Topic 14

14 Light emitting diodes (LEDs) -1

14.1 Introduction

14.2 Basic Concepts

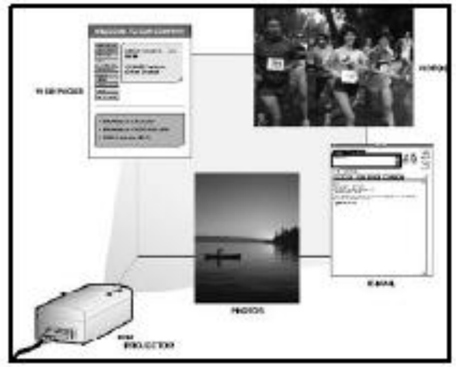
14.3 LED Structures

14.4 Characteristics of LEDs

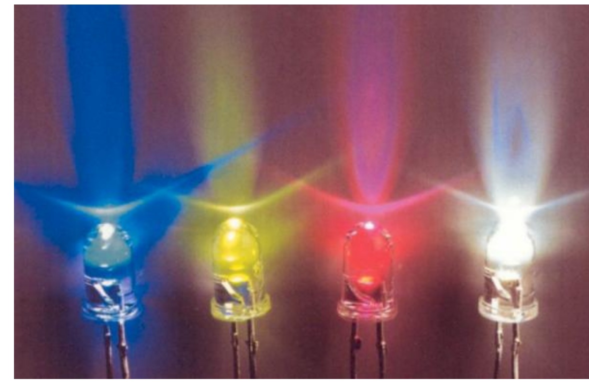
14.5 Modulation dynamics

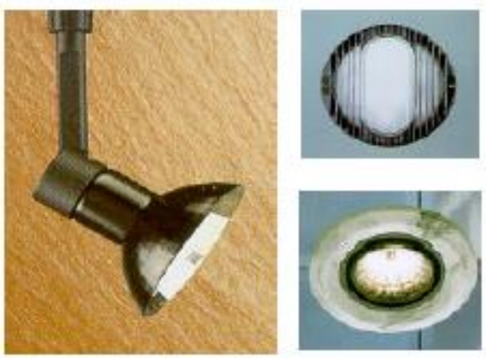
Introduction (i)

Flashlights

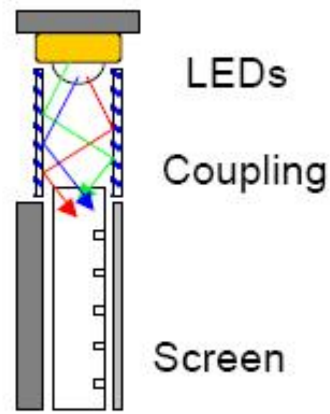


Mini Projection Displays





Accent Lighting



18” LCD monitor with LED backlight

Introduction (ii)

End Use Applications*

Motor Control	32%
Lighting	29%
Heating & Cooling	24%
Information Technology	15%

- U.S. DOE has chosen, energy efficient LED lighting to play the key role in reducing our electric light consumption by 50% by 2025
- Over the next 20 years, rapid adoption of LED lighting in the U.S. can:
  - Reduce electricity demands from lighting by 62%/year
  - Eliminate 300 million metric tons of carbon emissions/year
  - Avoid building 133 new power plants
  - Anticipate financial savings that could exceed $200 billion/year

Light Type	lm/W	CRI	CCT	Life (hrs)
White LEDs	60-130	60-90	2.5K – 6K	50k-70K
Metal halide	60-120	70 - 85	4K-6K	5k-20k
High-pressure sodium	70-140	22	2.5K	16k-24k
Low-pressure sodium	68-173	5	2500	16k-18k
Induction	60 – 80	65	5K	50K

Basic concepts (i)

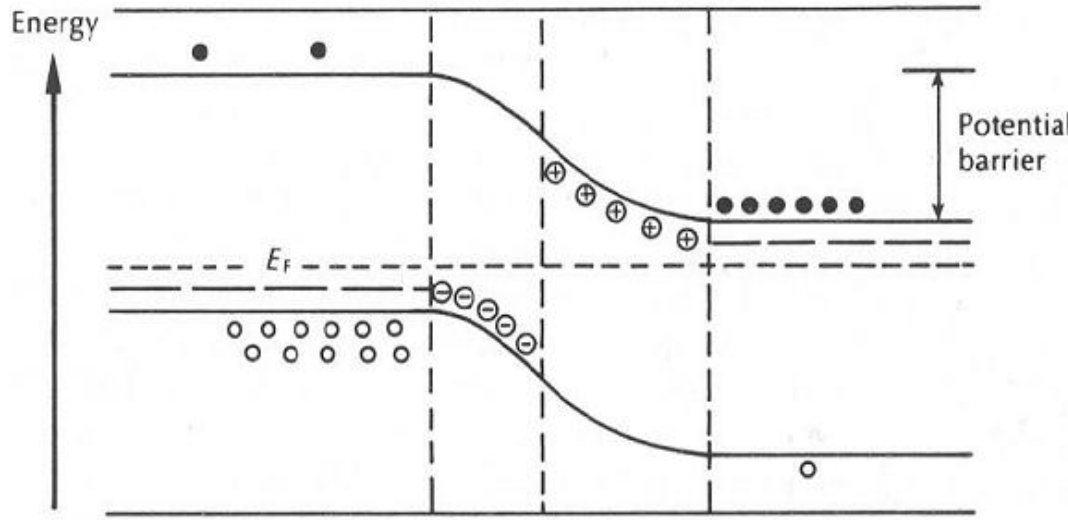
- What is LED?
  Semiconductor (inorganic semiconductor)
  p-doing, n-doping
  Fermi-level
  Depletion region
  Forward Bias
  Reverse Bias
  minority carrier
  majority carrier

- How does LED work?
  - **Recombination of minority carriers with majority carriers**

Homojunction LED

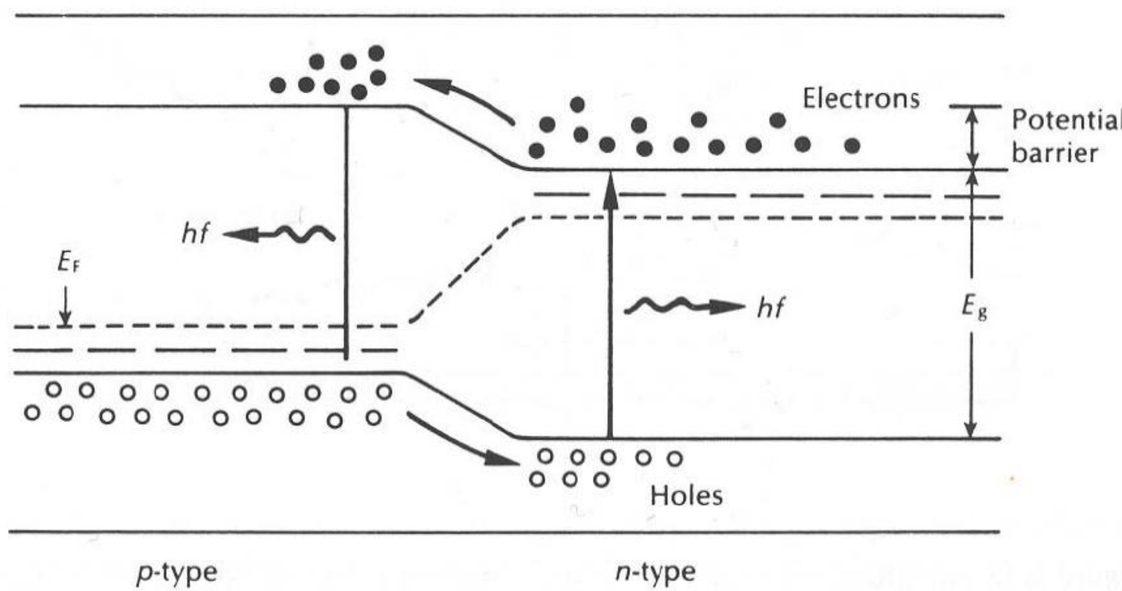
Zero biased
p-n junction

n_0, p_0= free carrier densities



Forward biased
p-n junction

Δn, Δp injected carrier densities



Review of p-n Junction

Review what we have learnt previously in p-n junction:
Excess minority charge (electrons and holes)
Contribution to currents: minority diffusion

$$\boxed{J_n(x) = q\mu_n n(x)\mathscr{E}(x) + qD_n \frac{dn(x)}{dx}}$$

Equilibrium: $V_0 = \frac{kT}{q}\ln\frac{p_p}{p_n} = \frac{\mathrm{kT}}{\mathrm{q}}\ln\frac{N_a}{n_i^2/N_d} = \frac{\mathrm{kT}}{\mathrm{q}}\ln\frac{N_aN_d}{n_i^2}$

$$\frac{p_p}{p_n} = \frac{n_n}{n_p} = e^{qV_0/kT} \quad (5\text{–}10) \qquad W = \left[\frac{2\epsilon(V_0 - V)}{q}\left(\frac{N_a + N_d}{N_aN_d}\right)\right]^{1/2} \quad (5\text{–}57)$$

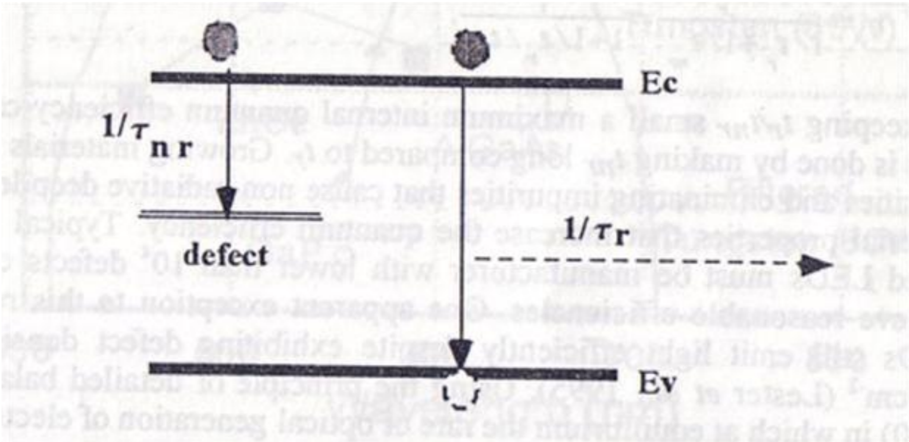
One-sided abrupt p^+-n: $x_{n0} = \frac{WN_a}{N_a + N_d} \simeq W$ (5–23) $\qquad V_0 = \frac{qN_dW^2}{2\epsilon}$

$$\Delta p_n = p(x_{n0}) - p_n = p_n(e^{qV/kT} - 1) \quad (5\text{–}29)$$

$$\delta p(x_n) = \Delta p_n e^{-x_n/L_p} = p_n(e^{qV/kT} - 1)e^{-x_n/L_p} \quad (5\text{–}31b)$$

$$\boxed{\text{Ideal diode:} \quad I = qA\left(\frac{D_p}{L_p}p_n + \frac{D_n}{L_n}n_p\right)(e^{qV/kT} - 1) = I_0(e^{qV/kT} - 1)} \quad (5\text{–}36)$$

Electron-hole recombination



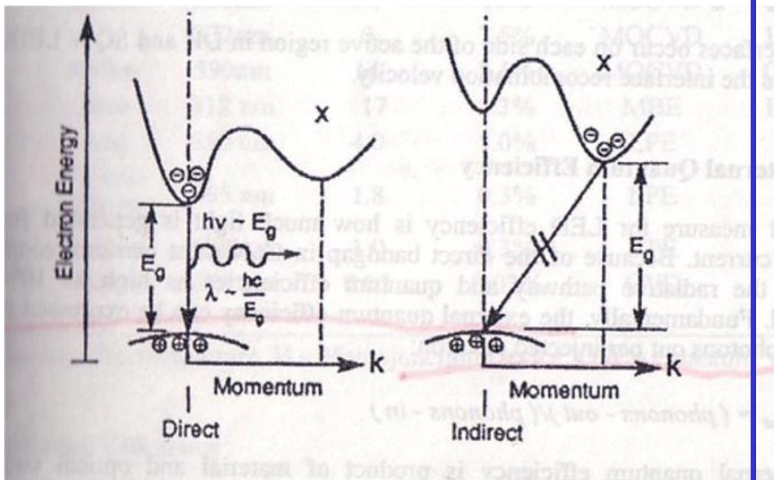
E-h recombination: radiative or non-radiative

•**Non-radiative recombination**: recombination at (i) defects; (ii) Auger recombination, etc

•**Radiative recombination** : intersubband transition, excitonic recombination, recombination through impurity center (InGaN:Zn, GaP:N)

•Very important issue: Internal quantum efficiency (IQE)

Choice of materials for LEDs

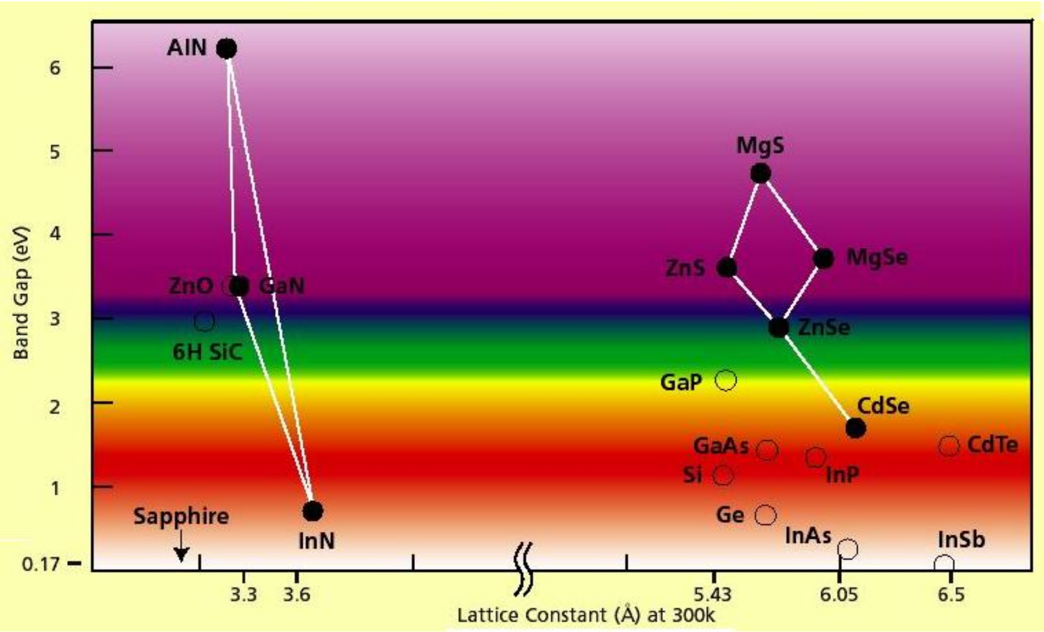


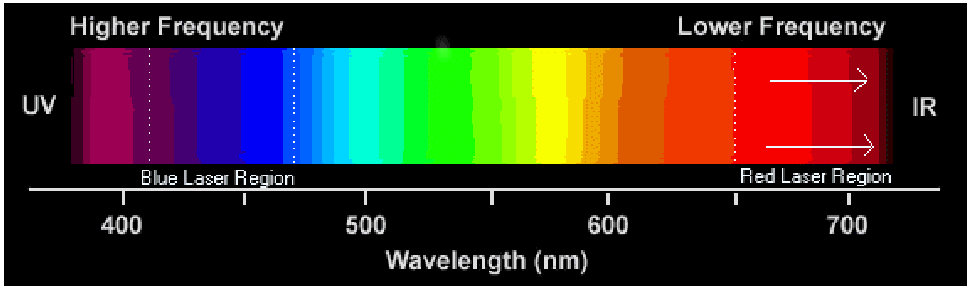
Direct bandgap:
Electrons in conduction band minima
Holes in valence band maxima
Both have the same momentum

Indirect bandgap:
Electron and hole have different momentum

Phonon is required to participate to allow the recombination **due to momentum conservation**
SiC LED : 0.02% quantum efficiency (first LED)
GaN LED: >20 % quantum efficiency

GaP, GaAs, GaP (N)





LED: Bandgap determines the emission wavelength (colour)
Band structure: direct bandgap
UV: III-nitrides, ZnO, II-VI groups
Visible: III-nitrides, GaNP, AlGaInP
Infrared: III-nitrides, InAs, InSb, InGaAs, etc

Basic parameters to describe LEDs

- How to characterise LED?

  Radiative recombination lifetime, Non-radiative recombination lifetime

  Internal quantum efficiency

  Extraction efficiency

  External quantum efficiency

Characteristics of LED performance (i)

(i) Internal quantum efficiency; (ii) Extraction efficiency; (iii) Injection efficiency; (iv) External quantum efficiency; (v) Luminous efficiency; (iii) wall plug efficiency;

IQE:

η_{int}= photons internally generated/electrons in

Extraction efficiency:

η_{ex}= photons out/photon generated

Injection efficiency:

fraction of the total diode current due to injection of electrons into p-side of junction

$$\eta_{inj} = \frac{\dfrac{D_e n_{po}}{L_e}}{\dfrac{D_e n_{po}}{L_e} + \dfrac{D_h p_{no}}{L_h}}$$

External quantum efficiency:

$\eta_{tot}= \eta_{\ inj} \bullet \eta_{\ int} \bullet \eta_{ex}$ (photons out/electrons)

Luminous efficiency:

η_{lum}= lumen out/electric power in

Characteristics of LED performance (ii)

IQE:

Ratio of radiative recombination rate to total recombination rate

Electrons in ⇨ Radiative ($\frac{\Delta n}{\tau_{rad}}$)+ non-radiative($\frac{\Delta n}{\tau_{non}}$)

photons ⇔ Radiative ($\frac{\Delta n}{\tau_{rad}}$)

$$\eta = \frac{\dfrac{\Delta n}{\tau_{rad}}}{\dfrac{\Delta n}{\tau_{rad}} + \dfrac{\Delta n}{\tau_{non}}} = \frac{\dfrac{1}{\tau_{rad}}}{\dfrac{1}{\tau_{rad}} + \dfrac{1}{\tau_{non}}}$$

Characteristics of LED performance (iii)

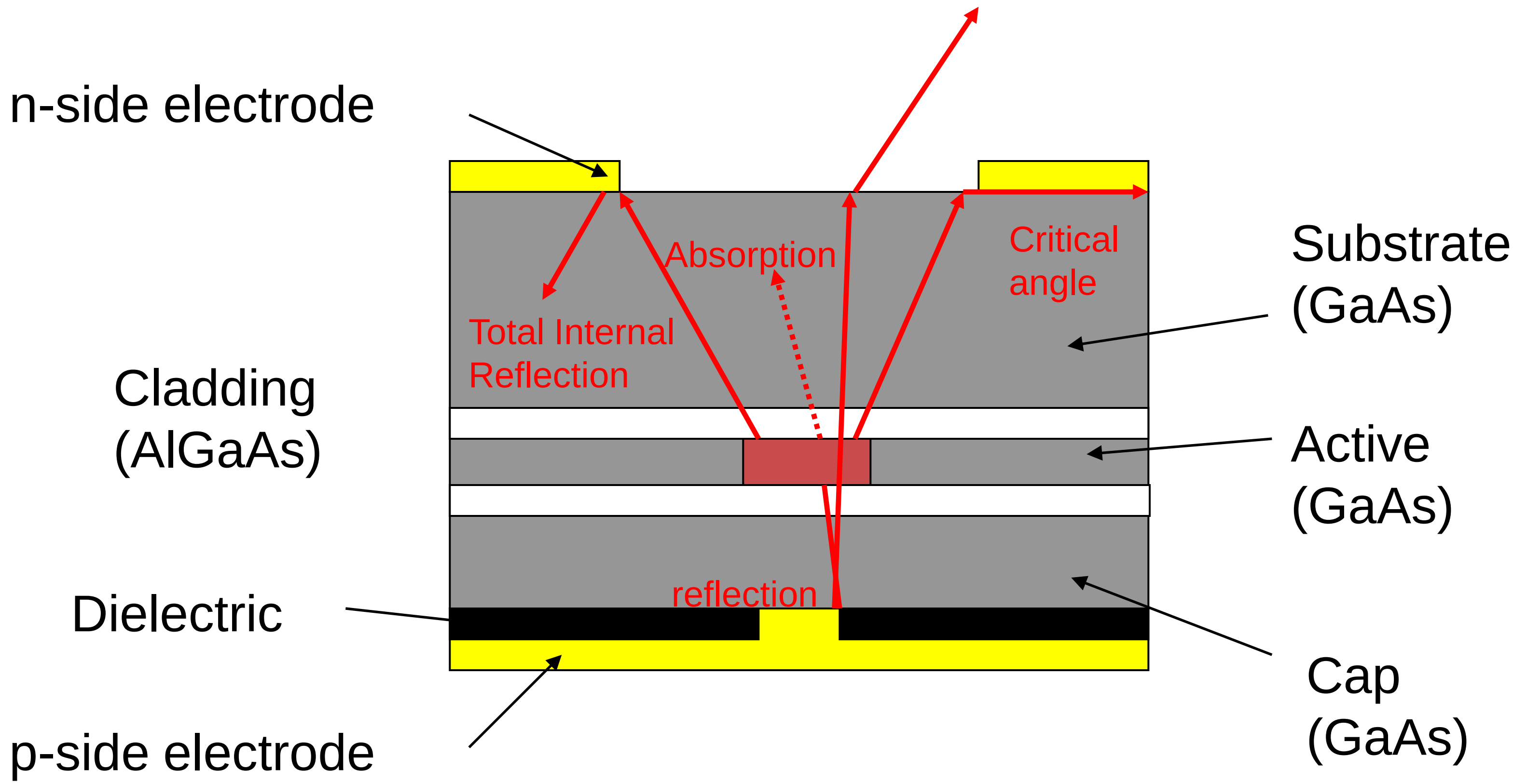
$$\eta = \frac{\frac{1}{\tau_{rad}}}{\frac{1}{\tau_{rad}} + \frac{1}{\tau_{non}}} = \frac{1}{1 + \frac{\tau_{rad}}{\tau_{non}}}$$

Make τ_{non} long compared to τ_{rad}:
Growing materials with low defect densities
Eliminating non-radiative impurities

To achieve reasonable IQE: GaP and GaAs-based LED
Defect density $<10^4/cm^2$

However: GaN-based LED with high IQE
defect density $> 10^8/cm^2$

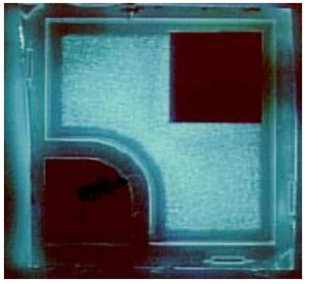
Optical Output Power



Typical external efficiencies of ~1-5%

Extraction efficiency (η_{ext})

Several factors determine η_{ext}:



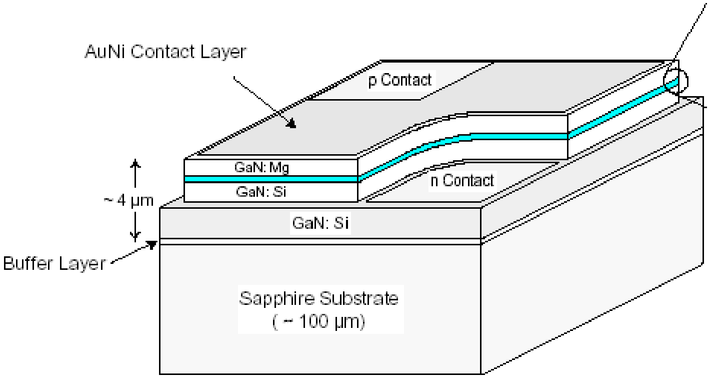
1. Absorption: $I=I_0 \exp(-\alpha d)$

•Homojunction LED:

d decreases, surface states destroy IQE

d increases, absorption is enhanced

•DH-LED: absorption will be significantly reduced



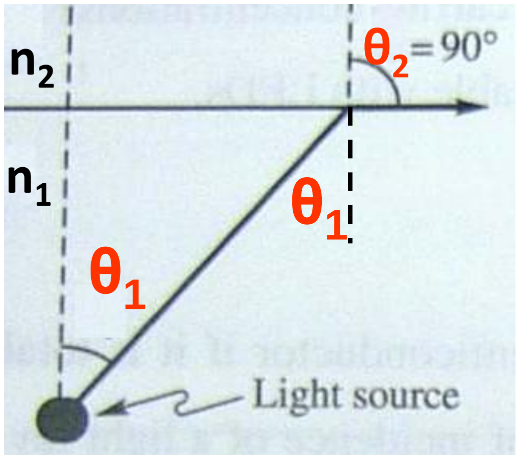
2. Substrate absorption

3. Transmission losses

4. Reflection at top contact

5. Absorption from top-contact

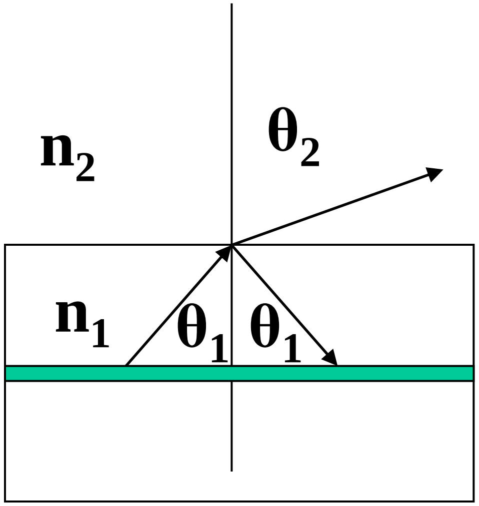
Transmission losses (i)



When light passes through from one material with n_1 to another one with n_2. The angle will be changed, and obeys: $n_1 \sin\theta_1 = n_2 \sin\theta_2$

When $n_1 > n_2$, $\theta_2 > \theta_1$. At a critical angle of θ_1(θ_c) , $\theta_2 = 90^0$

$$\theta_c = \sin^{-1}\left(\frac{n_2}{n_1}\right)$$



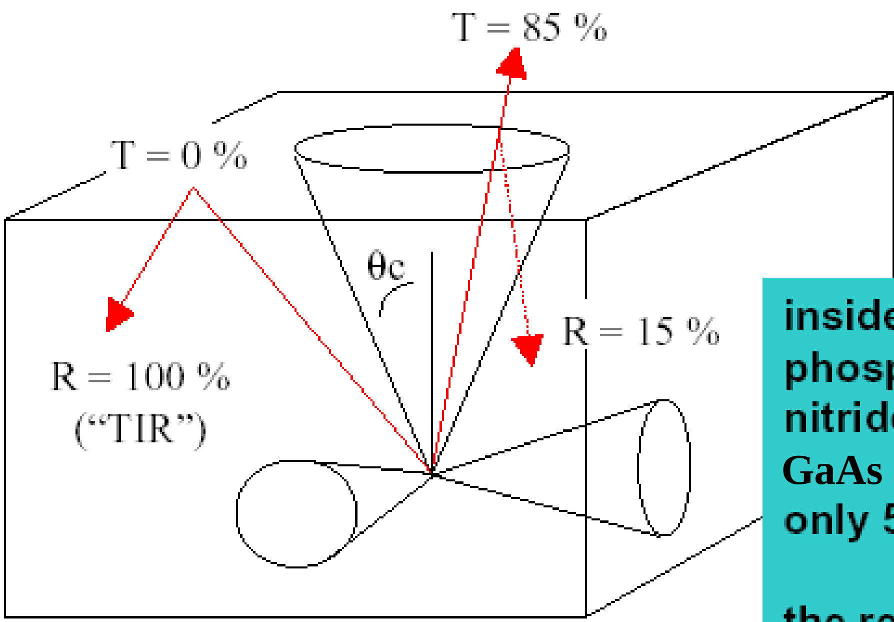
- $\theta_1 > \theta_c$: total internal reflection will take place
- $\theta_1 < \theta_c$: there is still loss of light due to reflection

For normal incident, i.e., $\theta_1 = 0^0$

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

$$T = 1 - \left(\frac{n_2 - n_1}{n_2 + n_1}\right)^2$$

Transmission losses (ii)



outside
n = 1.5 (polymers, epoxy ….)

inside
phosphides: n ≈ 3.3
nitrides: n ≈ 2.4
GaAs (0.8um): n=3.45
only 5 .. 10 % get through any plane surface,
the rest is internally reflected and bounces around until finally absorbed by free carriers, contacts, absorbing substrates, etc.

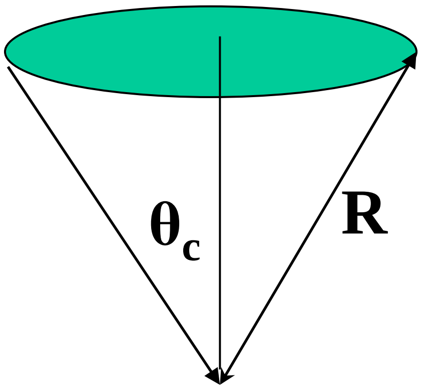
so, h_{ext} = 5% ???

Only emitted light with a cone of $2\theta_c$ can be extracted

Extraction efficiency

Assume the emitted light is constant in all directions, we can calculate how much the emitted light can be extracted, i.e., **Extraction efficiency.**

The distance from the original emitted point to the surface is R



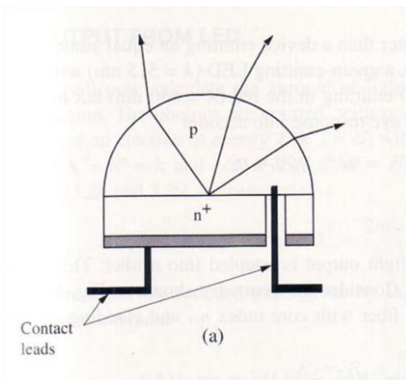
$$F = \frac{\pi (R\sin(\theta_c))^2}{4\pi R^2} = \frac{\sin^2(\theta_c)}{4} = \frac{(\frac{n_2}{n_1})^2}{4}$$

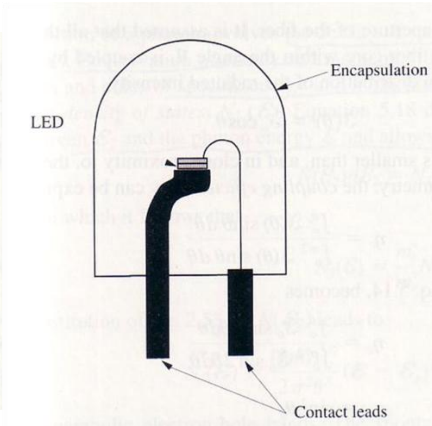
- **Extraction efficiency**

$$I = FT = \frac{1}{4}(\frac{n_2}{n_1})^2\left[(1-(\frac{n_1-n_2}{n_1+n_2})^2)\right]$$

For example: GaAs: n_1=3.45,
only 1.5% generated light can be extracted!!!

Solution to improve extraction efficiency (i)





$$I = FT = \frac{1}{4}\left(\frac{n_2}{n_1}\right)^2\left[\left(1-\left(\frac{n_1-n_2}{n_1+n_2}\right)^2\right)\right]$$

- **Polish the LED and make its surface as a hemisphere to avoid θ_c issue**

- **Depositing a material with an intermediate refractive index**

  n_2 increases, transmission increases

- **Depositing a layer which is an anti-reflection coating to make R $\rightarrow$ 0**

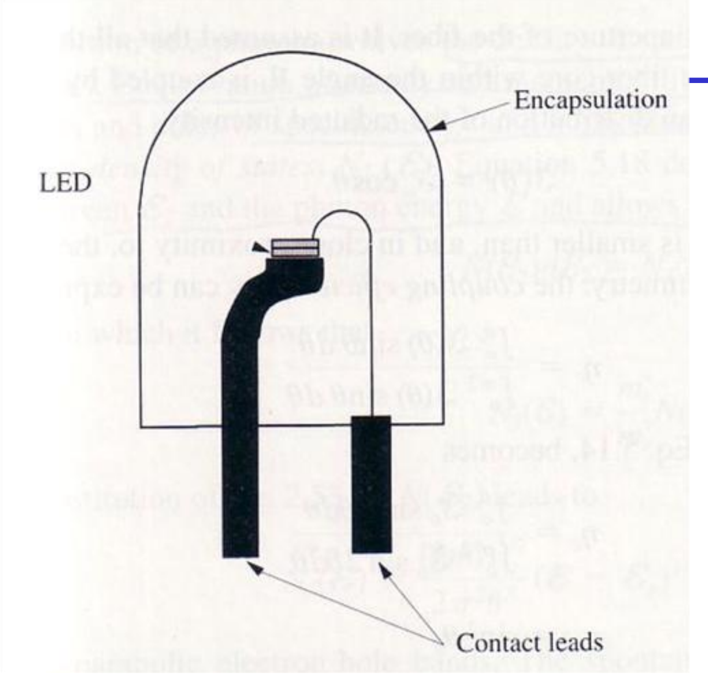
$$d = \frac{\lambda}{4n}(2L-1)$$

Solution to improve extraction efficiency (ii)

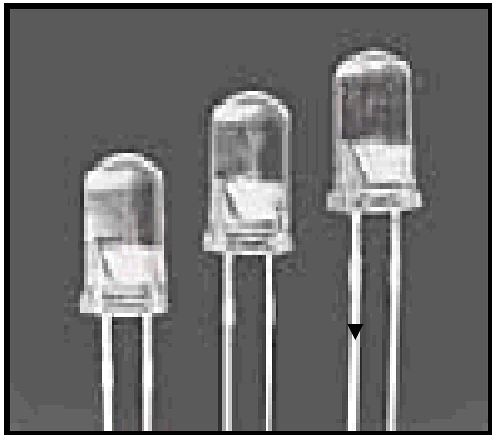
Combination of above the three methods

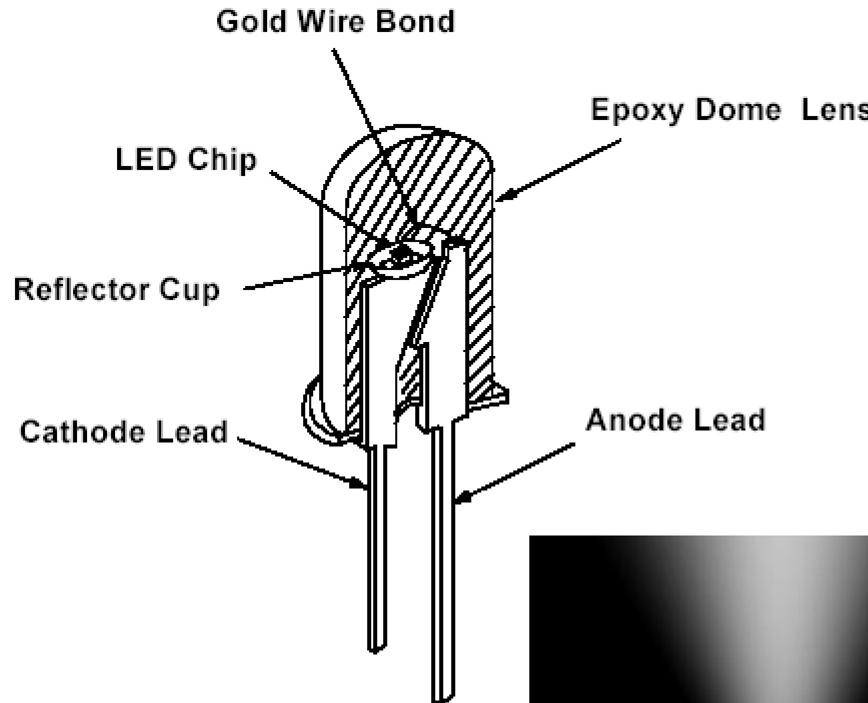
- **Make the intermediate layer shaped as a hemisphere to avoid θc issue, and then coat an anti-reflection layer to maximise efficiency**

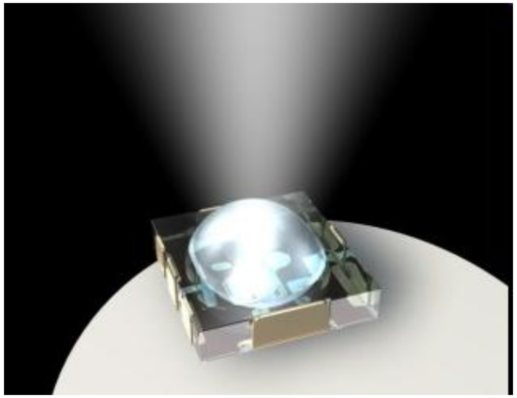
- **The method of using a hemispheric intermediate layer using epoxy has been generally used in the LED industry.**



Commercial LEDs

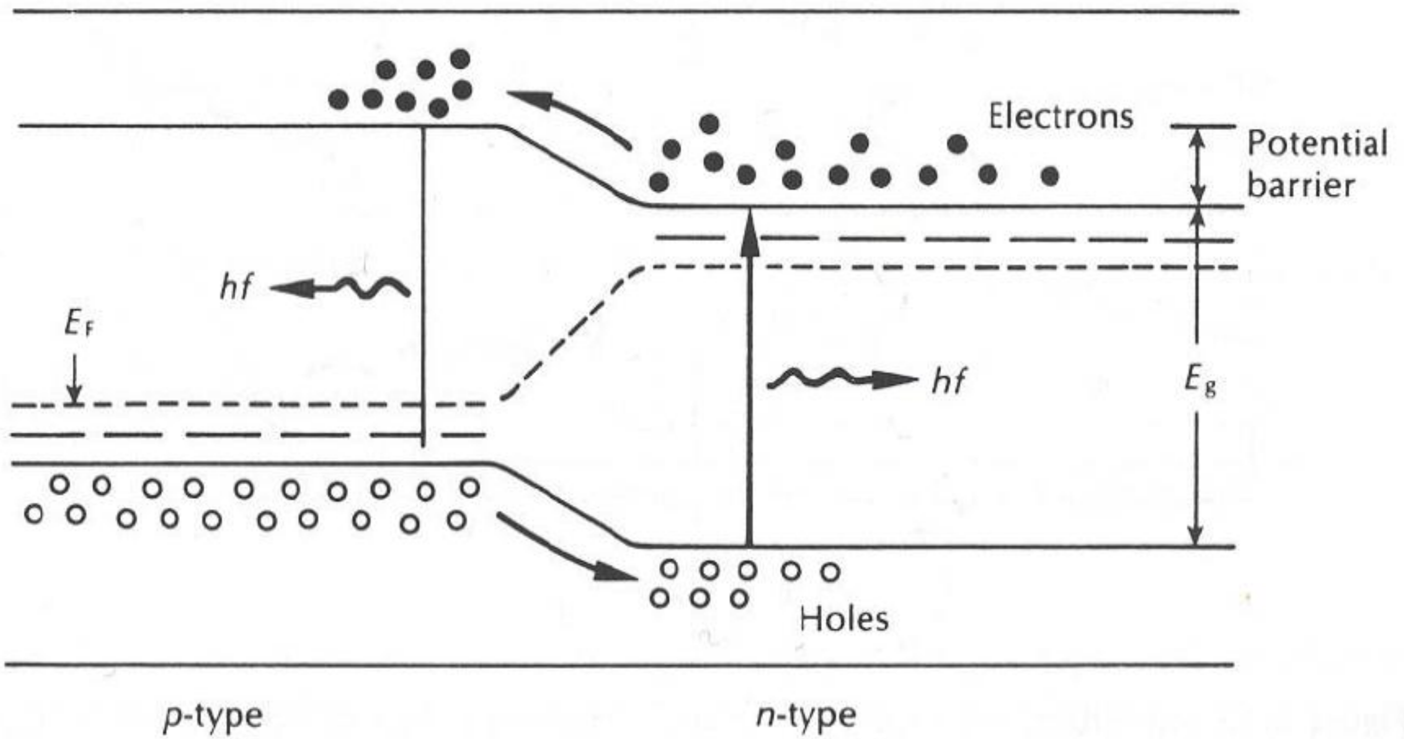






General use in the opto-electronics industry

LED Modulation (i)



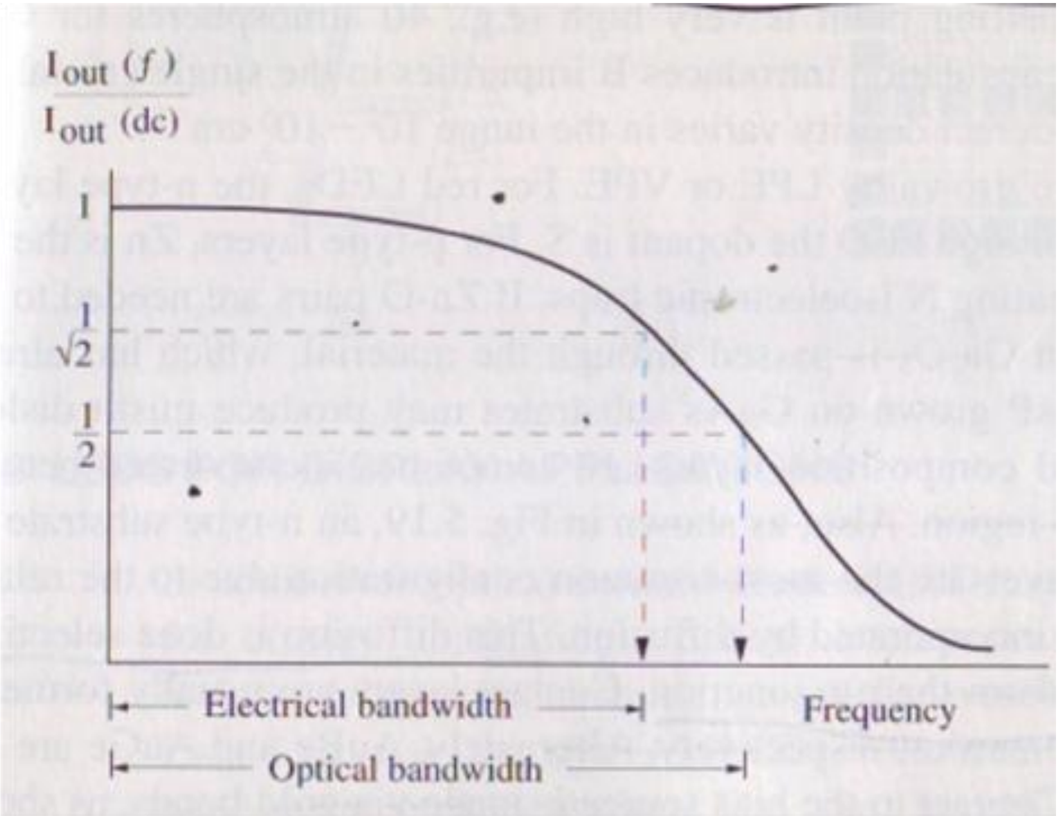
Forward Bias

Continuity equation:

$$\frac{d\Delta n}{dt} = \frac{J}{qd} - \frac{\Delta n}{\tau}$$

J = injected current density
q = electron charge
τ= recombination lifetime

LED Modulation (ii)



τ:
recombination lifetime –
$f_m \sim \frac{1}{2\pi\tau}$

The ultimate limit to modulation bandwidth ~ns

I_{out}: detector current

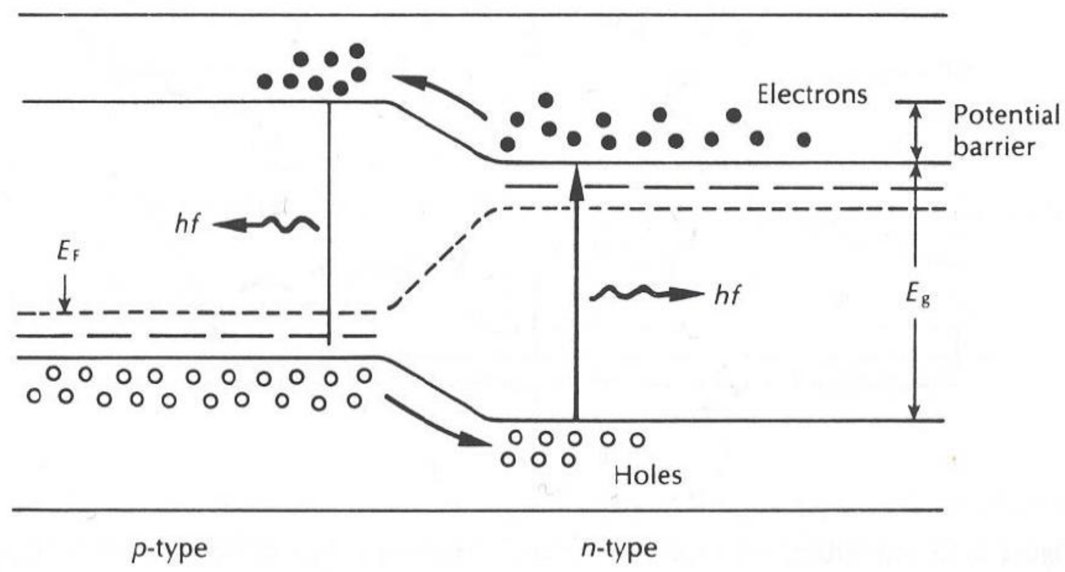
Optical bandwidth: $[\frac{I_{out}(f)}{I_{out}(dc)}]^2 = 1/2$

Electrical bandwidth: $\frac{I_{out}(f)}{I_{out}(dc)} = \sqrt{\frac{1}{2}}$

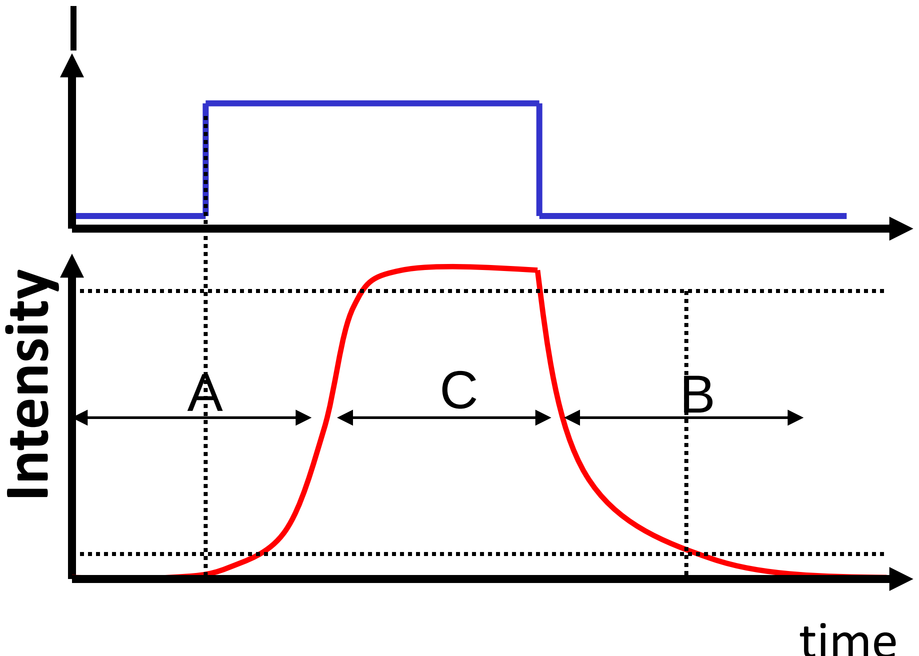
LED Modulation (iii)

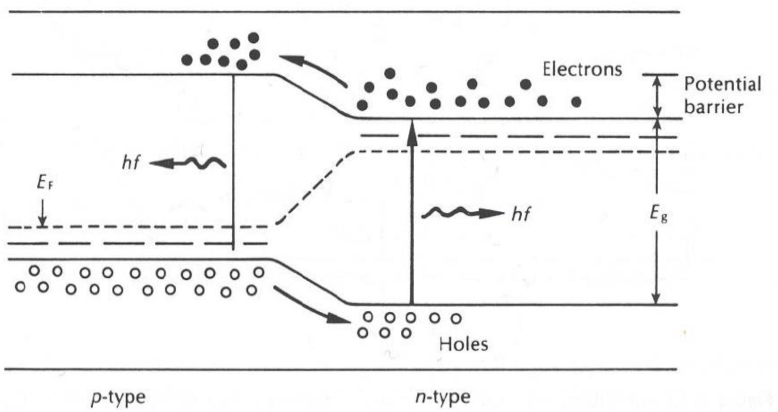
Limits:

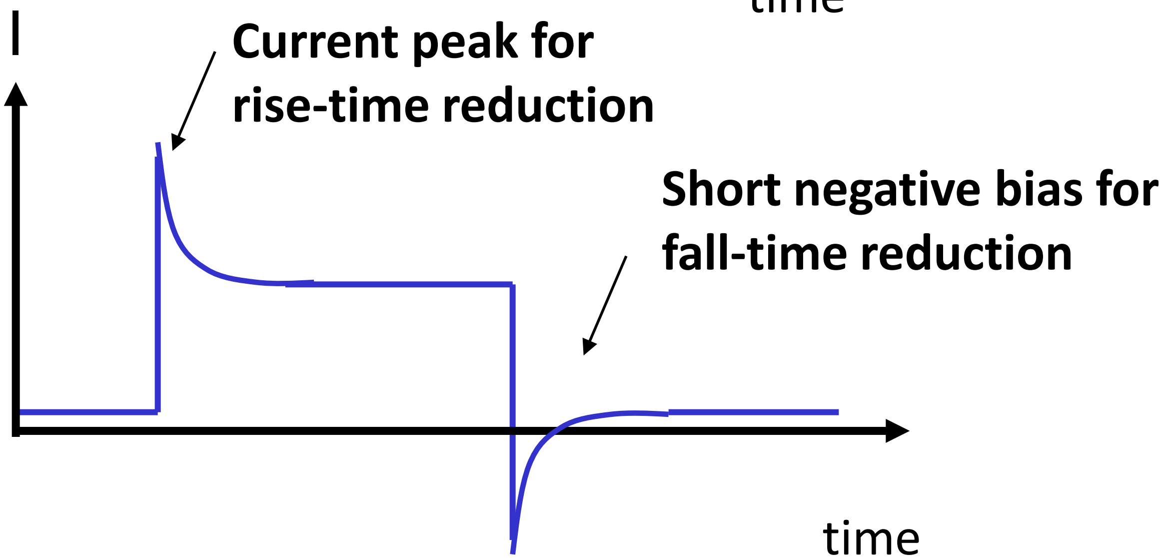
- LED structure is similar to a capacitor
- changing J instantaneously – RC time constant of device
  - junction capacitance
- Maximum frequency for a capacitor should be less than 1/RC



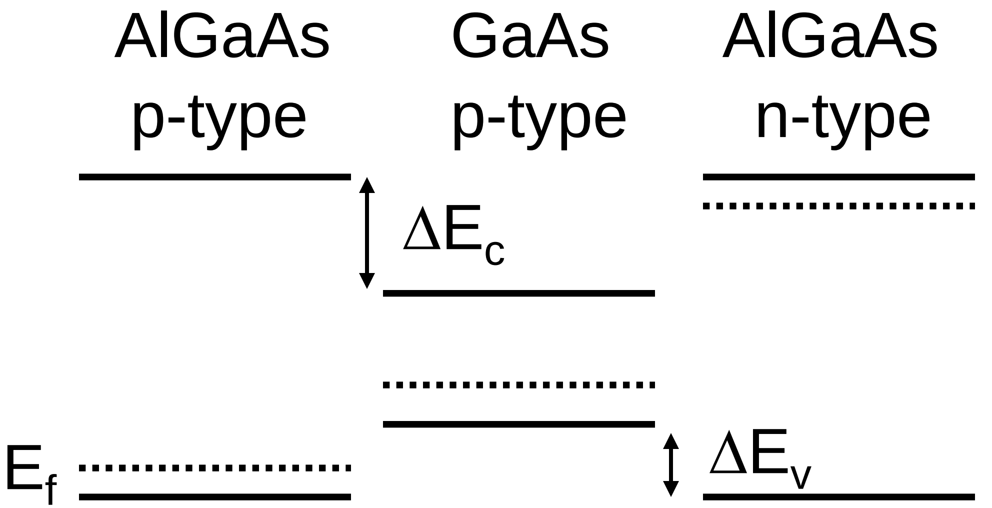
LED Modulation (iv) – Current Peaking



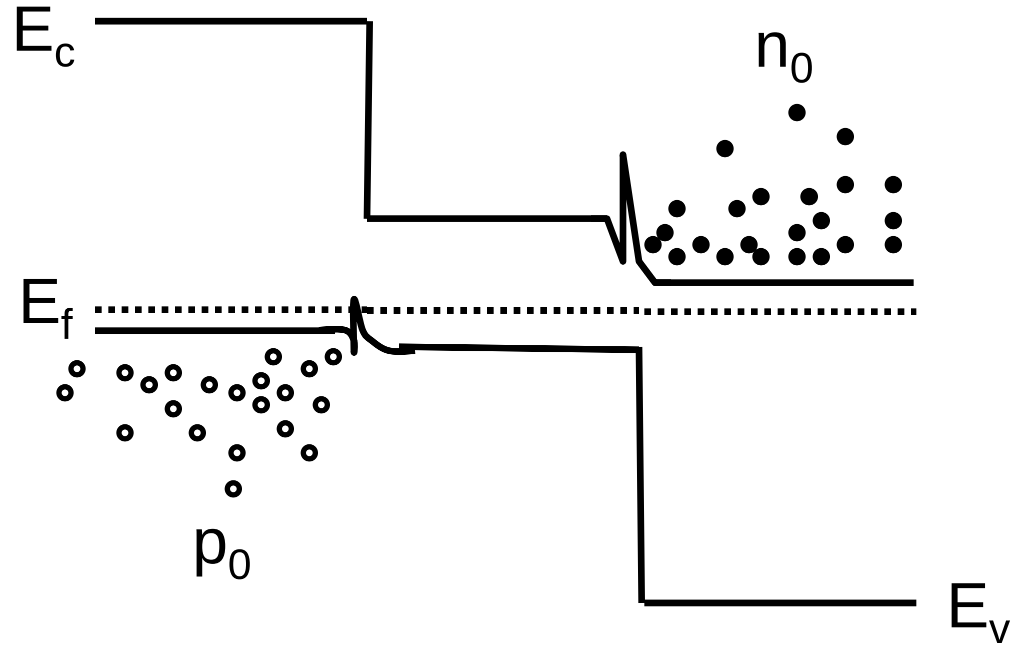




Double Heterostructure LED (i)

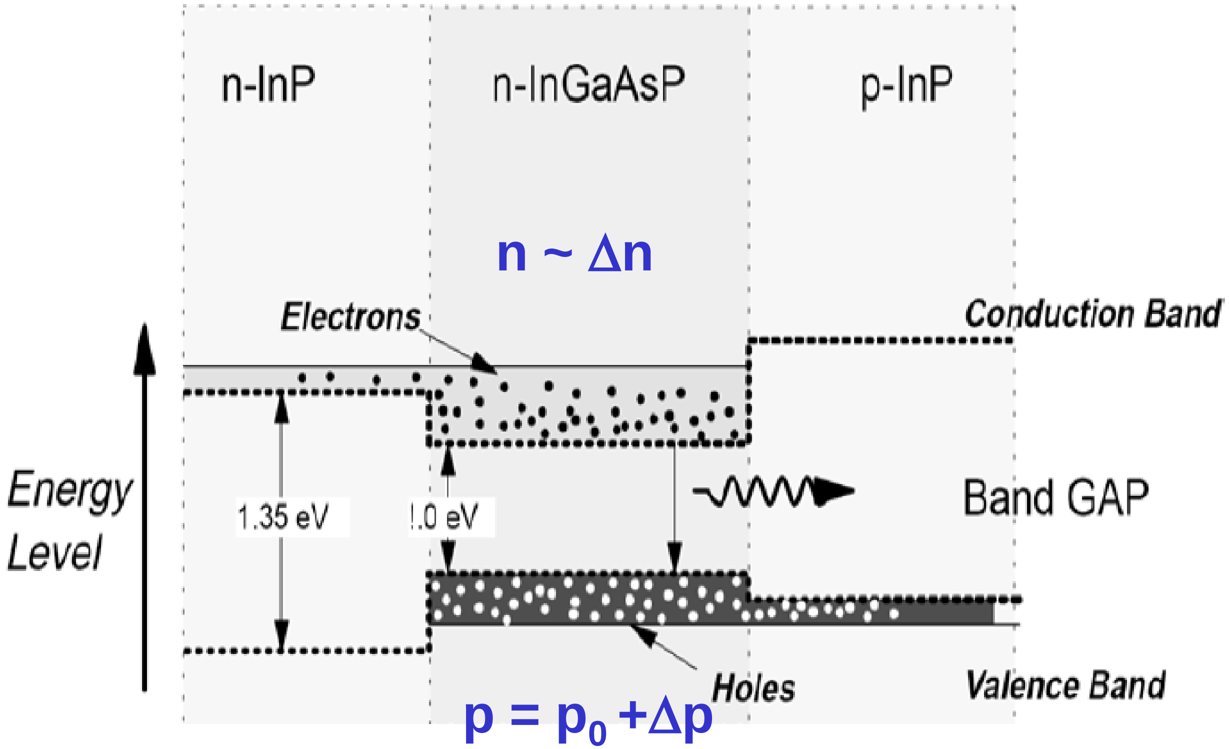


Band line-up and Fermi Levels



Equalize Fermi Levels – Thermal Equilibrium

Double Heterostructure LED (ii)



•DH LED: a layer with a lower bandgap material sandwiched between two layers with higher bandgaps.

•DH LED: consists of two heterojunctions.

•Recombination of carriers: restricted to the low bandgap region, i.e., „the active region“ of the diode.

Summary – LED (i)

- Diode formed of p and n doped semiconductors
- In forward bias electrons and holes occupy the same region of the LED
- Light emission via spontaneous recombination
- ~ns carrier lifetime of carriers for highly pure semiconductors
- The "i" region is often lightly p-doped to reduce lifetime of electrons – increasing internal efficiency
- Light emitted at a range of wavelengths (governed by band-gap and temperature) in all possible directions
- Due to reflection at semiconductor/air interface, external efficiency of an LED is low (hence low launch power)

Summary - LED (ii)

- Modulation rate is governed by the carrier lifetime
- Can be engineered by clever biasing arrangement (expensive) or introduction of non-radiative defects, decreasing carrier lifetime but reducing internal efficiency – and hence launch power

Tutorial Questions

T 14.1 Draw and label an InP based LED operating at 1.55 μm. Indicate materials, doping, and the direction from which light is collected.

T14.2 Sketch the band structure for the diode drawn in T14.1 under zero bias and at the operating voltage.

T14.4 Describe the limits to the modulation speed of an LED.