Session 9: Solid State Devices

Optical Devices

Outline

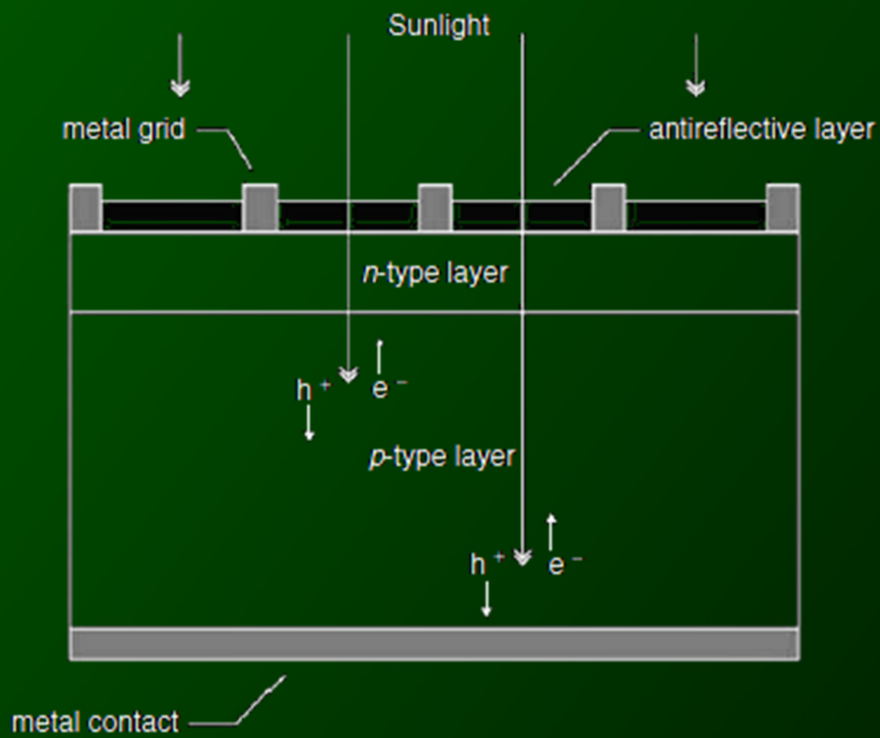
- A
  - B
  - C
  - D
  - E
- F
  - G
- H
- I
- J

Outline

- Ref: ?

Solar Cell

Solar cell is simply a semiconductor diode that has been carefully designed to efficiently absorb and convert light energy from the sun into electrical energy.



$$E_\lambda = \frac{hc}{\lambda}$$

$T_{SUN} \sim 5760\ K$ black body

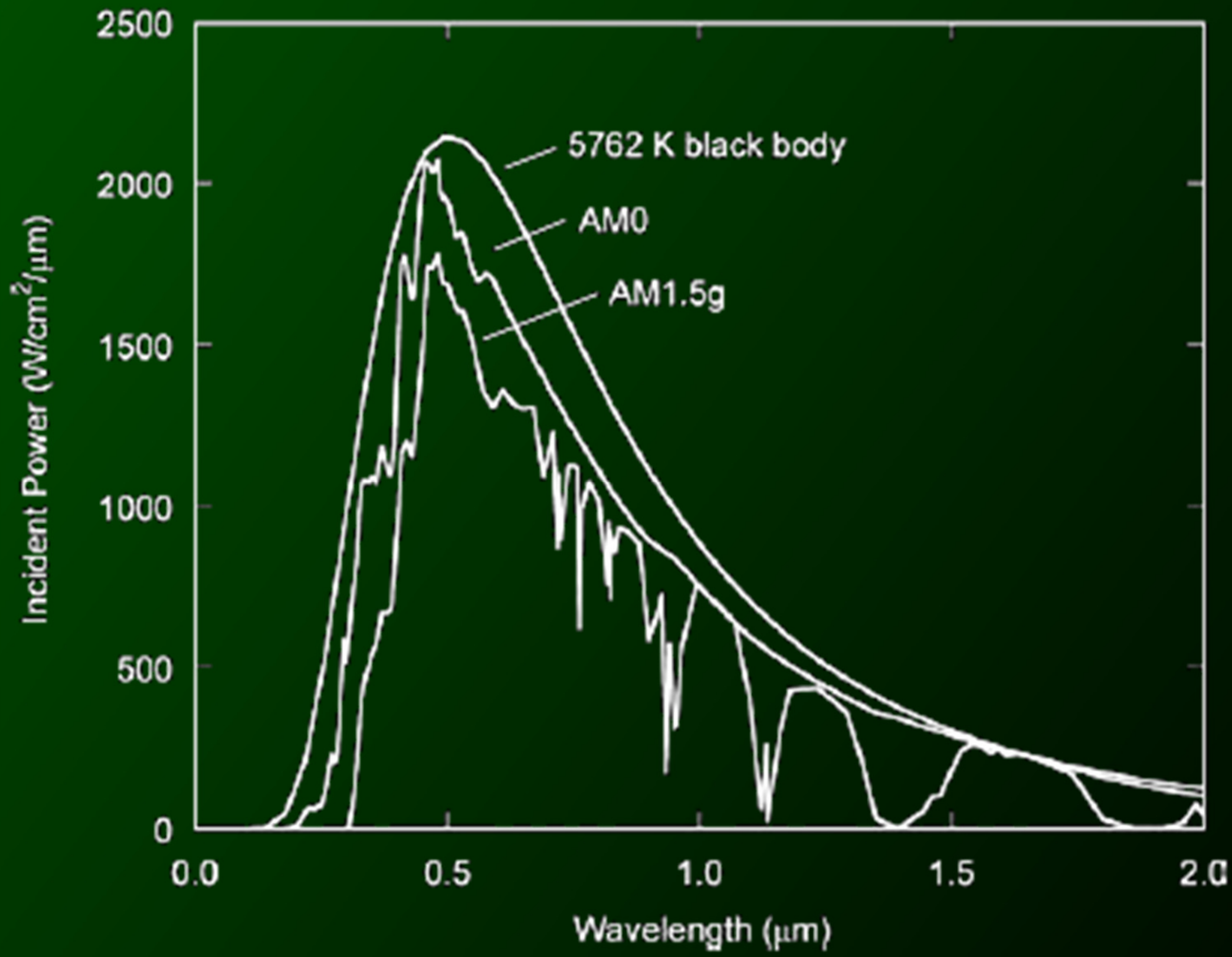
air mass zero (AM0): Just above the Earth's atmosphere 1.353 kW/m^2

AM1.5 (θ = 48.2°) 1 kW/m^2

AM1.5g (global)

AM1.5d (direct)

Radiation Spectrum



Light Absorption : Direct

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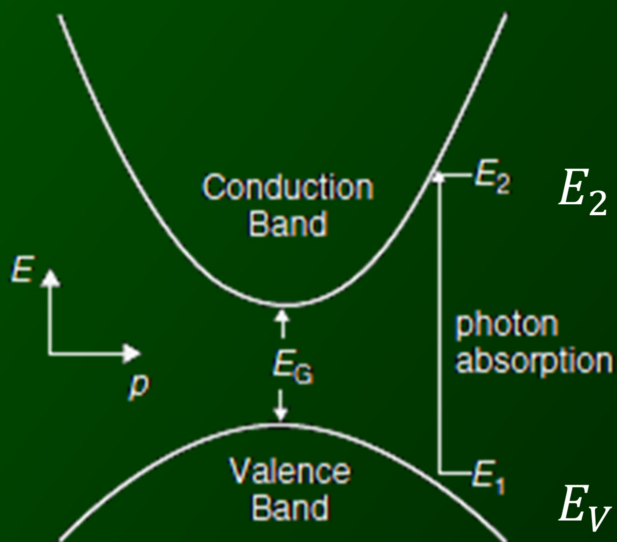
Si– GaAs, GaInP, Cu(InGa)Se2, and CdTe,

Si:

- well developed technology
- absorption characteristics are a fairly good match to the solar spectrum



$$E_2 - E_C = \frac{p^2}{2m_n^*}$$

$$E_V - E_1 = \frac{p^2}{2m_p^*}$$

$$h\upsilon - E_G = \frac{p^2}{2}\left(\frac{1}{m_n^*} + \frac{1}{m_p^*}\right)$$

$$\alpha(h\upsilon) = \sum P_{12} g_V(E_1) g_C(E_2)$$

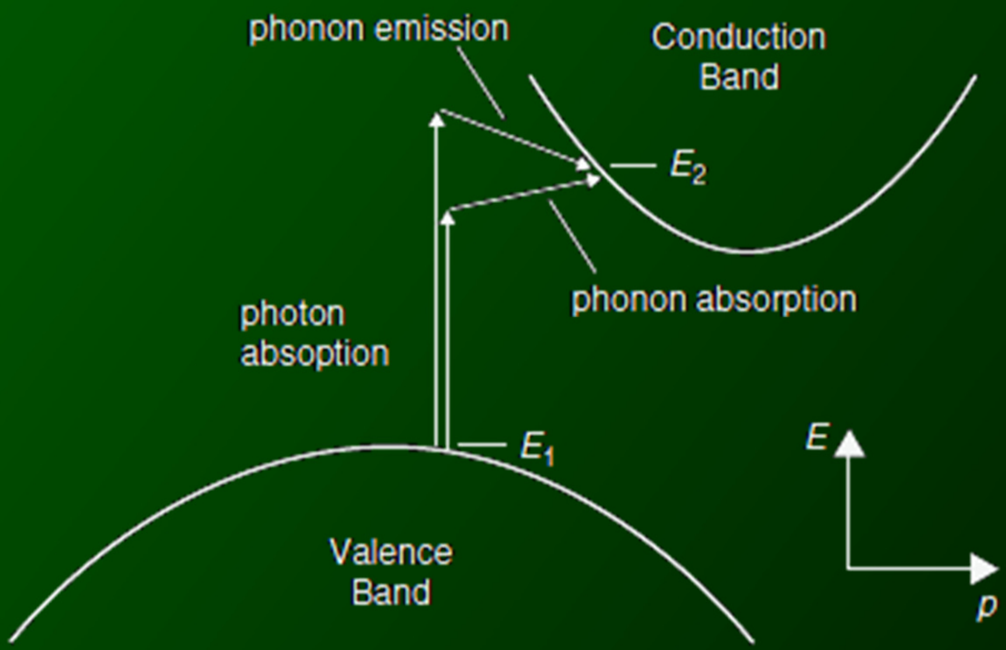
$$g_C(E) = \frac{\sqrt{2} {m_n^*}^{3/2}}{\pi^2 \hbar^3}\sqrt{E - E_C}$$

$$g_V(E) = \frac{\sqrt{2} {m_p^*}^{3/2}}{\pi^2 \hbar^3}\sqrt{E_V - E}$$

$$\alpha(h\upsilon) \approx A^*(h\upsilon - E_G)^{1/2}$$

$$\alpha(h\upsilon) \approx \frac{B^*}{h\upsilon}(h\upsilon - E_G)^{3/2}$$

Light Absorption : Indirect

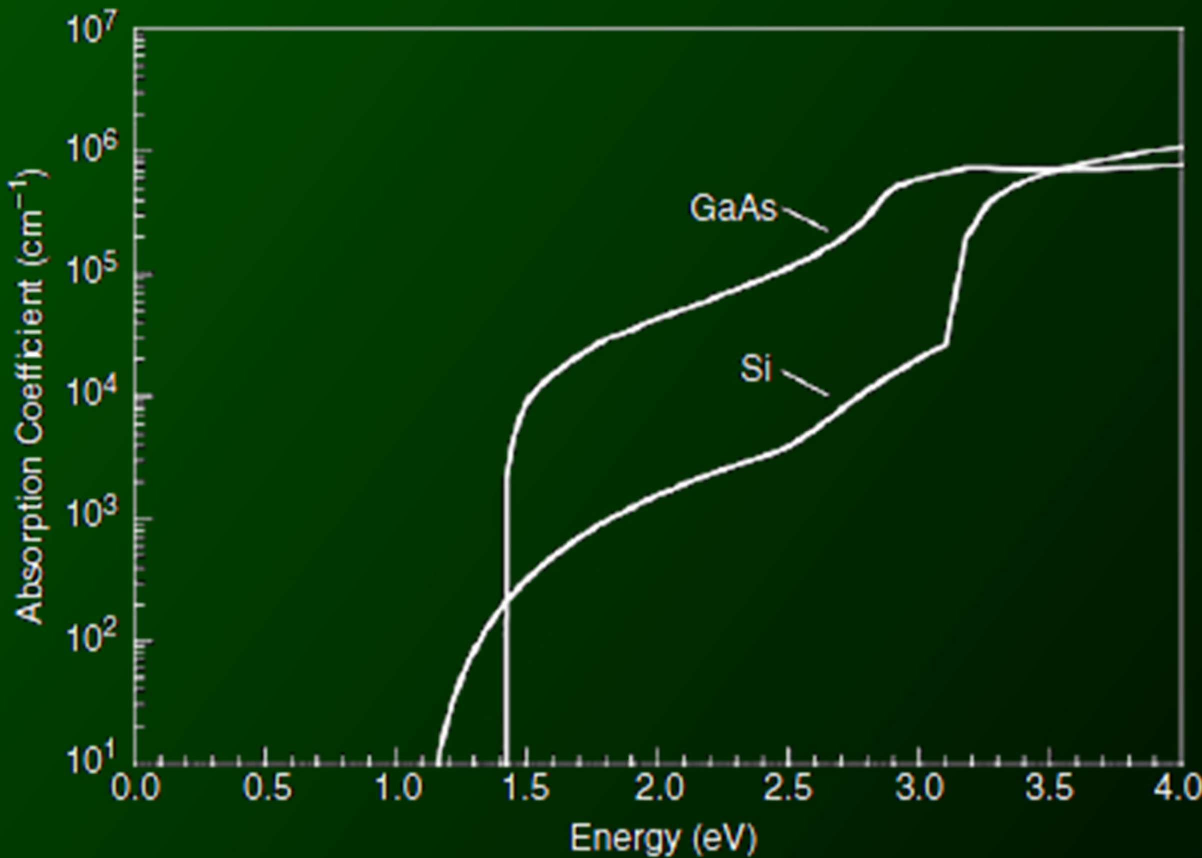


$$\alpha_a(h\upsilon) \approx \frac{A\left(h\upsilon - E_G + E_{ph}\right)^2}{e^{E_{ph}/kT} - 1}$$

$$\alpha_e(h\upsilon) \approx \frac{A\left(h\upsilon - E_G - E_{ph}\right)^2}{1 - e^{-E_{ph}/kT}}$$

$$\alpha(h\upsilon) = \alpha_e(h\upsilon) + \alpha_a(h\upsilon)$$

Absorption Coefficient vs. Photon Energy



$E_{G_{Si}}$ =1.12 eV $E_{G_{GaAs}}$ = 1.42 eV

light penetration?

Recombination

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5. □□□□□

SRH recom-gen: $$R_{SRH} = \frac{np - n_i^2}{\tau_p\left(n + n_i e^{\beta(E_T - E_i)}\right) + \tau_n\left(p + n_i e^{\beta(E_i - E_T)}\right)}$$ $$\tau = \frac{1}{\sigma v_{th} N_T}$$

p-type (low injection) $R_{SRH} \approx \frac{n - n_0}{\tau_n}$ High injection $R_{SRH} \approx \frac{n \approx p}{\tau_p + \tau_n}$

Direct $R_D = B(np - n_i^2)$ n-type (low injection) $R_D \approx \frac{p - p_0}{\tau_{p_D}}$

Auger $R_A = \left(C_n n + C_p p\right)(np - n_i^2)$ n-type low-level $R_A \approx \frac{p - p_0}{\tau_{p_A}}$

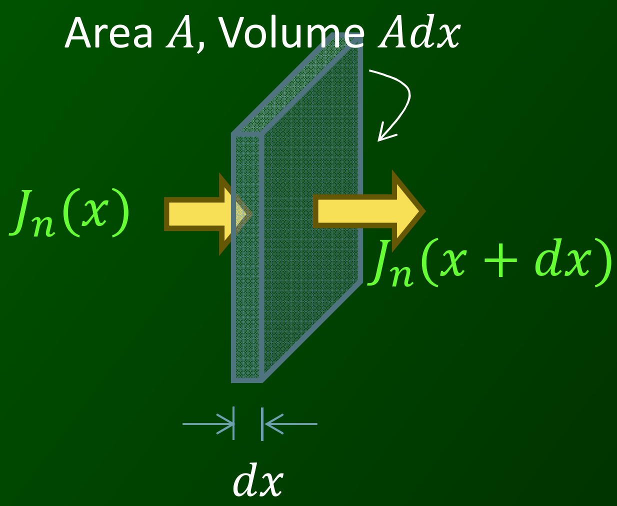
$$R = \left[\sum_{traps\ i} R_{SRH,i}\right] + R_D + R_A$$

minority-carrier lifetime
low-level injection $$\frac{1}{\tau} = \left[\sum_{traps\ i} \frac{1}{\tau_{SRH,i}}\right] + \frac{1}{\tau_D} + \frac{1}{\tau_A}$$

(surface states) ?

Derivation of Continuity Equation

Consider carrier-flux into/out-of an infinitesimal volume:



$$Adx\left(\frac{\partial n}{\partial t}\right) = -\frac{1}{q}\left[J_n(x)A - J_n(x+dx)A\right] - \frac{\Delta n}{\tau_n}Adx$$

$$J_n(x+dx) = J_n(x) + \frac{\partial J_n(x)}{\partial x}dx$$

$$\rightarrow \quad \frac{\partial n}{\partial t} = \frac{1}{q}\frac{\partial J_n(x)}{\partial x} - \frac{\Delta n}{\tau_n}$$

Continuity Equation:

$$\frac{\partial n}{\partial t} = \frac{1}{q}\frac{\partial J_n(x)}{\partial x} - \frac{\Delta n}{\tau_n} + G_L$$

$$\frac{\partial p}{\partial t} = -\frac{1}{q}\frac{\partial J_p(x)}{\partial x} - \frac{\Delta p}{\tau_p} + G_L$$

Continuity Equation

$$\nabla . J_p = q\left(G - R_p - \frac{\partial p}{\partial t}\right)$$

$$\nabla . J_n = q\left(R_n - G + \frac{\partial n}{\partial t}\right)$$

$$J_p = qp\mu_p\mathcal{E} - qD_p\nabla p = -qp\mu_p\nabla\varphi - qD_p\nabla p \quad = -qp\mu_p\nabla\left(\varphi - \varphi_p\right) - kT\mu_p\nabla p$$

$$J_n = qn\mu_n\mathcal{E} + qD_n\nabla n = -qn\mu_n\nabla\varphi + qD_n\nabla n \quad = -qn\mu_n\nabla(\varphi + \varphi_n) - kT\mu_n\nabla n$$

low-level injection

Thus the minority carrier diffusion equations are

$$\frac{\partial \Delta n_p}{\partial t} = D_n\frac{\partial^2 \Delta n_p}{\partial x^2} - \frac{\Delta n_p}{\tau_n} + G_L \qquad \text{in p-type material}$$

$$\frac{\partial \Delta p_n}{\partial t} = D_p\frac{\partial^2 \Delta p_n}{\partial x^2} - \frac{\Delta p_n}{\tau_p} + G_L \qquad \text{in n-type material}$$

PN junctions (Qualitative)

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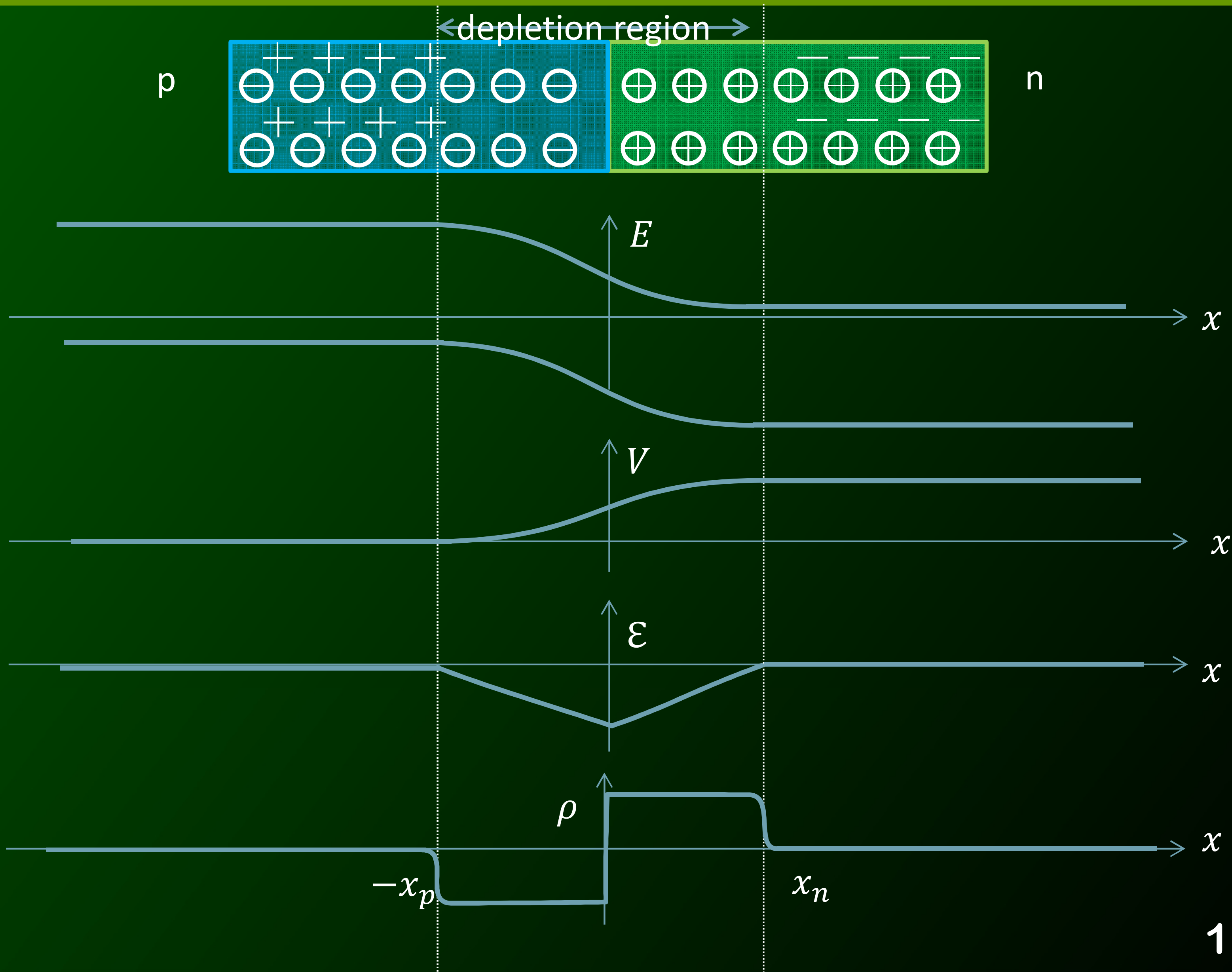
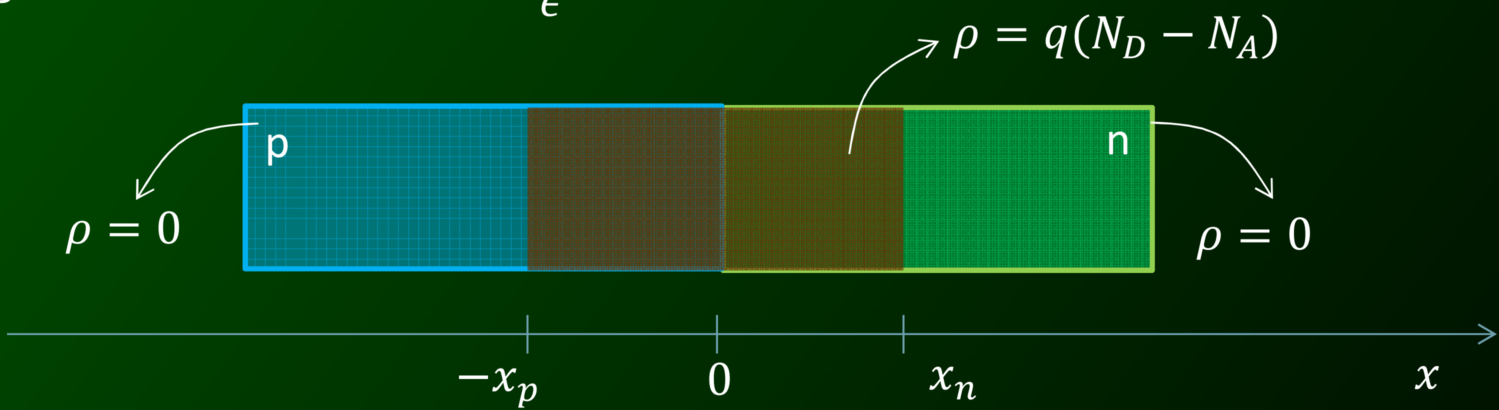


PN junctions - Assumptions

The Depletion Approximation : Obtaining closed-form solutions for the electrostatic variables

Charge Distribution : $\nabla^2\varphi = \frac{q}{\epsilon}(p - n + N_D - N_A)$



Note that

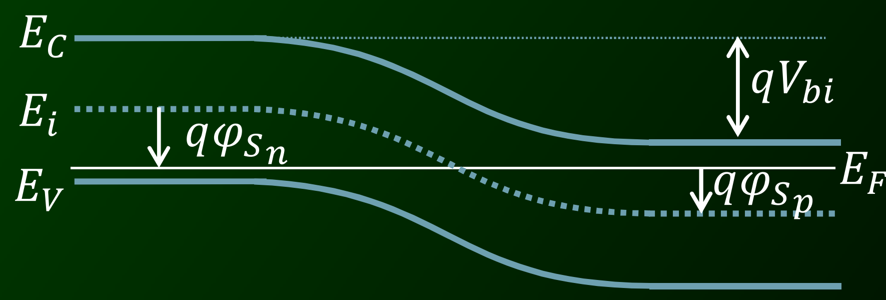
(1) $-x_p \le x \le x_n$: p & n are negligible ($\because \mathcal{E}$ exist).

(2) $x \le -x_p$ or $x \ge x_n$: $\rho = 0$

Built-In Potential V_{bi}

$$qV_{bi} = q\varphi_{s_p} + q\varphi_{s_n}$$

$$= (E_i - E_F)_p + (E_F - E_i)_n$$



For non-degenerately doped material:

$$\left.\begin{aligned}(E_i - E_F)_p &= kT\ln\left(\frac{p}{n_i}\right) = kT\ln\left(\frac{N_A}{n_i}\right)\\ (E_F - E_i)_n &= kT\ln\left(\frac{n}{n_i}\right) = kT\ln\left(\frac{N_D}{n_i}\right)\end{aligned}\right\} \rightarrow V_{bi} = \frac{kT}{q}\ln\left(\frac{N_A N_D}{n_i^2}\right)$$

What shall we do for $p^+ - n$ (or $n^+ - p$) junction?!?!?

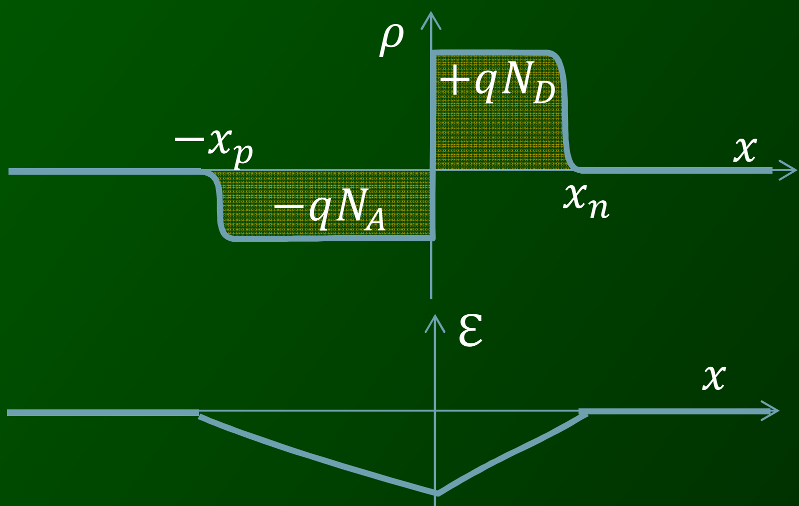
p^+:

$$(E_i - E_F)_p = \frac{E_G}{2}$$

n^+:

$$(E_F - E_i)_n = \frac{E_G}{2}$$

The Depletion Approximation



$$\frac{d\mathcal{E}}{dx} = \frac{\rho}{\epsilon}$$

$$\rho = -qN_A \rightarrow$$

$$\mathcal{E}(x) = \frac{-qN_A}{\epsilon} + C = \frac{-qN_A}{\epsilon}(x + x_p)$$

$$\rho = qN_D \rightarrow$$

$$\mathcal{E}(x) = \frac{qN_D}{\epsilon} + C' = \frac{qN_D}{\epsilon}(x - x_n)$$

The electric field is continuous at $x = 0$

$$x_p N_A = x_n N_D$$

Charge neutrality condition as well!

Depletion Layer Width

$-x_p < x < 0$: $\quad V(x) = \frac{qN_A}{2\epsilon}(x + x_p)^2$

$0 < x < x_n$: $\quad V(x) = V_{bi} - \frac{qN_D}{2\epsilon}(x_n - x)^2$

$$\left.\begin{aligned} V(0) = \frac{qN_A}{2\epsilon}x_p^2 = V_{bi} - \frac{qN_D}{2\epsilon}x_n^2 \\ x_p N_A = x_n N_D \end{aligned}\right\} \rightarrow \begin{cases} x_n = \sqrt{\frac{2\epsilon_s V_{bi}}{q}\left(\frac{N_A}{N_D(N_A+N_D)}\right)} \\ x_p = \sqrt{\frac{2\epsilon_s V_{bi}}{q}\left(\frac{N_D}{N_A(N_A+N_D)}\right)} \end{cases}$$

Summing, we have:

$$W = x_p + x_n = \sqrt{\frac{2\epsilon_s V_{bi}}{q}\left(\frac{1}{N_D} + \frac{1}{N_A}\right)}$$

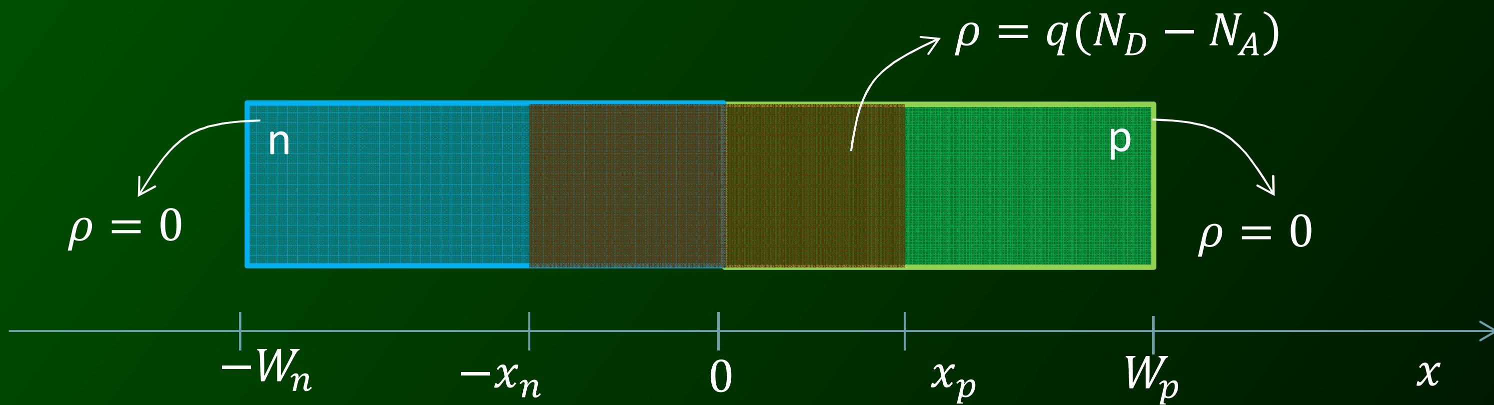
Va Applied Voltage

Now as we assumed all voltage drop is in the depletion region (Note that VA ≤ Vbi)

$$x_n + x_p = W = \sqrt{\frac{2\epsilon_s(V_{bi} - V_A)}{q}\left(\frac{1}{N_D} + \frac{1}{N_A}\right)}$$

$$x_p N_A = x_n N_D$$

Solar Cell Boundary Conditions



ohmic contact? $\Delta p(-W_n) = 0$

$$\frac{d\Delta p}{dx} = \frac{S_{surf}}{D_p}\Delta p(-W_n)$$

back contact: ohmic $\Delta n(W_p) = 0$

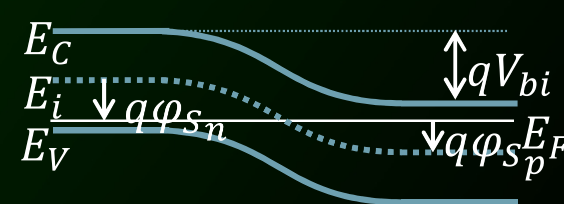
back-surface field (BSF),

$$\left.\frac{d\Delta n}{dx}\right|_{x=W_p} = -\frac{S_{BSF}}{D_n}\Delta n(W_p)$$

? BC at x_p and -x_n

$$qV = F_N(-W_n) - F_p(W_p)$$

$$p_n(-x_n) = \frac{n_i^2}{N_D}e^{qV/kT} \qquad n_p(x_p) = \frac{n_i^2}{N_A}e^{qV/kT}$$



Generation Rate

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grid-shadowing factor
reflectance
photon flux
absorption coefficient

$$G(x) = (1 - s)\int_{\lambda} \big(1 - r(\lambda)\big) f(\lambda)\alpha(\lambda)e^{-\alpha(x+W_n)}d\lambda$$

See text for derivations!

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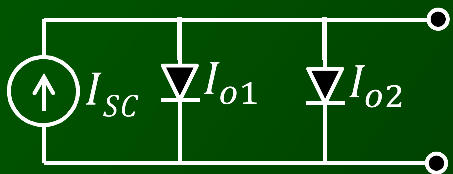
Solar Cell Equivalent Circuit



$$I = I_{o2}\left(e^{qV/2kT} - 1\right)$$ recombination in the depletion region

$$I = I_{o1}\left(e^{qV/kT} - 1\right)$$ recombination current in the quasi-neutral regions

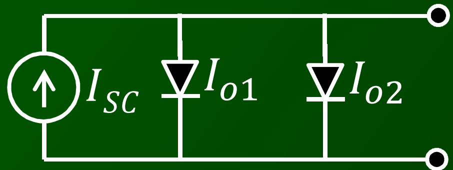
$$I_{o1} = I_{O1,n} + I_{O1,p}$$

$$I_{O1,p} = qA\frac{n_i^2}{N_D}\frac{D_P}{L_P}\left[\frac{\frac{D_P}{L_P}\sinh\frac{W_n - x_n}{L_P} + S_F\cosh\frac{W_n - x_n}{L_P}}{\frac{D_P}{L_P}\cosh\frac{W_n - x_n}{L_P} + S_F\sinh\frac{W_n - x_n}{L_P}}\right]$$

$$I_{O1,n} = qA\frac{n_i^2}{N_A}\frac{D_n}{L_n}\left[\frac{\frac{D_n}{L_n}\sinh\frac{W_p - x_p}{L_n} + S_{BSF}\cosh\frac{W_p - x_p}{L_n}}{\frac{D_n}{L_n}\cosh\frac{W_p - x_p}{L_n} + S_{BSF}\sinh\frac{W_p - x_p}{L_n}}\right]$$

$$I_{o2} = qA\frac{W_D n_i}{\tau_D}$$

Solar Cell Equivalent Circuit



$$I_{SC} = I_{SCd} + I_{SCn} + I_{SCp}$$

$$I_{SCd} = qA(1-s)\int_{\lambda} \left(1-r(\lambda)\right) f(\lambda) \left(e^{-\alpha\left(W_n - x_n\right)} - e^{-\alpha\left(W_n + x_p\right)}\right) d\lambda$$

Solar Cell I –V Characteristic

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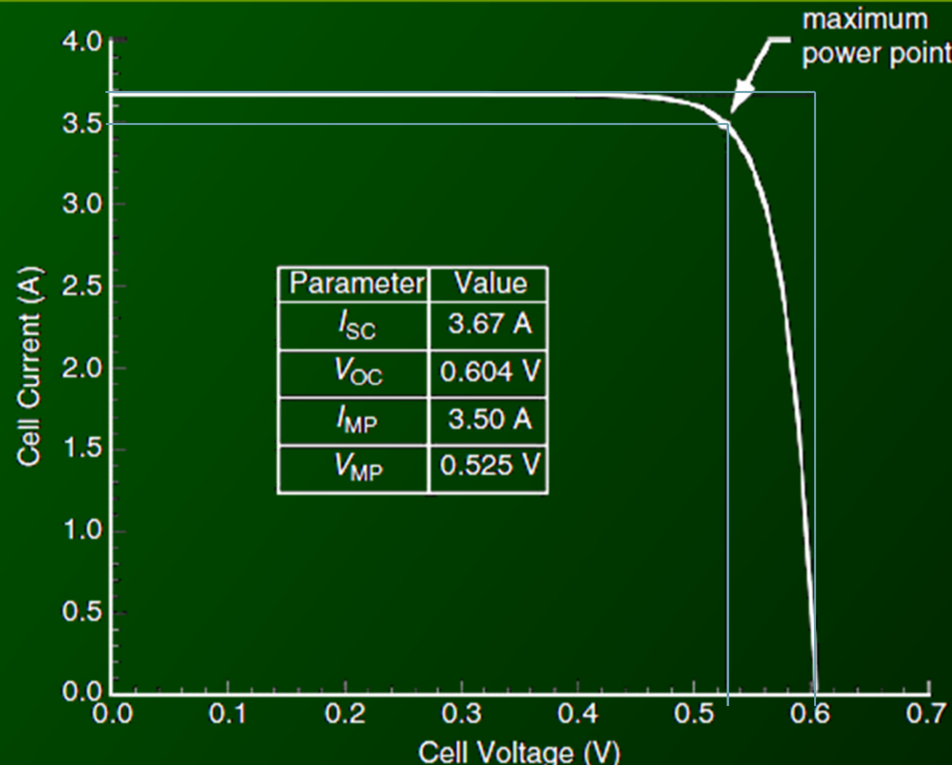
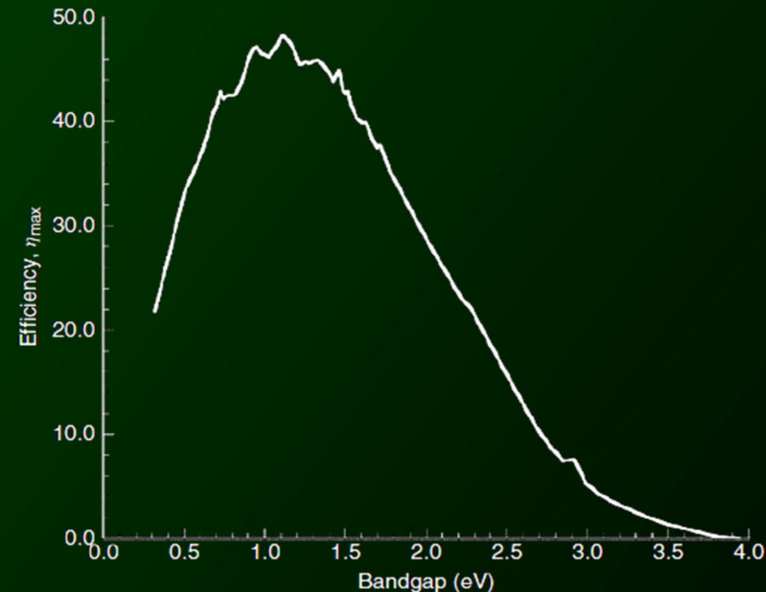
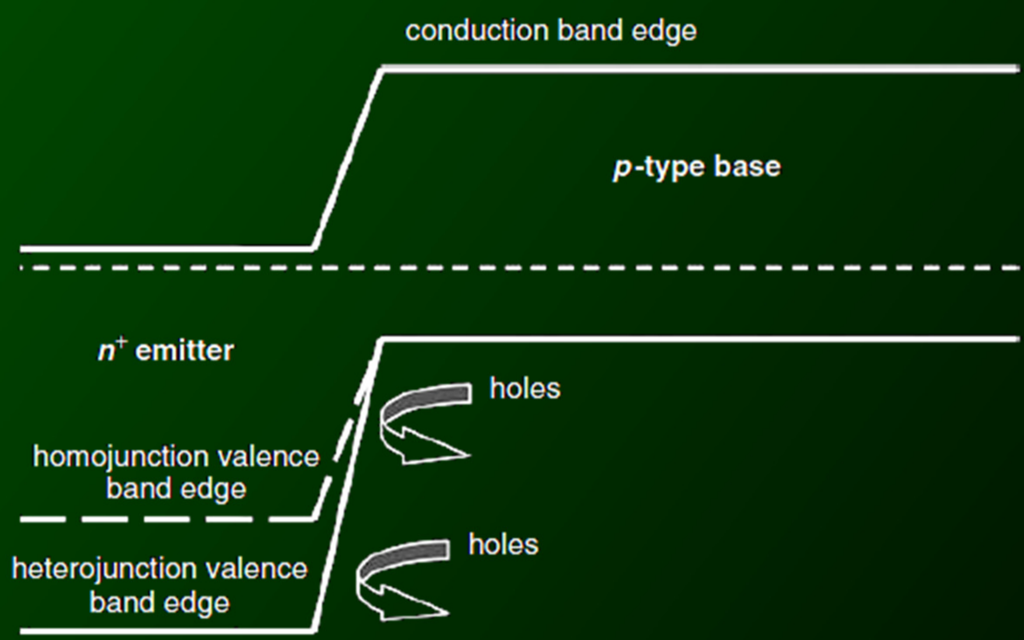




Parameter	n-type Si emitter	p-type Si base
Thickness	$W_N = 0.35\,\mu m$	$W_P = 300\,\mu m$
Doping density	$N_D = 1 \times 10^{20}$ cm^{-3}	$N_A = 1 \times 10^{15}$ cm^{-3}
Surface recombination	$D_p = 1.5$ cm^{-2}/V s	$D_n = 35$ cm^{-2}/V s
Minority-carrier diffusivity	$S_{F,eff} = 3 \times 10^4$ cm/s	$S_{BSF} = 100$ cm/s
Minority-carrier lifetime	$\tau_p = 1\,\mu s$	$\tau_n = 350\,\mu s$
Minority-carrier diffusion length	$L_p = 12\,\mu m$	$L_n = 1100\,\mu m$

Heterojunction Solar Cell

recombination losses in emitter $\downarrow$ $\rightarrow$ $\eta \uparrow$



Solar Cell Efficiency

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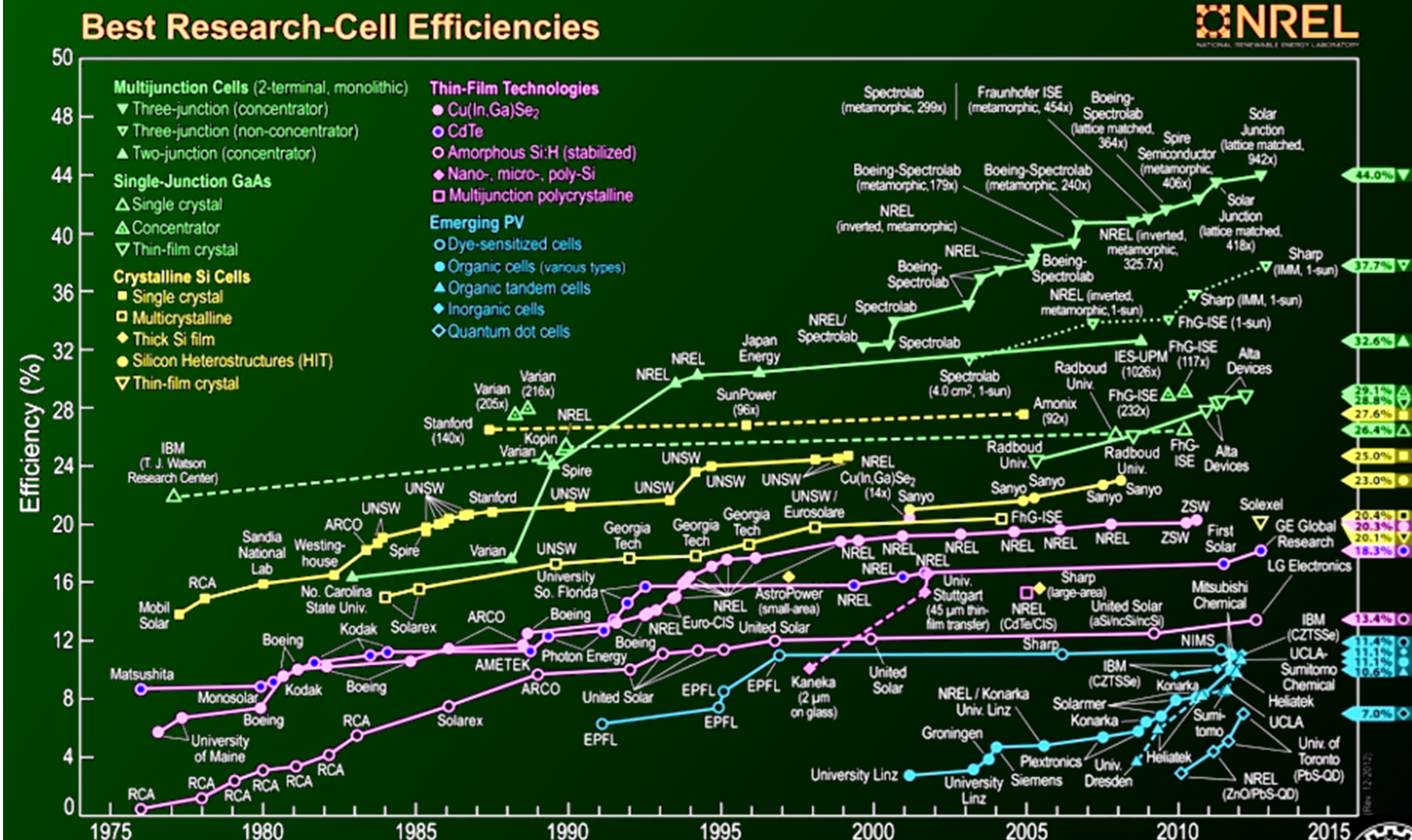
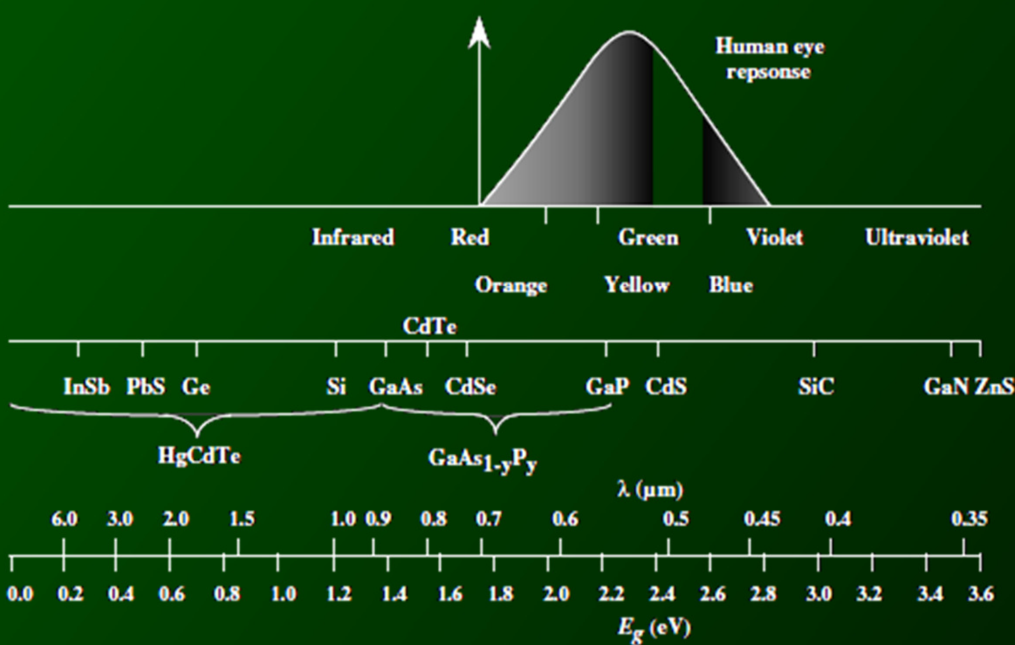
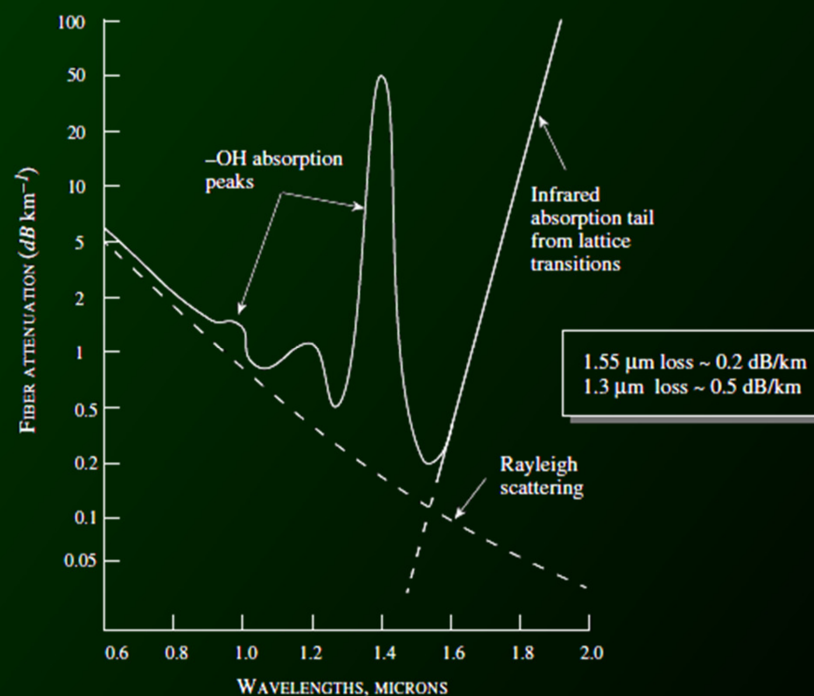


LED - Light emitting diode

LED : a p-n junction in forward biased $E_{light} \sim E_G$

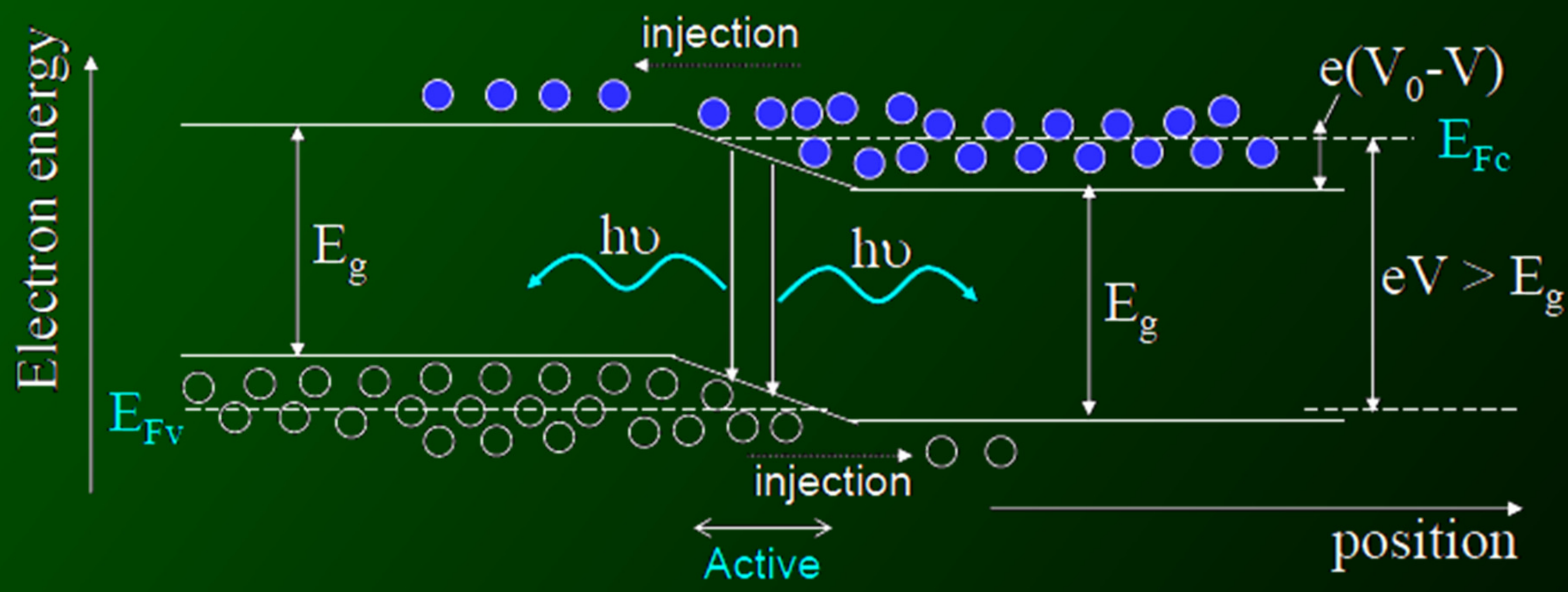




LED for optical communication sources (InP , GaAs)

LED for display (GaN, InGaN, AlGaInP)

p+ - n+ junction under forward bias



- At high injection carrier density in such a junction there is an active region near the depletion layer that contains simultaneously degenerate populations of electrons and holes.
- An LED emits incoherent, non-directional, and unpolarized spontaneous photons that are not amplified by stimulated emission.
- An LED does not have a threshold current. It starts emitting light as soon as an injection current flows across the junction.

Emission Energy

$$\frac{1}{\tau} = \frac{1}{\tau_r} + \frac{1}{\tau_{nr}}$$

radiative lifetime

nonradiative lifetime

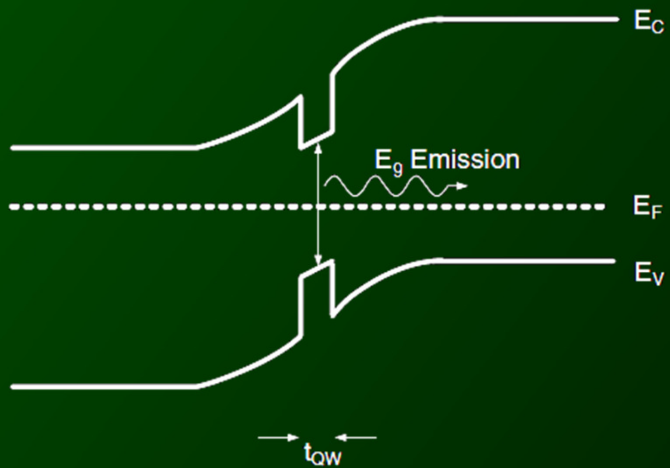
$$\tau_r = \frac{1}{R_{ec}N_A}$$

$$\tau_{nr} = \frac{1}{\sigma v_{th} N_T}$$

high-quality direct $\eta \sim 1$

indirect $\eta \sim 10^{-2}$ ... 10^{-3}

$$\eta = \frac{1}{1 + \frac{\tau_r}{\tau_{nr}}}$$



(i) increasing the direct recombination rate and leading to higher light output,

(ii) having an emission region that is lower in energy that the injection (cladding) regions which allows the generated photons to escape without being re-absorbed in the injection regions,

(iii) minimizing the overflow of electrons into the cladding regions where the injected carriers either recombine non-radiatively or generate light of an undesired wavelength.

recombination coefficients and lifetimes

	$R_r[cm^{-3}s^{-1}]$	$\tau_r[ns]$	$\tau_r[ns]$	$\tau[ns]$	η_{int}
Si	10^{-15}	10000000	100	100	10^{-5}
GaAs	10^{-10}	100	100	50	0.5

R_r Carrier pair injection rate $[cm^{-3}s^{-1}]$

steady-state excess-carrier concentration $\delta n = R_r\,\tau \quad [1/cm^3]$

$$\Phi\left[\frac{photon}{s}\right] = \eta_{int} R_r V$$

$$= V\frac{\delta n}{\tau_{\ r}} = \frac{\eta_{int} i}{q}$$

$\delta n \uparrow$

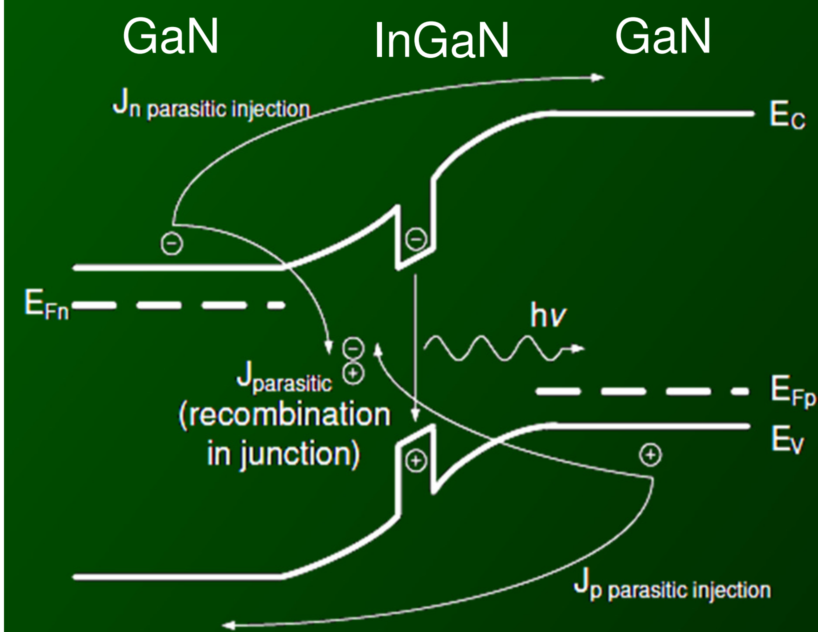
$\tau_r \downarrow$

output optical power

$$P = h\upsilon\,\Phi$$

Very effective carrier and optical confinement can be simultaneously accomplished with double heterostructures . A basic configuration can be either P-p-N or P-n-N (the capital P, N represents wide-gap materials, p, n represents narrow -gap materials). The middle layer is a narrow-gap material. (e.g. $Ga_{1-y}Al_yAs$ – GaAs - $Ga_{1-x}Al_xAs$)

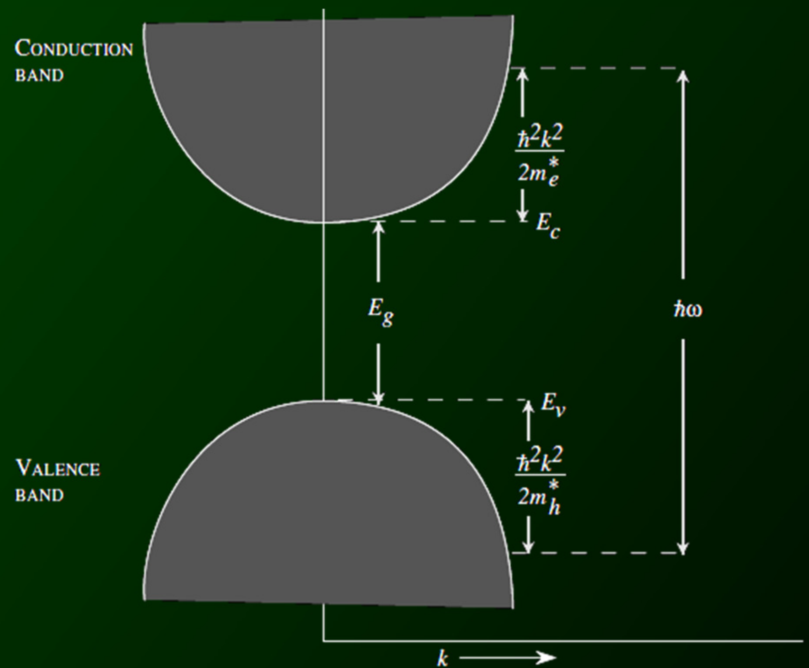
Recombination Rate



$$J = J_{parasitic} + eR_{spon}\, t_{QW}$$

$$V_{bi} = 3.4V$$

$$V_{ON} = 2.8V$$



$$\hbar\omega - E_g = \frac{\hbar^2 k^2}{2}\left[\frac{1}{m_e^*} + \frac{1}{m_h^*}\right]$$

$$W_{em} \sim 1.5 \times 10^9 \hbar\omega \;\; [eVs^{-1}]$$

$$t_0 \sim \frac{0.67}{\hbar\omega[eV]}[ns]$$

Lightly doped:

$$R_{spon} = \frac{1}{2t_0}\left(\frac{2\pi\hbar^2 m_r^*}{k_B T m_e^* m_h^*}\right)^{3/2} np \qquad \frac{R_{spon}}{n} = \frac{1}{t_r} = \frac{1}{2t_0}\left(\frac{2\pi\hbar^2 m_r^*}{k_B T m_e^* m_h^*}\right)^{3/2} p$$

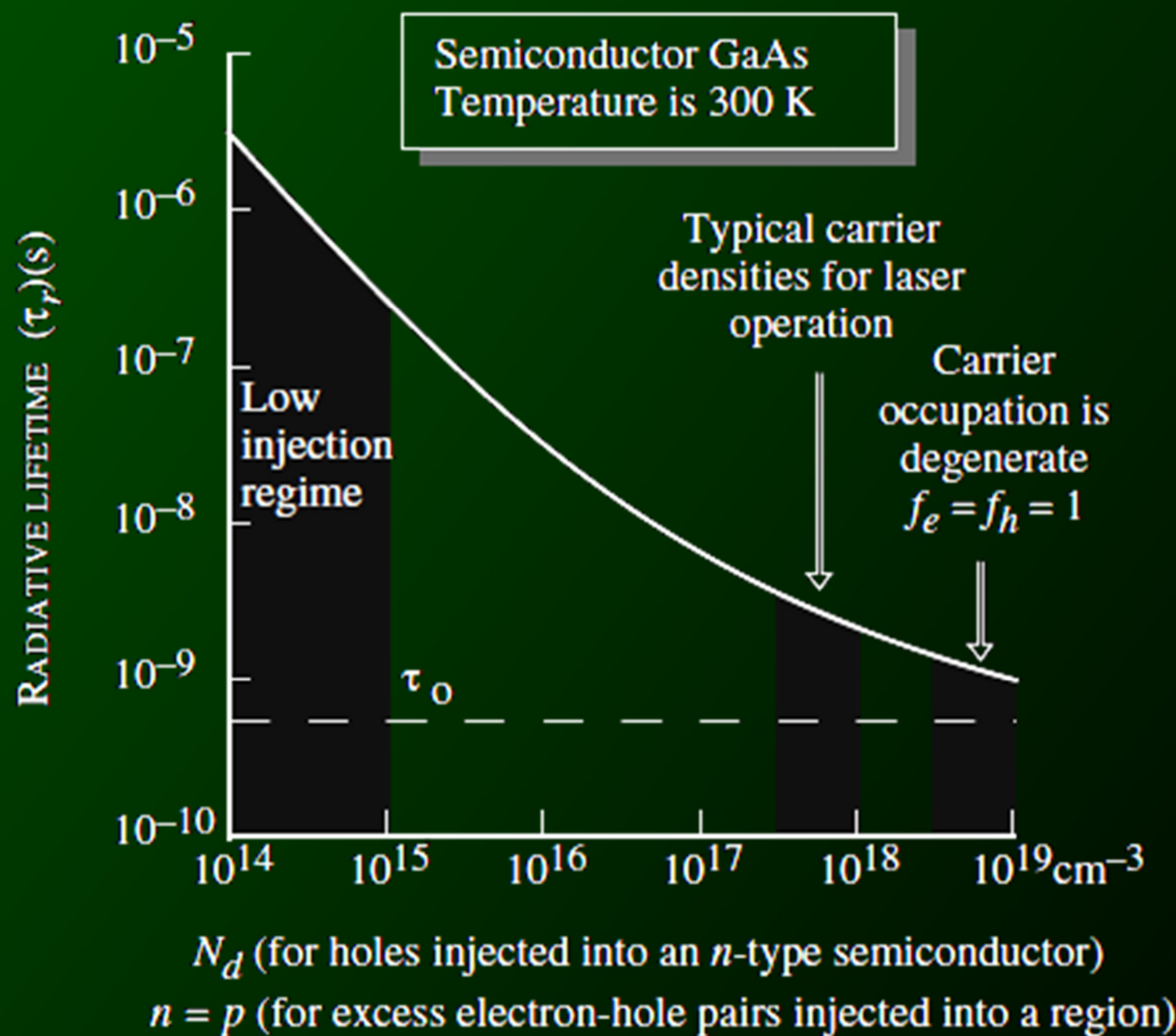
heavy doped:

$$R_{spon} \sim \frac{1}{2t_0}\left(\frac{m_r^*}{m_h^*}\right)^{3/2} n \qquad R_{spon} \sim \frac{1}{2t_0}\left(\frac{m_r^*}{m_h^*}\right)^{3/2} p$$

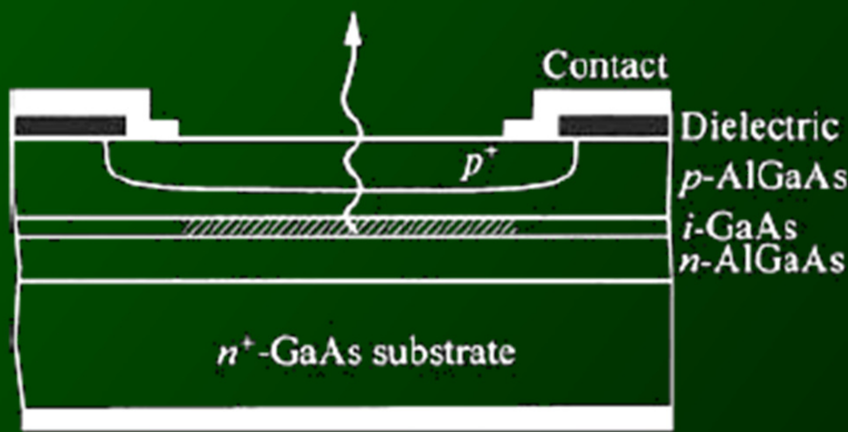
High injection

$$R_{spon} \sim \frac{n}{t_0} \sim \frac{p}{t_0}$$

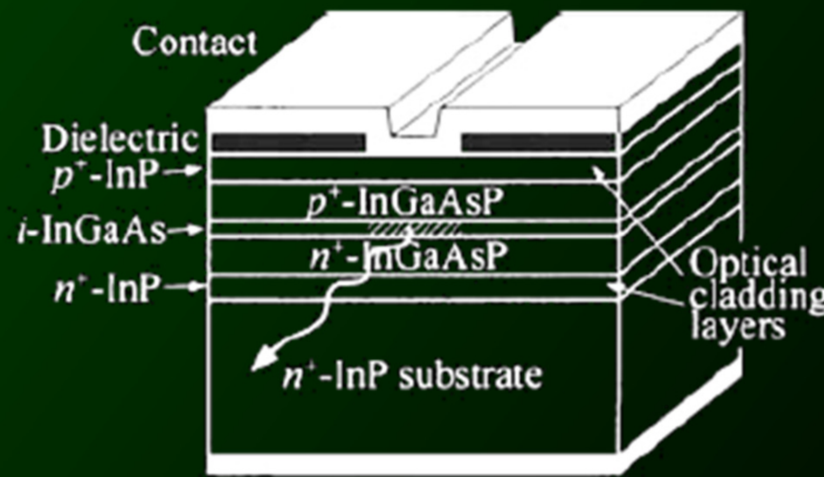
Radiative Lifetime



Direction of Emitted Light



surface emitter



edge emitter

Luminous Efficiency

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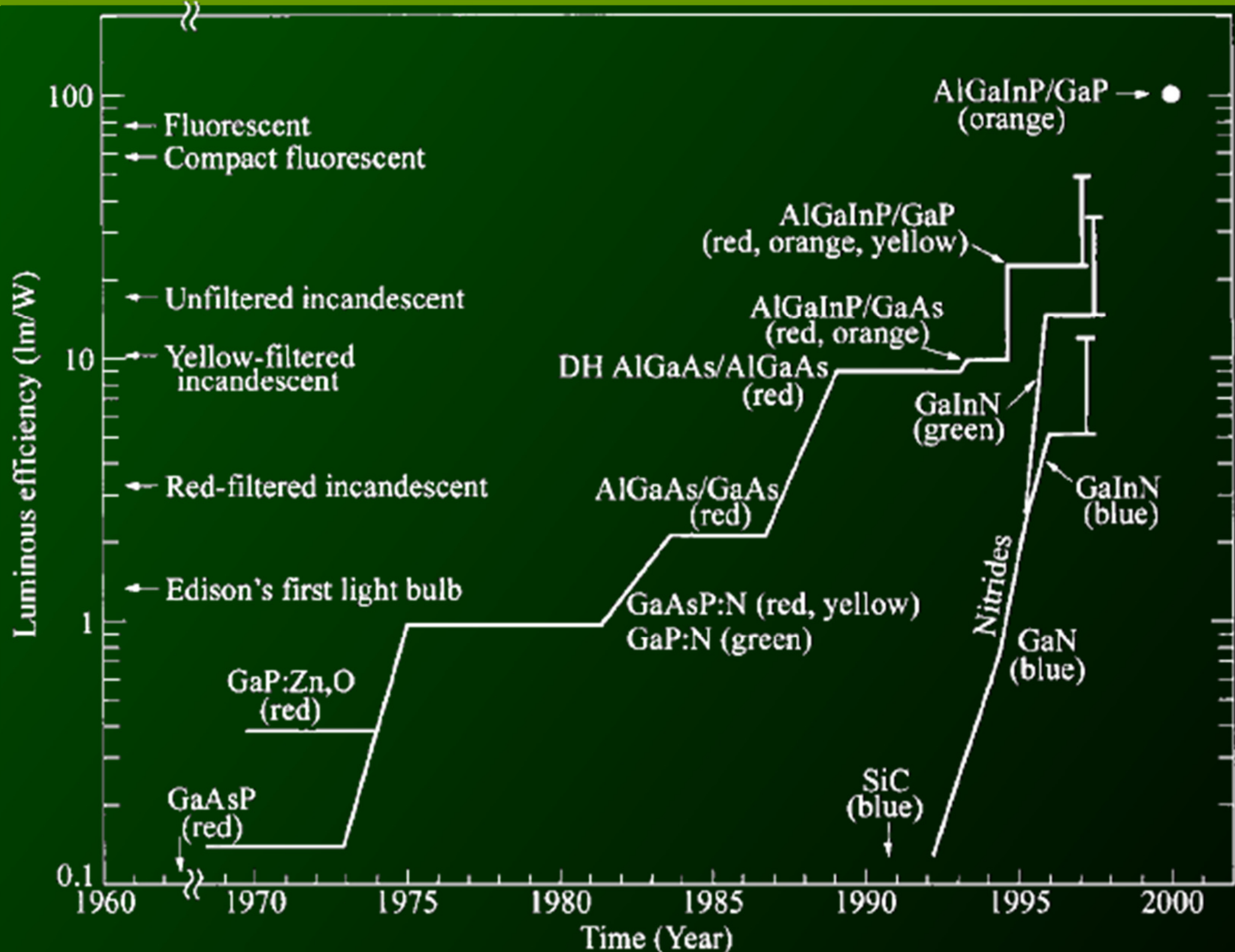

LED luminous efficiency with time

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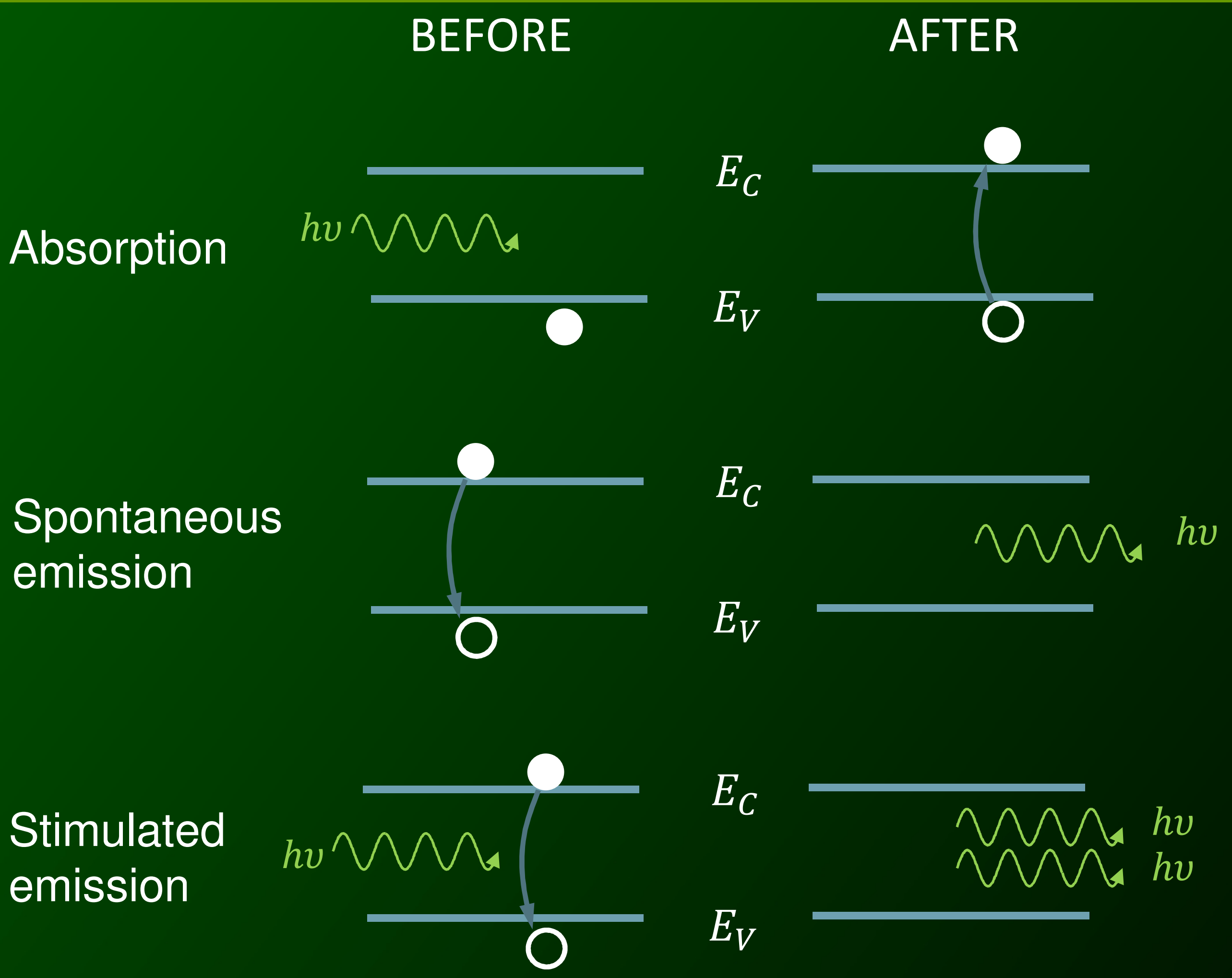
5.

3 Optical Processes



Laser

1. l □□□□□□□□
2. □□□□□□□□□□
3. □□□□□□□
4. □□□□
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Laser: "light amplification by stimulated emission of radiation"

Spatial coherence: focused to a tight spot

narrow over long distances (collimation)

narrow spectrum (high temporal coherence) (pulses of light—as short as a femtosecond)

Components of a typical laser:

1. Gain medium
2. Laser pumping energy
3. High reflector
4. Output coupler
5. Laser beam

Watch movie

Semiconductor lasers

1. Capable of emitting high powers (e.g. continuous wave ~ W).

2. A relatively directional output beam (compared with LEDs) permits high coupling efficiency (~ 50 %) into single-mode fibers.

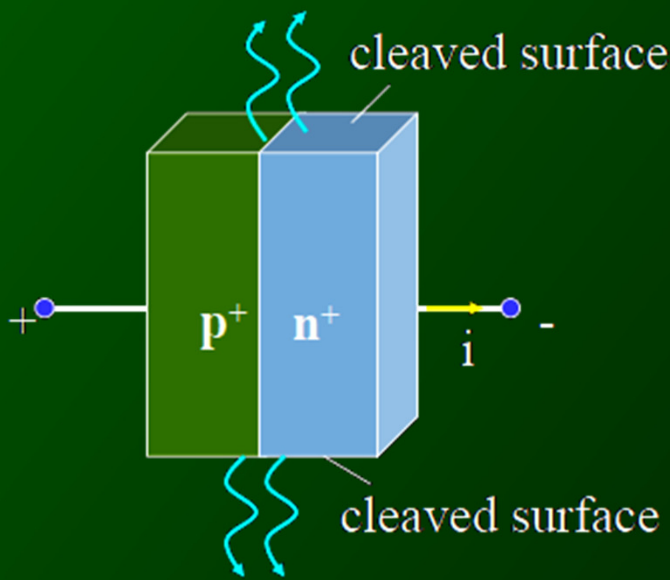
3. A relatively narrow spectral width of the emitted light allows operation at high bit rates (~ 10 Gb/s), as fiber dispersion becomes less critical for such an optical source.

laser diode:
semiconductor optical amplifier (SOA) that has an optical feedback.

SOA : Forward -biased p+-n+ junction from a direct-bandgap material

The sharp refractive index difference between the crystal (~3.5) and the surrounding air causes the cleaved surfaces to act as reflectors

Laser Diodes

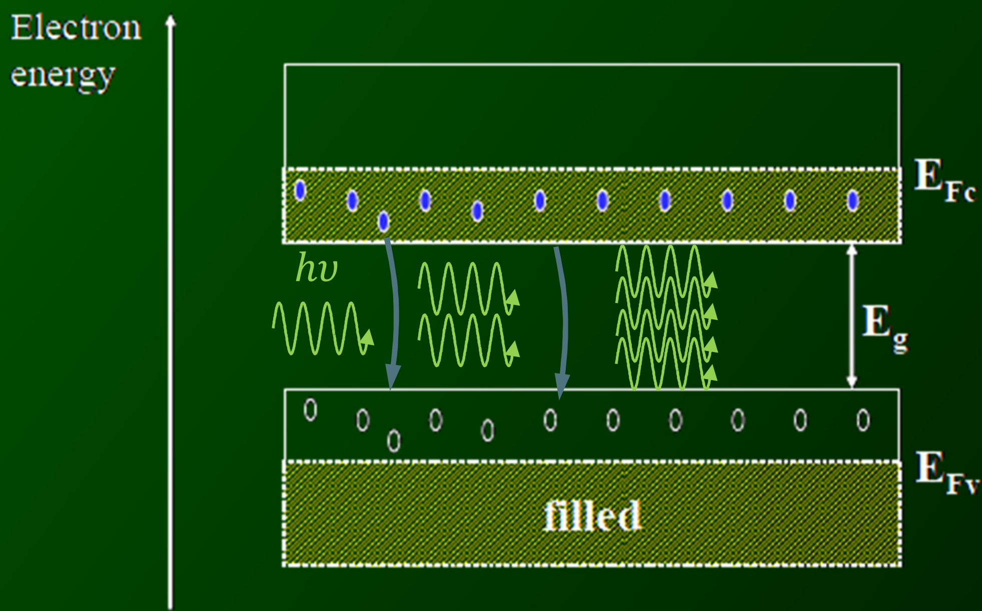


Fabry-Perot optical resonator.

gain coefficient is sufficiently large :
Amplifier + optical feedback → oscillator

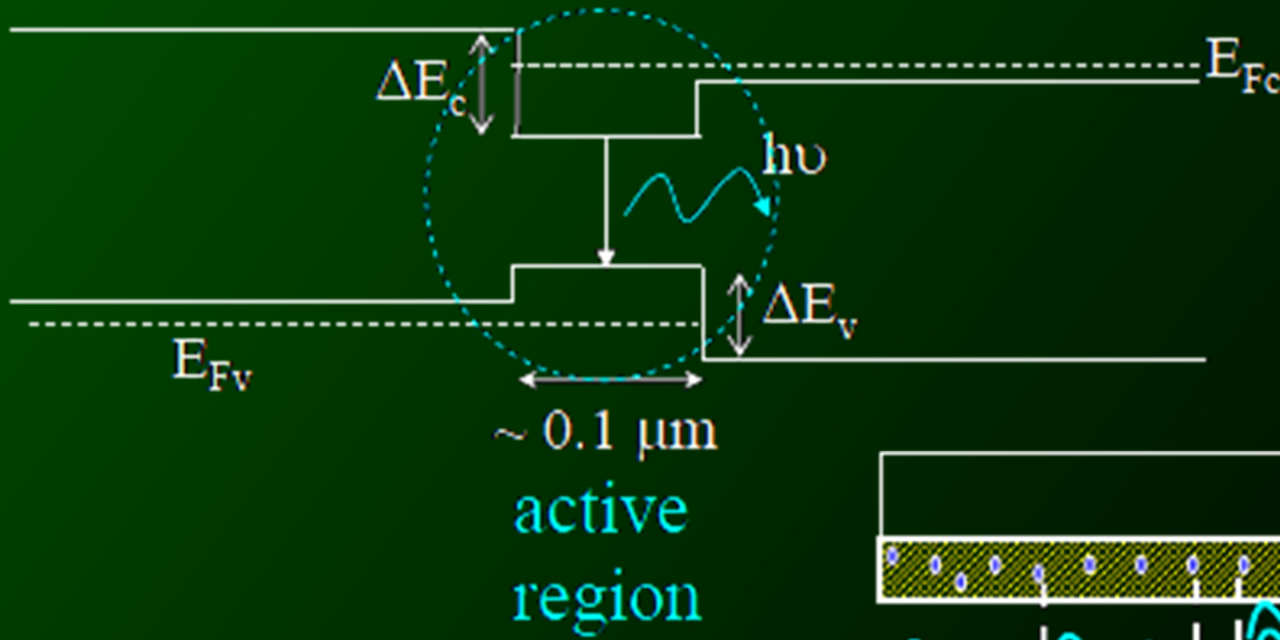
When stimulated emission is more likely than absorption
=> net optical gain (a net increase in photon flux)
=> material can serve as a coherent optical amplifier

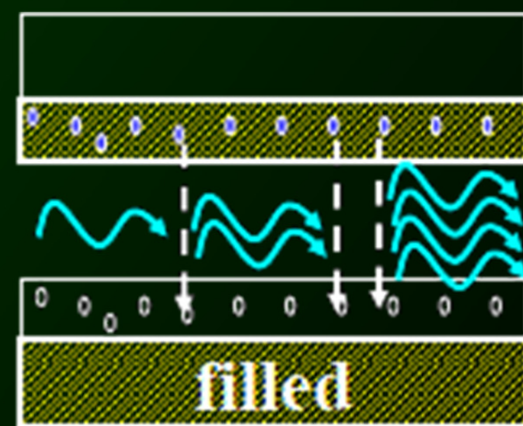
Population inversion by carrier injection



Light Amplification by stimulated emission!

Population inversion

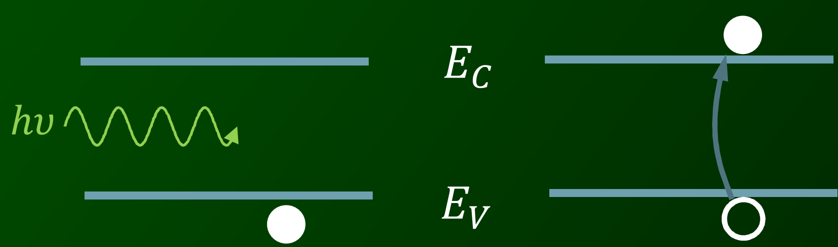




3 Optical Processes

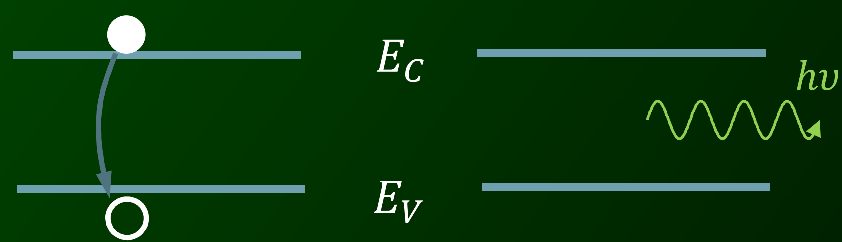
BEFORE AFTER

Absorption



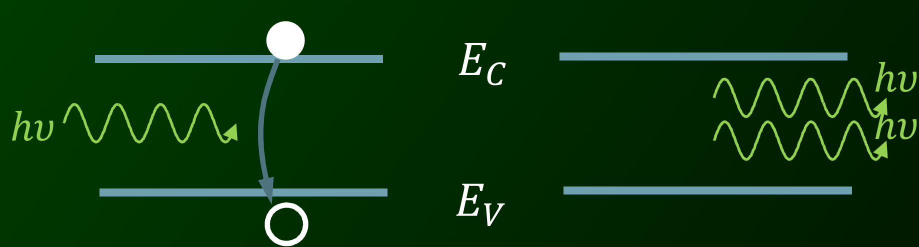
$$R_{abs} \propto \rho(hv)P_V(E_1)[1 - P_C(E_2)]$$

Spontaneous emission



$$R_{spon} \propto P_C(E_2)[1 - P_V(E_1)]$$

Stimulated emission



$$R_{stim} \propto \rho(hv)P_C(E_2)[1 - P_V(E_1)]$$

Lase Condition

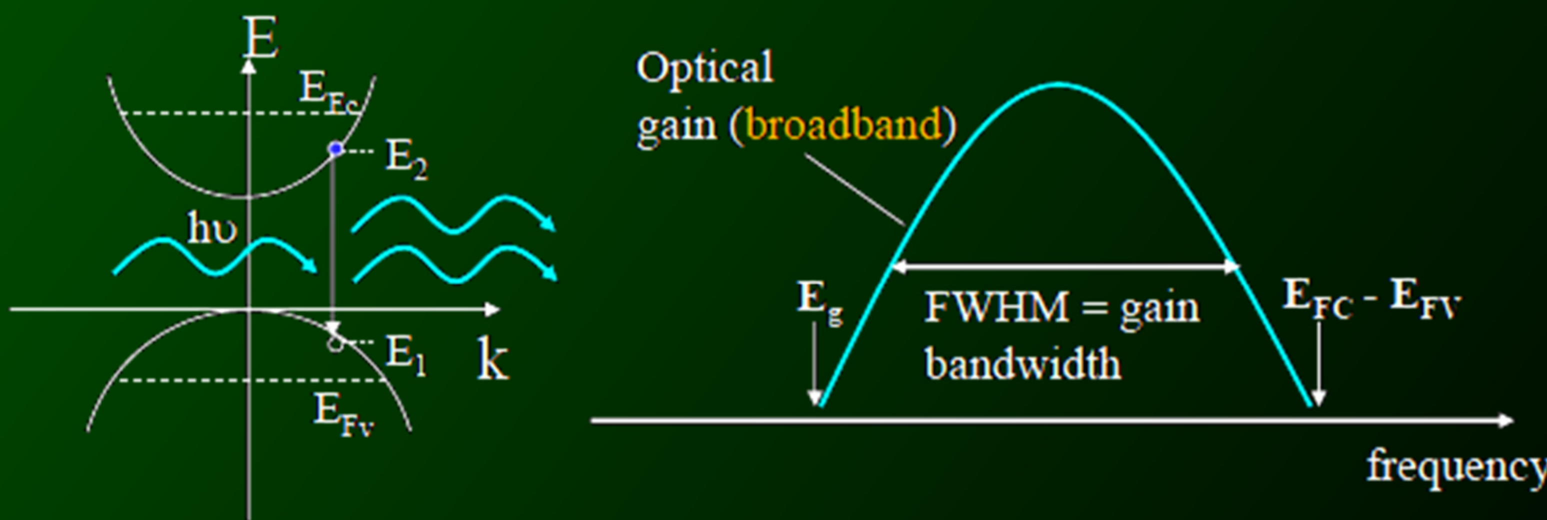
$$R_{stim} \propto \rho(hv)P_C(E_2)[1 - P_V(E_1)] > R_{abs} \propto \rho(hv)P_V(E_1)[1 - P_C(E_2)]$$

$$P_C(E_2)[1 - P_V(E_1)] > P_V(E_1)[1 - P_C(E_2)]$$

$$P_C(E_2) > P_V(E_1)$$

This defines the population inversion in a semiconductor

Optical Gain



LED and Laser Diode

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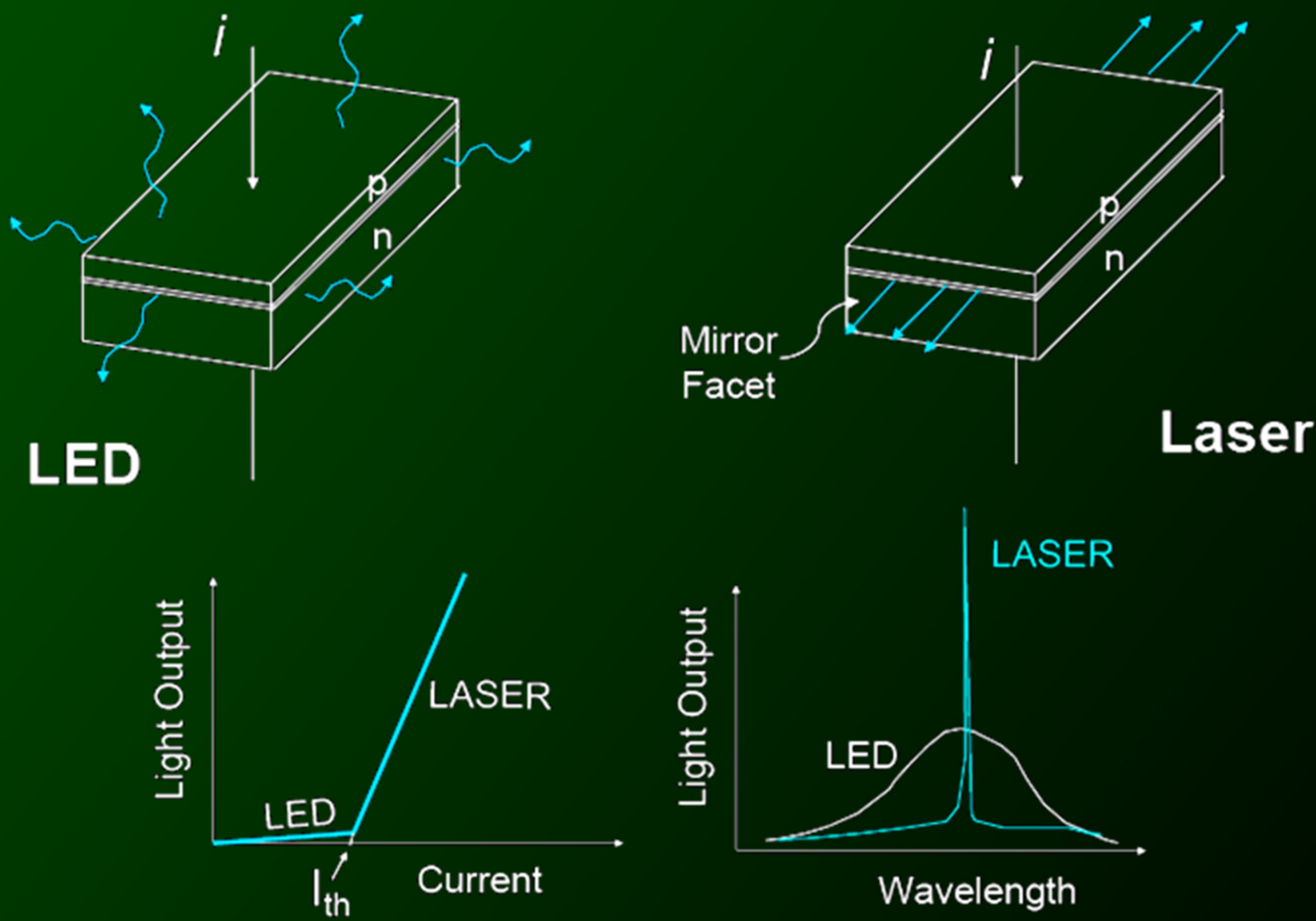

Single Frequency Laser

Single frequency lasers is desirable in the optical fiber communication system to increase the bandwidth of an optical signal.
This is because light pulses of different frequencies travel through optical fiber at different speeds thus causing pulse spread.
Dispersion mechanisms for a step-index fiber:
(1) intermodal dispersion
(2) waveguide dispersion
(3) material dispersion
Dispersion effects can be minimized by using long wavelength sources of narrow spectral width (a single frequency laser) in conjunction with single mode fibers.
Methods to achieve the single frequency lasers:

(1) Frequency Selective Feedback

External Grating, Distributed-Feedback (DFB), Distributed Bragg Reflector (DBR)

(2) Coupled Cavity

Cleaved Coupled Cavity (C3) laser