most critical and expensive issues for these devices



Semiconductor Optical Sources

⇨ Compact integrated devices used to convert a modulated electrical signal to a modulated optical signal that is then efficiently coupled to the optical fiber.

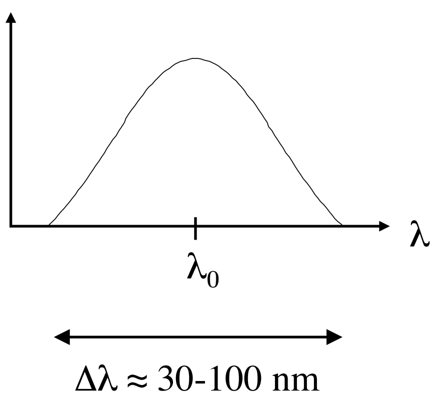
Characteristic	Description
Number of longitudnal modes	Number of optical frequencies laser emits. Plays a key role in both laser cost and how fiber dispersion will limit link bit rate.
Side Mode Suppression Ratio (SMSR)	A measure of how good a single mode laser is.
Threshold current	The minimum current required to turn on the laser. Low values are key to decrease transmitter power dissipation
Laser Noise	A measure of how random the optical laser output is. This characteristic can determine the ultimate performance of a link.
Linewidth	A measure of how noisy the laser. Plays a key role in how dispersion and crosstalk limits the transmission bit rate and capacity.
Wavelength	Determines the dispersion and loss operating points in the fiber and other network components.
Modulation Bandwidth	Determines the bit rate that can be attained by current modulation.
Chirp	A measure of how the optical output frequency changes with current modulation. Impacts transmission bit rate.
Linearity	Ability to reproduce and analog signal with low distortion.
Fiber Output Power	Power launched into fiber to achieve high signal-to-noise ratio.
Wavelength Tunability	The ability to tune the output wavelength over a wide range.
Long Term Stability	In terms of wavelength, output power and other key factors.

Laser Diode Issues

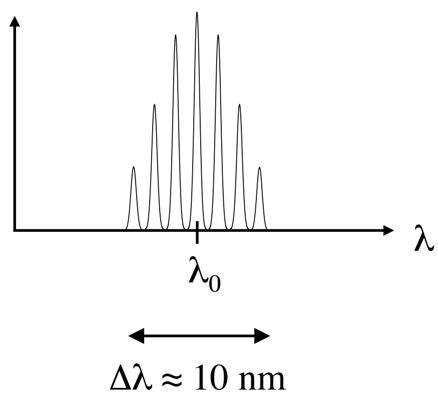
- Direct modulation vs. External modulation
  - Lower cost vs. less chirp and less pattern effect
- InGaAsP active region vs. InGaAlAs
  - No aluminum issues vs. higher temp operation
- Bulk vs quantum well active region
  - Less complexity vs. lower threshold
- Single transverse mode (vertical direction)
  - Essential for single mode fiber. Not an issue.
- Single lateral mode (horizontal direction)
  - Essential for single mode fiber. Narrow waveguide required.
- Single longitudinal mode
  - Important for long distance communication (smaller spectral width)
- Current confinement?
  - Needed for low threshold, but don't increase thermal resistance
- Optical confinement?
  - Needed for single mode operation, but don't increase thermal res.
- Carrier confinement?
  - Needed for low threshold, but don't affect lifetime.

Semiconductor Optical Sources

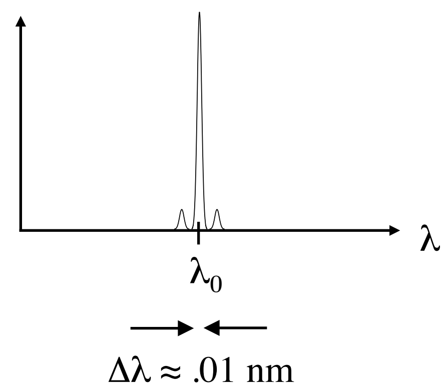
Light Emitting Diode (LED)



Multimode Laser Diode



Single Mode Laser Diode

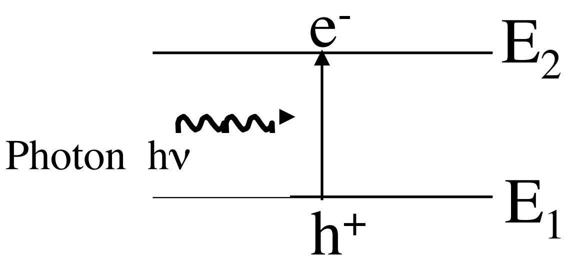


The linewidth, $\Delta\lambda$, is often measured at the full width half maximum point (FWHM)

Semiconductor Optical Source Basics

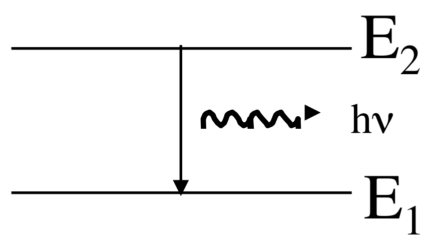
- Three basic optical semiconductor interactions
- E_2 is the bottom of the conduction band and E_1 is the top of the valance band

Absorption



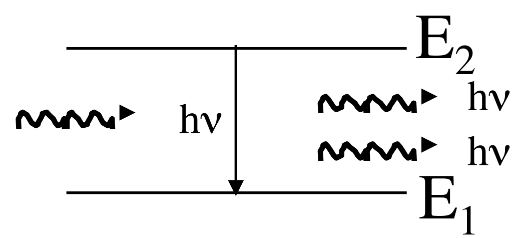
- Incident photon $E_{photon} = h\nu = E_2 - E_1$
- Electron - hole pair generated (EHP)

Spontaneous emission



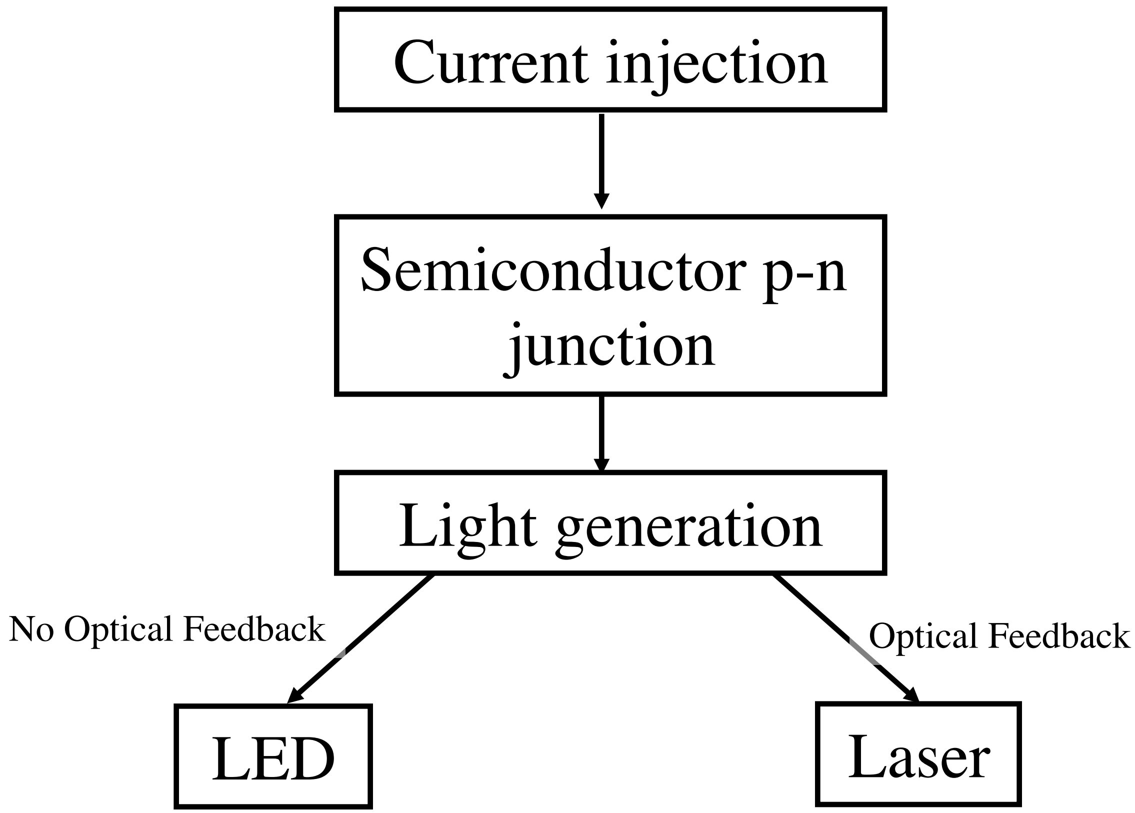
- Radiative recombination
- Photon spontaneously emitted with energy $E_{photon} = h\nu = E_2 - E_1$

Stimulated emission



- Incident photon causes radiative recombination
- Two photons with same characteristics created

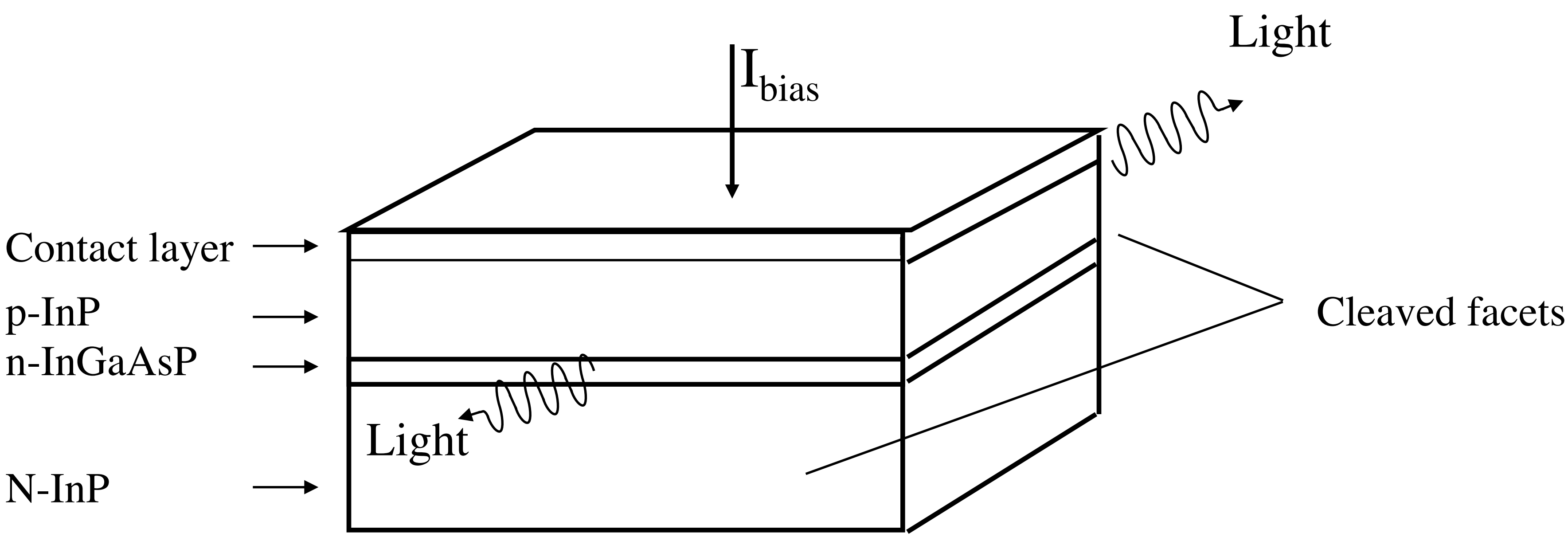
Semiconductor Optical Source Basics



Semiconductor Lasers

- Laser = Gain medium + optical cavity
- Lasing occurs with population inversion or when gain exceeds losses

Ex : Double Heterostructure laser



Rate Equations

$$\frac{dN}{dt} = G - R$$

N is the electron density (assumed equal to hole density)

G is the generation rate of electrons

R is the total recombination rate

Rate Equations

$$\frac{dN}{dt} = G - R$$

$$G = \frac{\eta_i I}{qV}$$

$$R = R_{sp} + R_{nr} + R_i + R_{st}$$

$$R = BN^2 + AN + CN^3 + R_{st}$$

$$R \approx \frac{N}{\tau}$$

N is the electron density (assumed equal to hole density)

G is the generation rate of electrons

R is the total recombination rate

Absorption and Amplification

- For a 2-level atomic system, we define the following transition rates assuming the induced rates from levels 1 to 2 and 2 to 1 are proportional to the photon densities (per unit frequency)

$$\left(W_{21}^{'}\right)_{induced} = B_{21}\rho(\nu)$$
$$\left(W_{12}^{'}\right)_{induced} = B_{12}\rho(\nu)$$

- The total downward rate (2 to 1) is the sum of the induced and spontaneous rates

$$W_{21}^{'} = B_{21}\rho(\nu) + A_{21}$$
$$W_{12}^{'} = \left(W_{12}^{'}\right)_{induced} = B_{21}\rho(\nu)$$

- We also assume that the atoms are blackbody radiators in thermal equilibrium at temperature T with spectral density

$$\rho(\nu) = \frac{8\pi n^3 h\nu^3}{c^3}\frac{1}{e^{h\nu/k_B T} - 1}$$

Einstein Relations

- In thermal equilibrium, the number of 2 to 1 and 1 to 2 transition rates are balanced

$$N_2 W'_{21} = N_1 W'_{12}$$

$$N_2\left(B_{21}\frac{8\pi n^3 h\nu^3}{c^3}\frac{1}{e^{h\nu/k_B T}-1}+A_{21}\right)=N_1\left(B_{12}\frac{8\pi n^3 h\nu^3}{c^3}\frac{1}{e^{h\nu/k_B T}-1}\right)$$

- The distribution of energy states for atoms in TE for a two level system will follow the Boltzman distribution

$$\frac{N_2}{N_1}=e^{-h\nu/k_B T}$$

- Equating N_2/N_1 above, we see that the following relations (Einstein relations) must be satisfied

$$B_{12}=B_{21}$$

$$\frac{A_{21}}{B_{21}}=\frac{8\pi n^3 h\nu^3}{c^3}$$

Energy Density

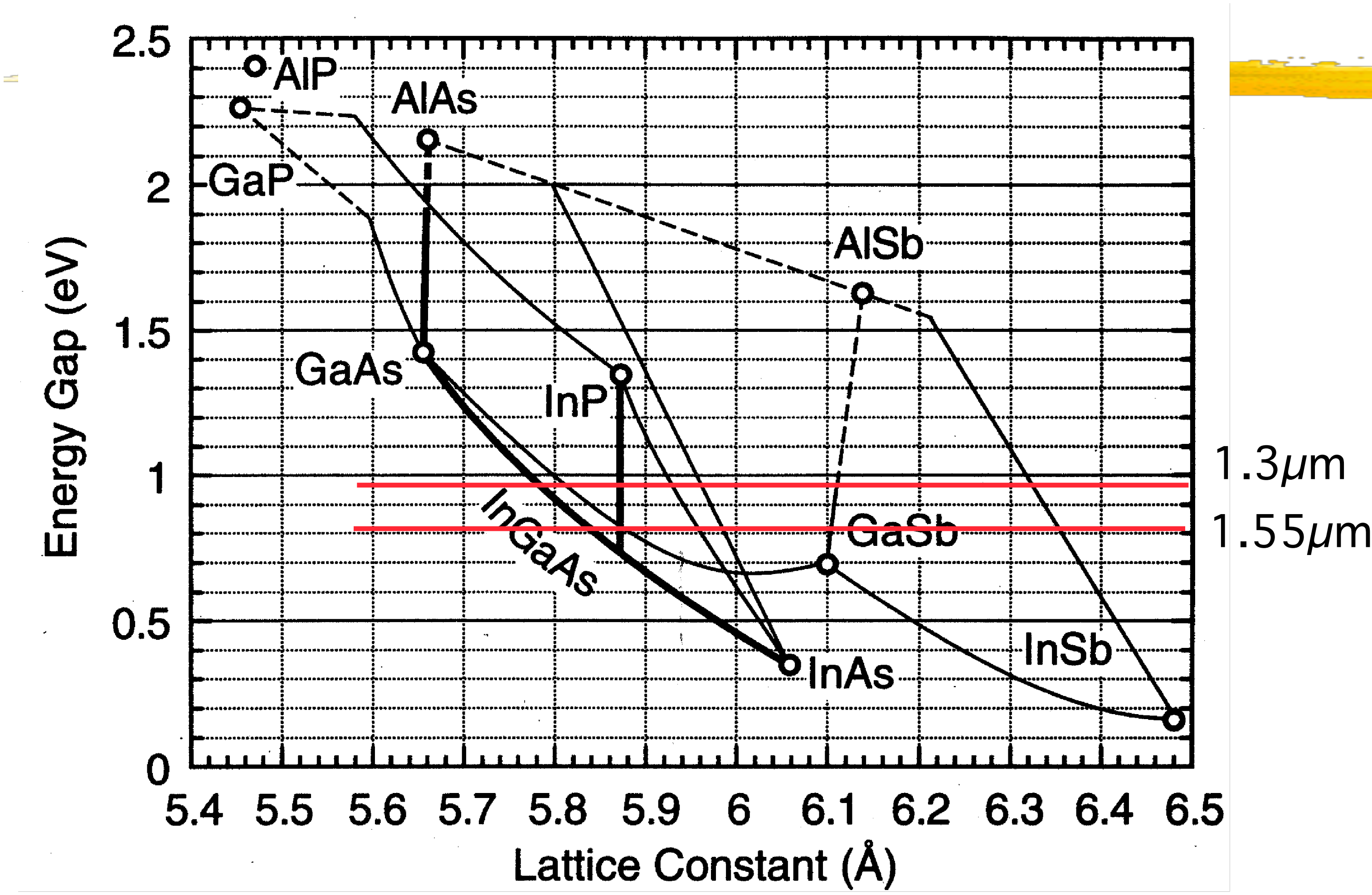
⇨ Defining the spontaneous lifetime by $t_{spont}=1/A_{21}$, we can write the transition rate per atom due to an incident optical field with a uniform spectrum and energy density $\rho(\nu)$, beam intensity $I_0=cU_0/n$ (watts per square meter), U_0 is the energy density of a monochromatic field

$$W_i' = \frac{A_{21}c^3}{8\pi n^3 h\nu^3}\rho(\nu)$$

$$= \frac{c^3 U_0}{8\pi n^3 h\nu^3 t_{spont}} g(\nu)$$

$$= \frac{\lambda^2 I_0}{8\pi n^2 h\nu t_{spont}} g(\nu)$$

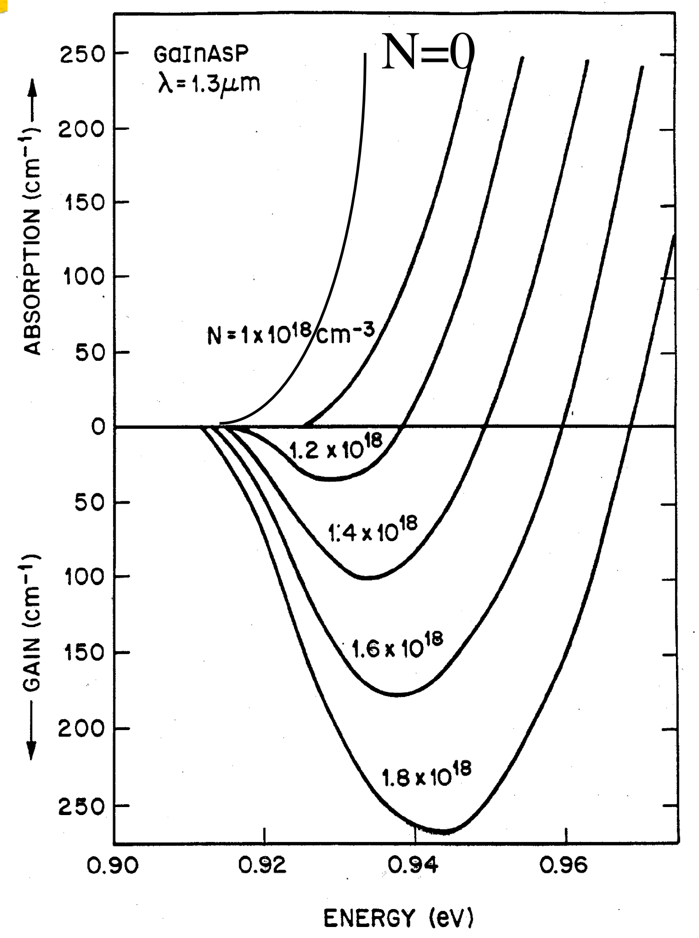
III-V Semiconductor Materials



Material Gain

Calculated gain curves for InGaAsP/ InP laser operating at 1.3μm

- Gain peak moves to shorter wavelengths with higher pumping
- Higher differential gain for wavelengths shorter than the gain peak



N.K.. Dutta, J. Appl. Phys., **51**, 6095 (1980)

Carrier Density

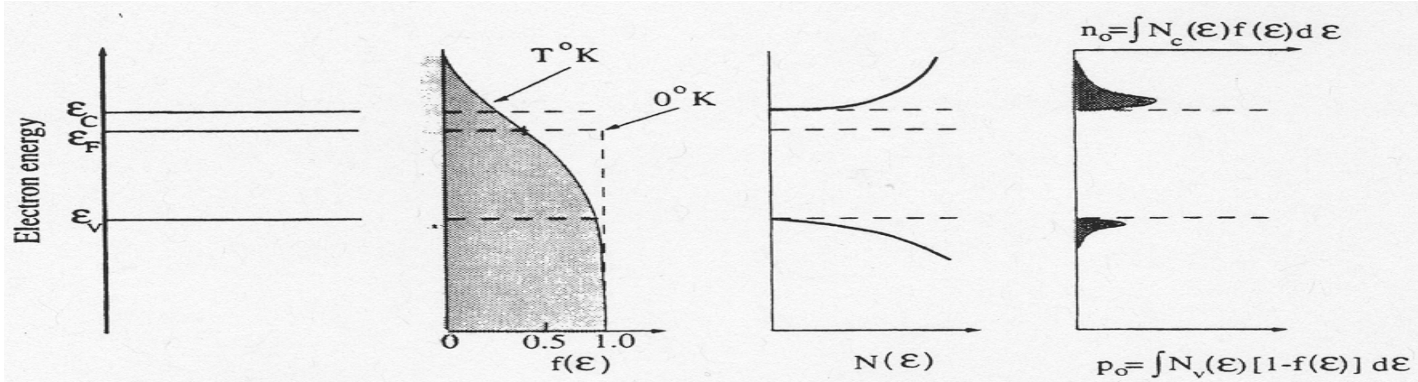


Figure 2.18 Distribution functions, density-of-states functions, and carrier distributions (in energy) in an n-type nondegenerate semiconductor.

Density of electrons with energies between E and E+dE

$$N_c = \frac{I\tau}{eV} = \int_0^\infty \rho_c(E) f_c(E) dE$$

$$= \frac{1}{2\pi^2}\left(\frac{2m_c}{\hbar^2}\right)^{3/2} \int_0^\infty \frac{E^{1/2}}{e^{(E-E_{Fc})/\kappa_B T}+1} dE$$

Quasi-Fermi Level

$$E_{Fc}(T=0) = \left(3\pi^2\right)^{2/3} \frac{\hbar^2}{2m_c} N_c^{2/3}$$

Energy Band Structures

- The wave function of an electron in any band is characterized by its wave function (ψ) and wave vector (k)

$$\Psi(\bar{r}) = u_k(\bar{r})e^{i\bar{k}\cdot\bar{r}}$$

$$\lambda_e = \frac{2\pi}{\left|\bar{k}\right|} = \frac{2\pi}{k}$$

- k can only take on a quantized set of values set by boundary conditions in the crystal, where the total phase shift of the electron wave vector across a crystal with dimension L_x, L_y, L_z is 2π and the volume of a unit cell in k-space is ΔV_k

$$k_i = \frac{2\pi}{L_i}s,\ s = 1,2,3,\ \ldots$$

$$\Delta V_k = \Delta k_x \Delta k_y \Delta k_z = \frac{(2\pi)^3}{L_x L_y L_z} = \frac{(2\pi)^3}{V}$$

Energy Band Structures

- The number of states in a spherical shell (k-space) of thickness dk and radius k is

$$\text{Number of states within dk} = \text{Number of states per unit volume of shell dk}$$

$$=\rho(\mathrm{k})\mathrm{d}\kappa = 2\frac{4\pi \mathrm{k}^2}{\Delta V_k}\mathrm{d}\kappa = 2\frac{4\pi \mathrm{k}^2}{(2\pi)^3/V}\mathrm{d}\kappa = \frac{V\mathrm{k}^2}{\pi^2}\mathrm{d}\kappa$$

- The energy of an electron with effective mass m_c and wave vector k in the conduction band is (we will assume energy depends on magnitude k and not direction)

$$E_c(\bar{k}) = \frac{\hbar^2 k^2}{2m_c}$$

- The number of electron and holes per unit volume as a function of energy ($\rho_c(E)$, $\rho_h(E)$) is found from the number of available states per energy level per unit volume

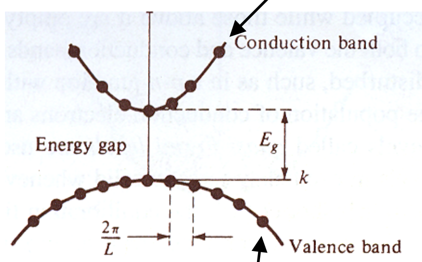
$$\rho(E)dE = \frac{1}{V}\rho(k)dk$$

$$\rho_c(E) = \frac{1}{2\pi^2}\left(\frac{2m_c}{\hbar^2}\right)^{3/2} E^{1/2}$$

$$\rho_c(\omega) = \hbar\rho_c(E) = \frac{1}{2\pi^2}\left(\frac{2m_c}{\hbar^2}\right)^{3/2} \omega^{1/2}$$

$$\rho_h(\omega) = \hbar\rho_h(E) = \frac{1}{2\pi^2}\left(\frac{2m_h}{\hbar^2}\right)^{3/2} \omega^{1/2}$$

Parabola curvature determined by electron mass



Parabola curvature determined by hole mass

Photon Energy and Bandgap

Energy of Photon

$$E_a - E_b = \hbar\omega = E_g + \frac{\hbar^2 k^2}{2m_c} + \frac{\hbar^2 k^2}{2m_v}$$

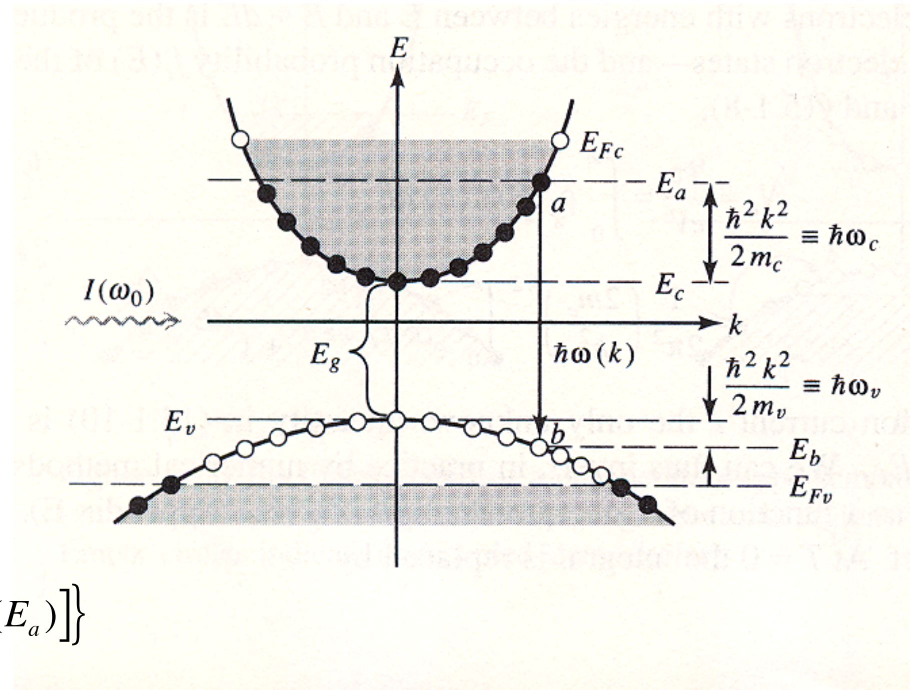
For an electron in upper state a and potential lower state b, the downward rate of transition is

$$R_{a\to b} \propto f_c(E_a)\left[1 - f_v\left(E_b\right)\right]$$

Effective inversion due to electrons and holes within dk

$$N_2 - N_1 \to \frac{\rho(k)dk}{V}\left\{f_c(E_a)\left[1 - f_v(E_b)\right] - f_v(E_b)\left[1 - f_c(E_a)\right]\right\}$$

$$= \frac{\rho(k)dk}{V}\left[f_c(E_a) - f_v(E_b)\right]$$



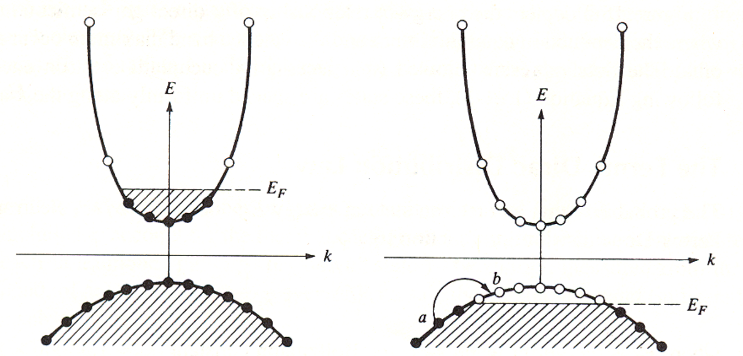
Fermi-Dirac Statistics

- The probability that a state at energy (E) is occupied by an electron is given by

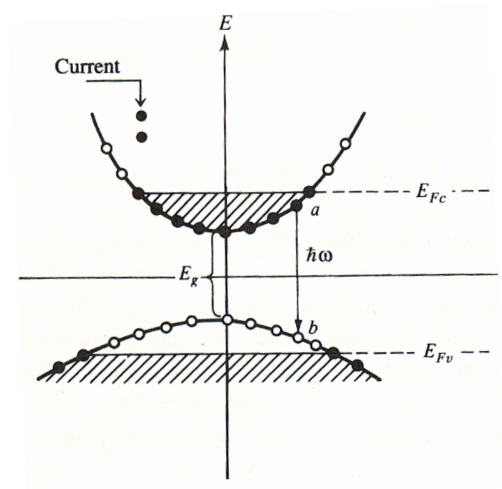
$$f(E) = \frac{1}{e^{(E-E_F)/\kappa_B T} + 1}$$

- Doping the semiconductor can move the Fermi level into the conduction or valance bands depending on the doping concentration

- Disturbing the SC from TE, for example with current injection, will create Quasi-Fermi levels E_{Fc} and E_{Fv}



(a) (b)



Gain

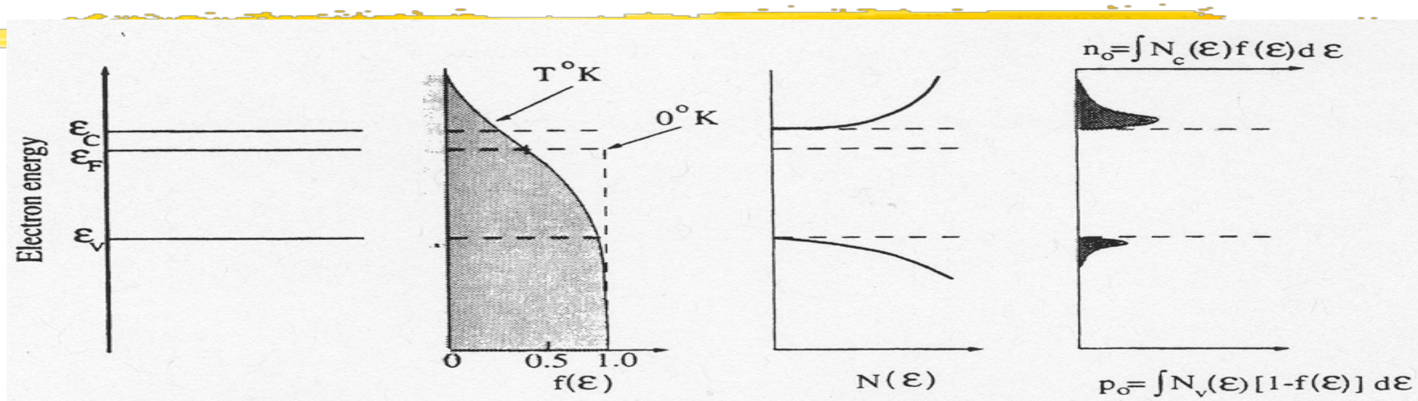


Figure 2.18 Distribution functions, density-of-states functions, and carrier distributions (in energy) in an n-type nondegenerate semiconductor.

High gain requires

1) upper level full (f~1)

2) lower level empty (f~0)

$$f(E) = \frac{1}{1 + e^{(E - E_F)/kT}}$$

Optical Gain in Semiconductors (1)

- For plane wave propagation in a complex medium, with k_0 the free space wave vector and n' and n'' the real and imaginary part of the refractive index respectively

$$\beta = \kappa_0 \left(n' + jn'' \right)$$

$$\kappa_0 = \frac{\omega}{c} = \frac{2\pi}{\lambda}$$

- The optical gain (loss) for a plane wave propagating in a semiconductor in the z-direction can be approximated by

$$g = -\alpha = \frac{1}{I}\frac{dI}{dz} = 2\kappa_0 n''$$

Optical Gain in Semiconductors

- The band structure and electron probability distribution is given by

$$W_c(E) = \left[1 + \exp\left(\frac{E - E_{Fc}}{k_B T}\right)\right]^{-1}$$

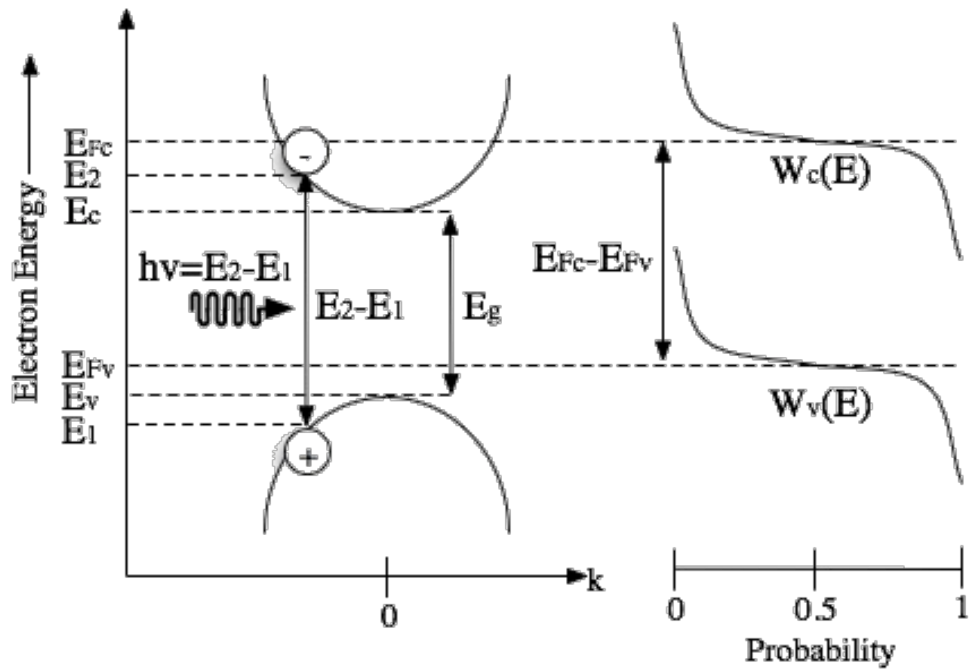
$$W_v(E) = \left[1 + \exp\left(\frac{E - E_{Fv}}{k_B T}\right)\right]^{-1}$$

$$N = N_c \frac{2}{\pi}\int_{E_c}^{\infty} Z_c(E) W_c(E)\, dE$$

$$P = N_v \frac{2}{\pi}\int_{-\infty}^{E_v} Z_v(E)\left[1 - W_v(E)\right] dE$$

Carrier density (↑ N_v)

Density of states (↑ $Z_v(E)$)



Optical Gain in Semiconductors (3)

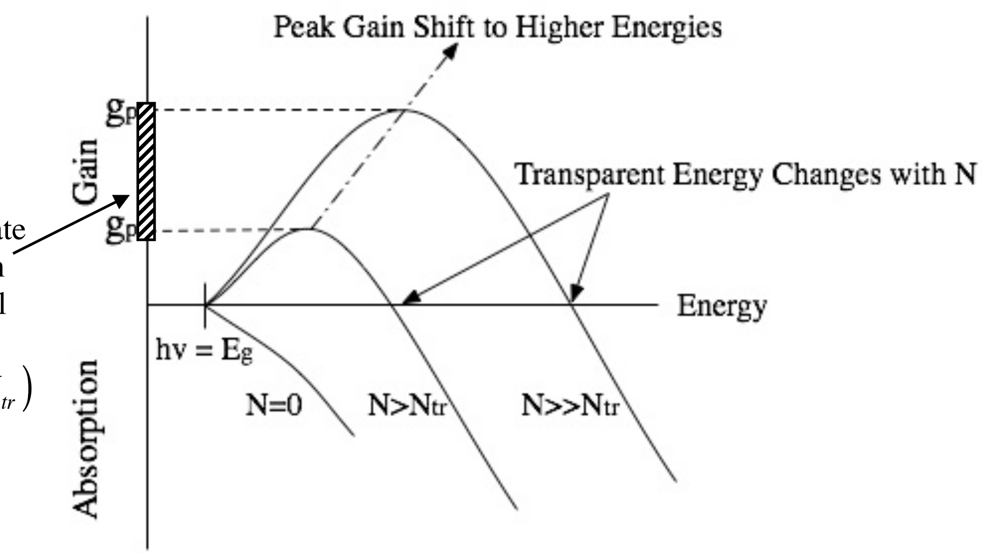
- Optical gain by stimulated emission for a photon of energy hν exceeds band to band absorption if

$$E_{Fc} - E_{Fv} \geq h\nu = E_2 - E_1 \geq E_g$$

- The gain is wavelength dependent with a peak gain that shifts as a function of carrier density.

Can approximate g_p as a function of N over small range

$$g_p = a\left(N - N_{tr}\right)$$



Optical Gain in Semiconductors (4)

- The injected carrier density N is determined by the laser current *I*, the recombination rate *R(N)* and the active region volume V

$$I = qR(N)V$$

$$R(N) = \frac{N}{\tau_s} + BN^2 + CN^3$$

$$\tau_n = \frac{N}{R(N)}$$

where $A=N/\tau_s$ is the linear non-radiative recombination rate, B is the radiative bimolecular (band-to-band) recombination rate and C is the non-radiative Auger recombination rate

- Note: We will see that while the gain is coupled to the carrier density, the carrier density is coupled to the photon density and therefore to the gain. This coupling will lead to nonlinear gain or gain saturation, as will be discussed later in the carrier rate equations.

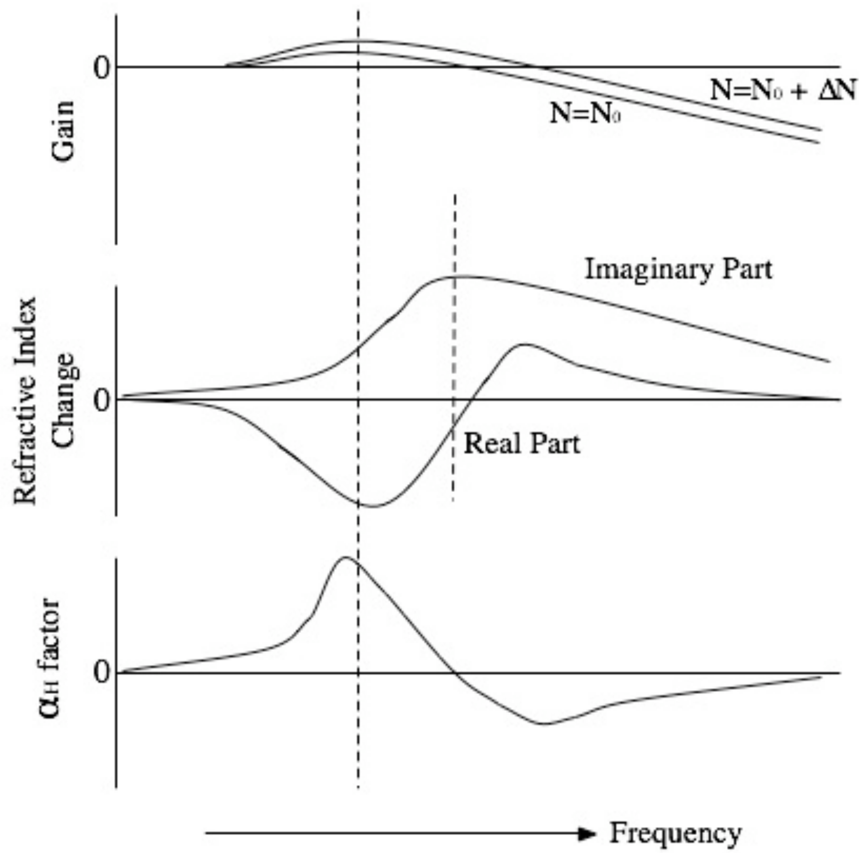
Coupling between Optical Gain and Phase

- The Kramers-Kronig relations tell us that changes in the in the imaginary (Δg) and real parts of the refractive index (Δn) are related by

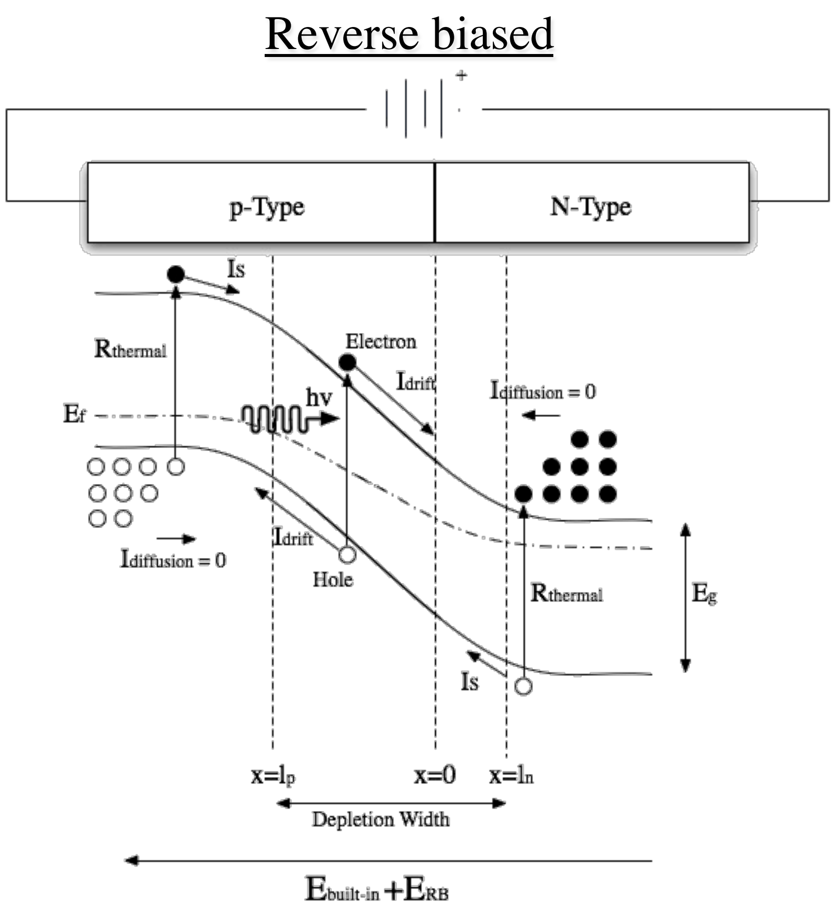
$$\Delta n'(\omega) = \frac{c}{\pi} P \int_0^{\infty} \frac{\Delta g(\omega')}{\omega'^2 - \omega^2} d\omega'$$

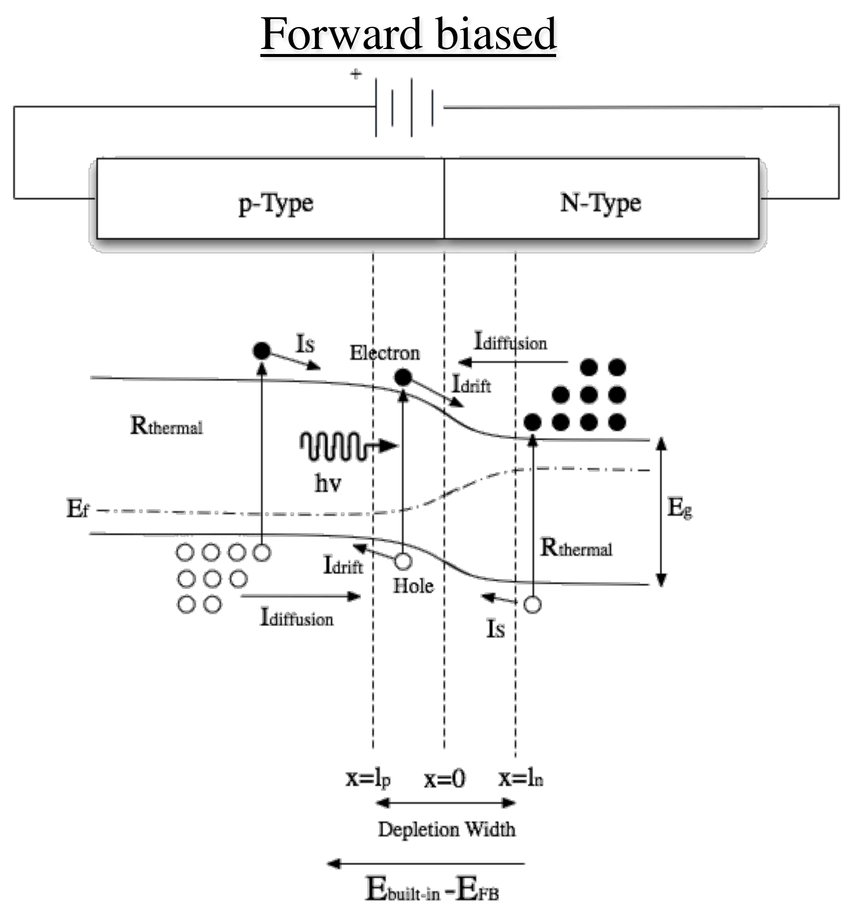
- The coupling between gain and phase is described by the linewidth enhancement (or alpha) factor

$$\alpha_H = -\frac{\partial n' / \partial N}{\partial n'' / \partial N}$$



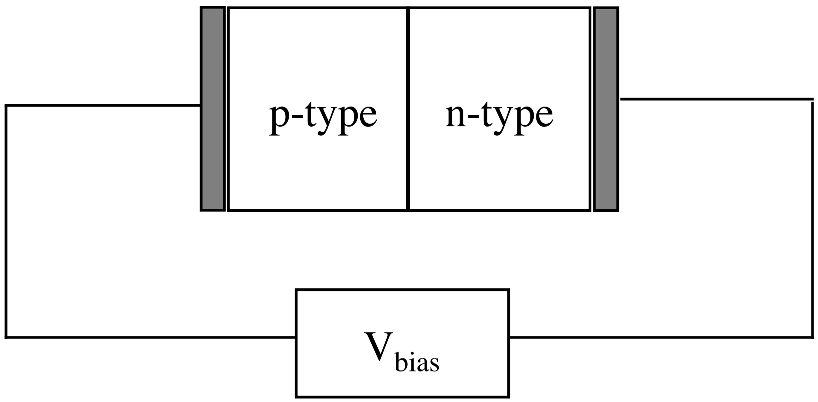
Biased p-n Junction Photodiodes





P-type : Semiconductor doped with acceptor atoms
N-type : Semiconductor doped with donor atoms

p-n Junction Equation



$$I = (I_s)[\exp^{qV_{bias}/K_BT} - 1]$$

- $I_s = I_{th}$ is the thermal or saturation current that occurs in normal (non-illuminated) diode operating mode
- q is the electron charge
- V_{bias} is applied bias voltage (positive = forward, negative=reverse)
- K_B is Boltzman's constant
- T is temperature (usually in Kelvin, depending on units of K_B)

Carrier Injection

- In equilibrium,

$$pn = n_i^2$$

- Under forward bias,

$$pn >> n_i^2$$

- Under reverse bias,

$$pn << n_i^2$$

Carrier Injection

- In equilibrium,

$$pn = n_i^2 \qquad E_{Fn} = E_{Fp} = E_F$$

- Under forward bias,

$$pn >> n_i^2 \qquad E_{Fn} - E_{Fp} > 0$$

- Under reverse bias,

$$pn << n_i^2 \qquad E_{Fn} - E_{Fp} < 0$$

Quasi Fermi Levels

$$n = n_i e^{(E_{Fn} - E_i)/kT}$$

$$p = n_i e^{-(E_{Fp} - E_i)/kT}$$

$$pn = n_i^2 e^{(E_{Fn} - E_{Fp})/kT}$$

Quasi Fermi Levels

$$n = n_i e^{(E_{Fn} - E_i)/kT}$$

$$p = n_i e^{-(E_{Fp} - E_i)/kT}$$

$$pn = n_i^2 e^{(E_{Fn} - E_{Fp})/kT}$$

- Gain occurs when

$$g(\hbar\omega) > 0 \quad when \quad E_{Fn} - E_{Fp} > \hbar\omega$$

Optical Gain in Semiconductors

Gain between two levels depends on:

- ⇨ Carrier density, i.e. level of inversion
- ⇨ Reduced density of states

$$\frac{R_{21}}{R_{12}} = \frac{f_2(1-f_1)}{f_1(1-f_2)} = e^{(\Delta E_f - E_{21})/kT}$$

- ⇨ Transition matrix element $|M|^2$

$$\frac{1}{\rho_r} = \frac{1}{\rho_c} + \frac{1}{\rho_v}$$

Gain : Reduced Density of States

The optical gain is proportional to the reduced density of state at the transition energy:

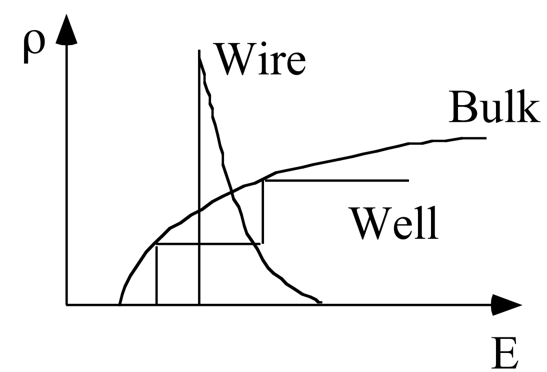
$$g(\omega) \propto (f_2 - f_1)\rho_r(\hbar\omega)$$

The reduced density of states:

$$\rho_r(E) = \frac{\sqrt{E}}{4\pi^2}\left(\frac{2m}{\hbar^2}\right)^{3/2}$$ (Bulk)

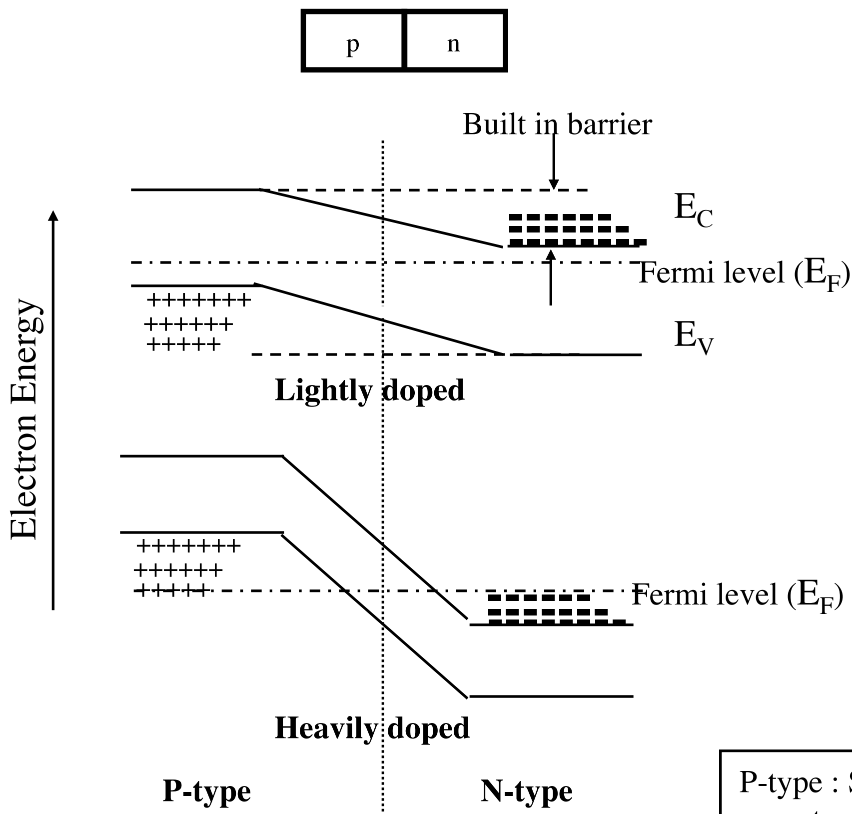
$$\rho_r(E) = \frac{m}{2\pi\hbar^2}\frac{1}{L_z}$$ (Well)

$$\rho_r(E) = \frac{\sqrt{2m}}{\hbar}\frac{1}{2\pi L_x L_y \sqrt{E}}$$ (Wire)

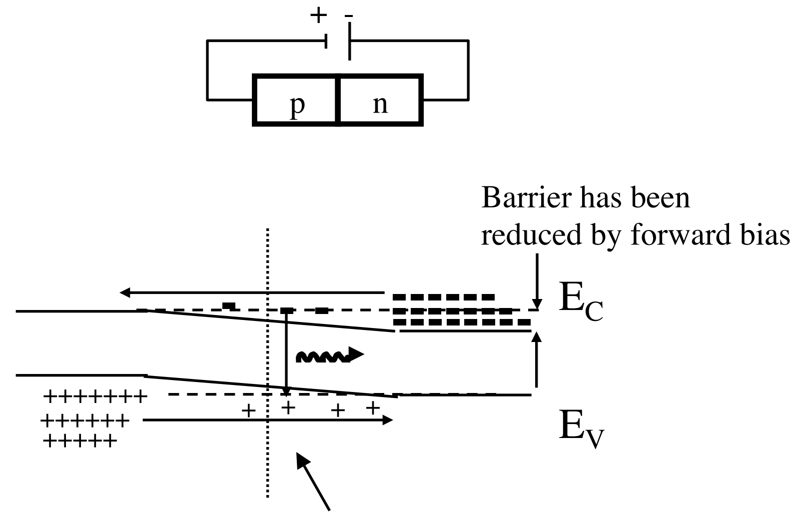


Semiconductor p-n Junctions

Unbiased



Forward biased



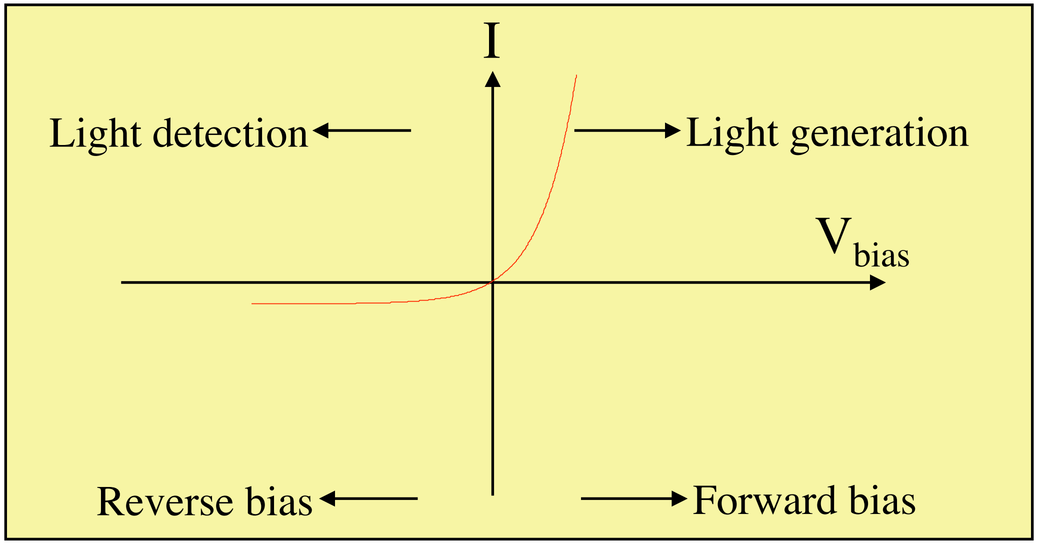
Electrons in conduction band and holes in valence band now move due to diffusion and spatially overlap in the depletion region and can recombine radiatively

P-type : Semiconductor doped with acceptor atoms
N-type : Semiconductor doped with donor atoms

p-n Junction Characteristics

- From the electrical point of view, the junction acts as a diode, which for light generation is always forwardly biased
- Note that the same structure can also be used, when under reverse bias, for photodetection

$$I = I_S[\exp(qV_{bias}/K_BT) - 1]$$



- I_S is thermally generated current
- q is electron charge
- V_{bias} is applied bias voltage (positive = forward, negative=reverse)
- K_B is Boltzman's constant
- T is temperature (usually in Kelvin, depending on units of K_B)

Note : qV_{bias} and K_B T are both in units of energy

Nonradiative Recombination

- For any light emitting semiconductor source, we want injected electrons (I_{bias}) to contribute to light emission.
  - Any EHP recombination that does not produce light decreases the operating efficiency and increases heat generation.

- Define : Internal Quantum Efficiency

$$\eta_{\text{int}} = \frac{\tau_{nr}}{\tau_{nr} + \tau_{rr}} = \frac{1}{1 + \tau_{rr}/\tau_{nr}}$$

τ_{rr}= radiative lifetime = Spontaneous + Stimulated
τ_{rr}= non radiative lifetime