OPTOELCTRONIC DEVICES

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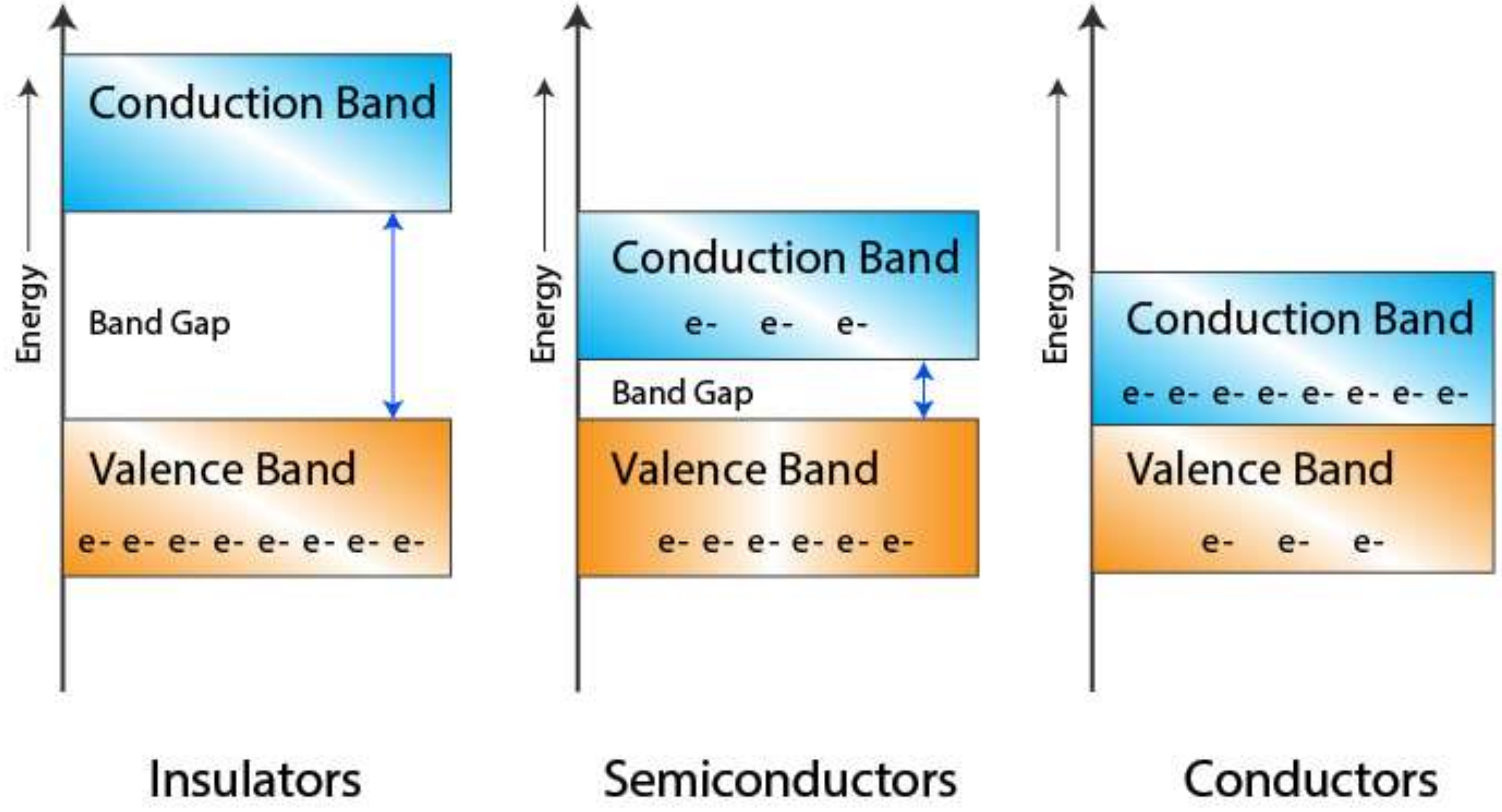
SYLLABUS

Syllabus:

Introduction to semiconductors- PN Junction- Direct and Indirect band gap semiconductors- LED and Laser diode- Photodetectors- PN and PIN

INTRODUCTION TO SEMICONDUCTORS



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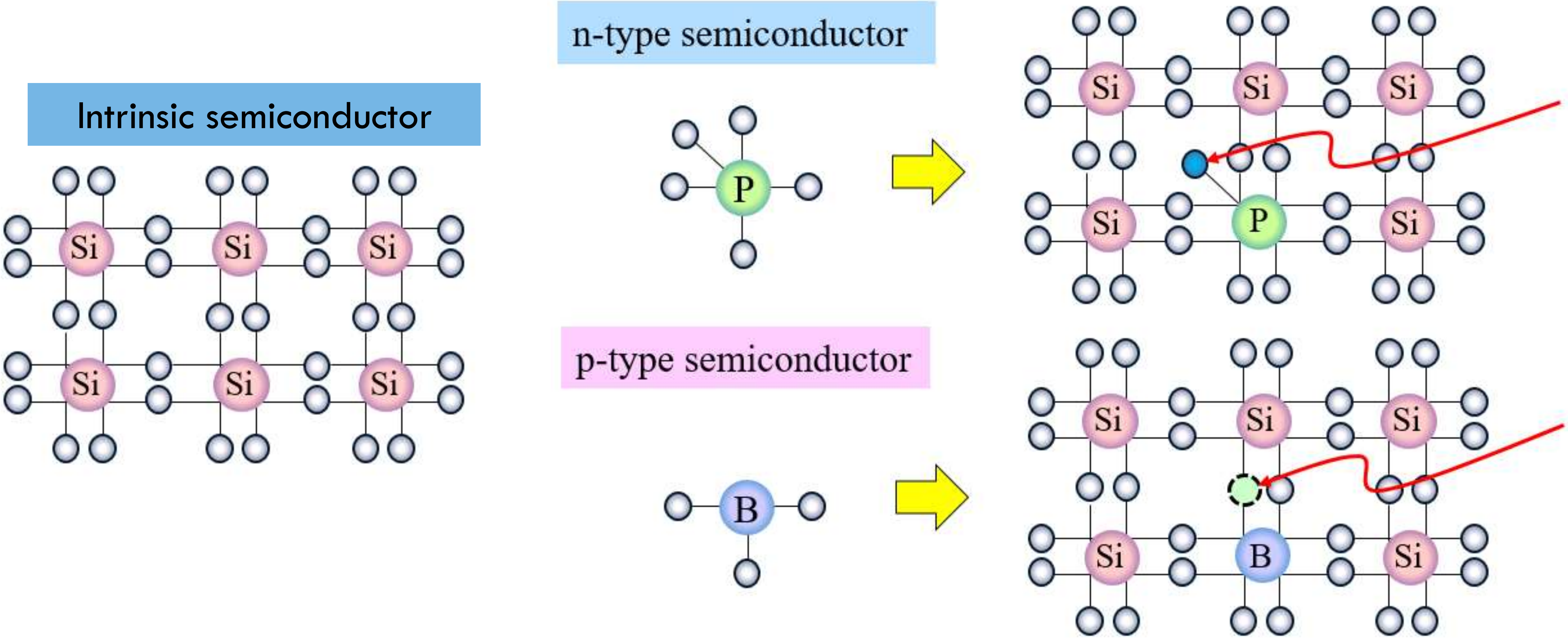
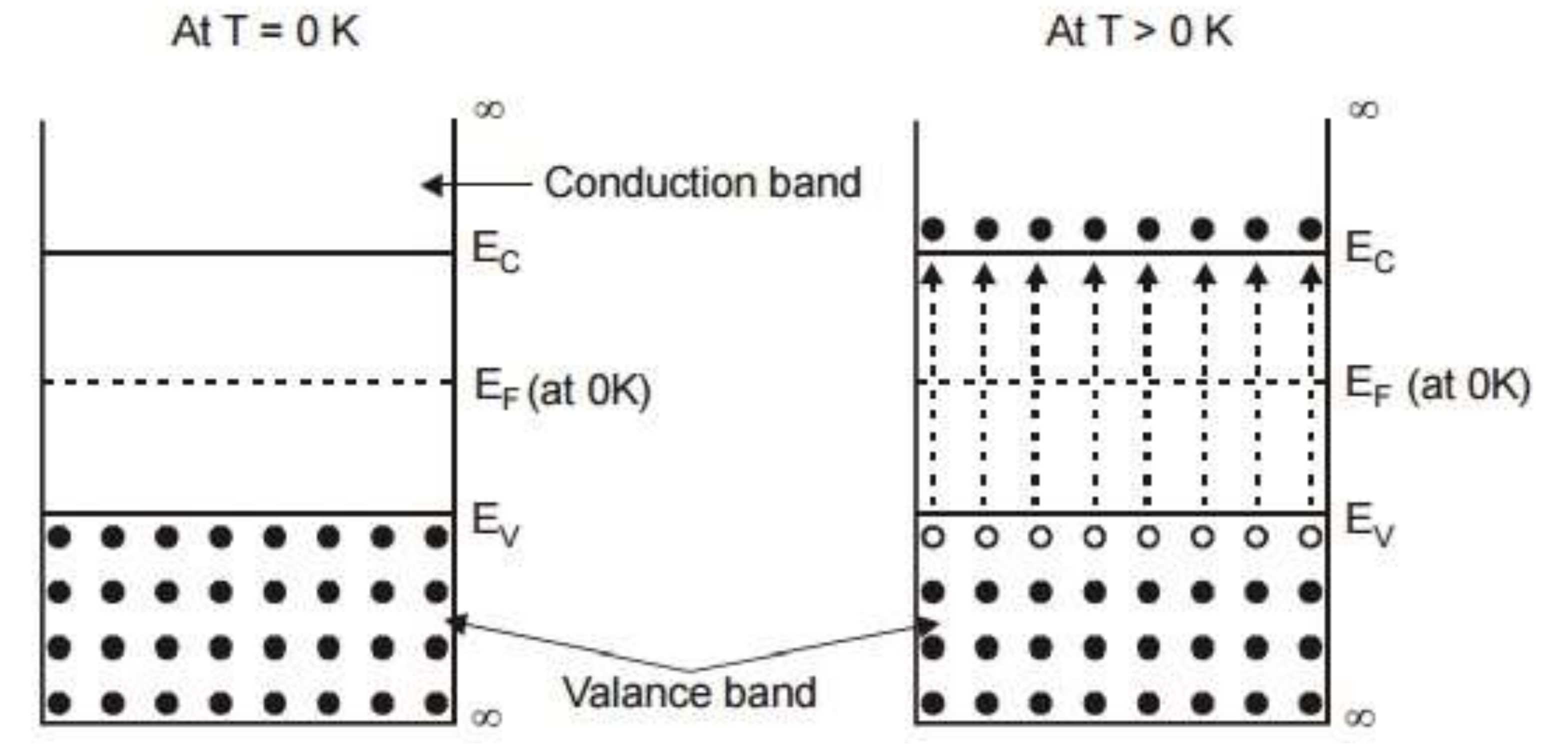


Intrinsic semiconductor
Si Si Si
Si Si Si
n-type semiconductor
P
Si Si Si
Si P Si
p-type semiconductor
B
Si Si Si
Si B Si

ENERGY BAND DIAGRAMS

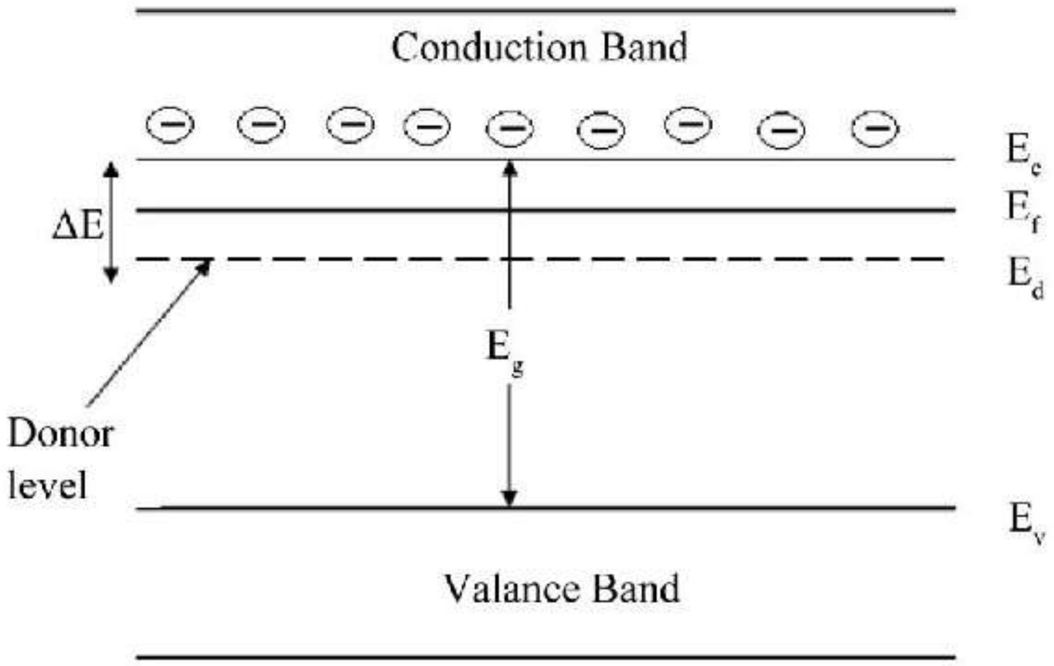


An intrinsic semiconductor behaves like insulator at T=0 K

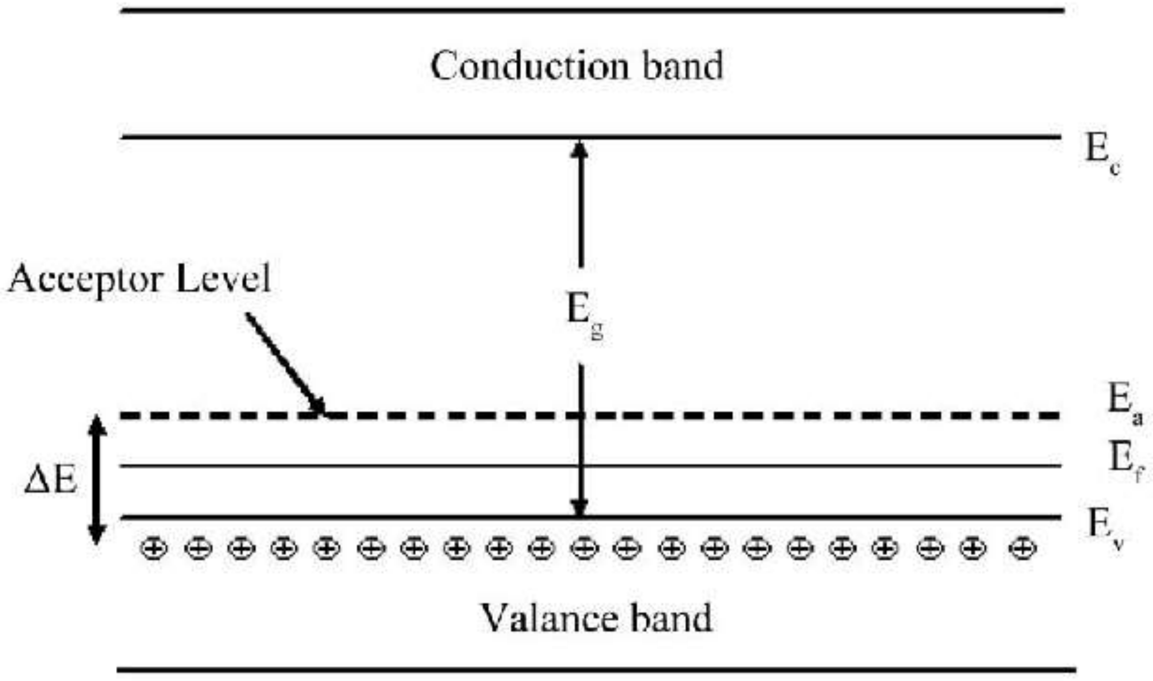
An intrinsic semiconductor at T > 0 K

CONT'D….

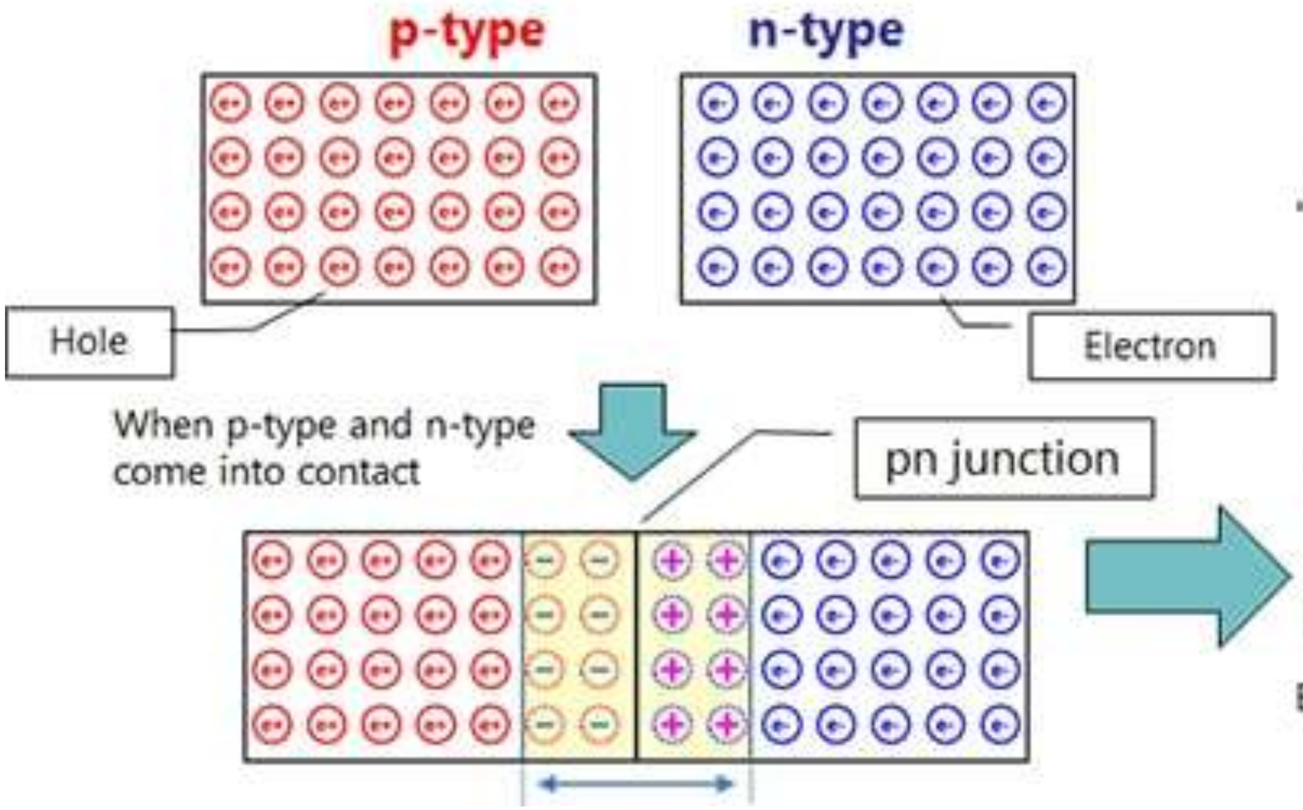
N-type semiconductor



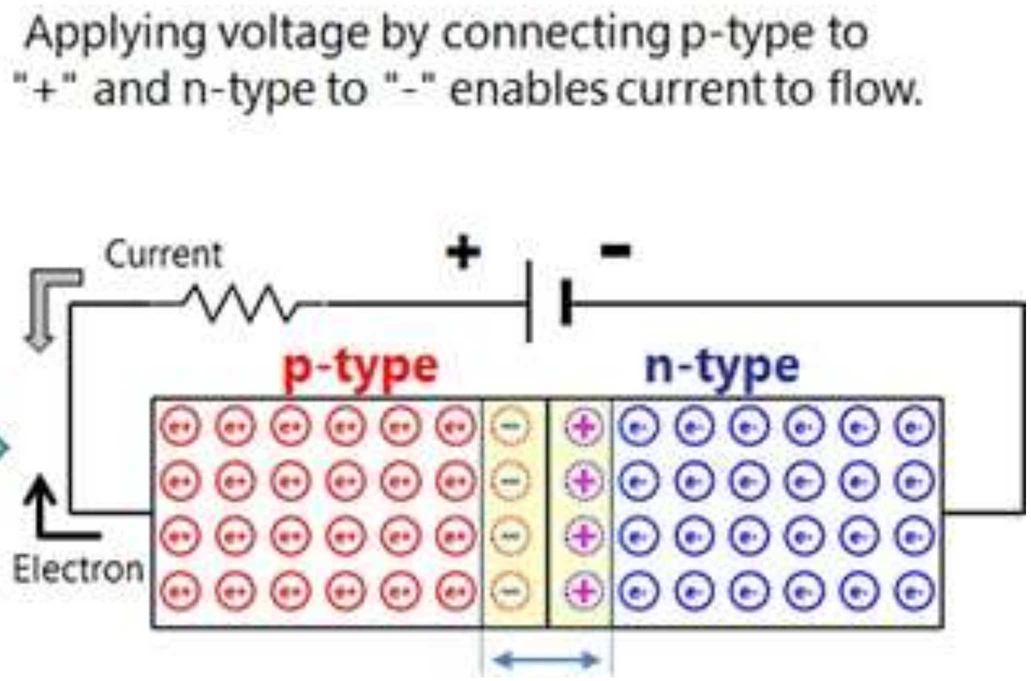
P-type semiconductor



PN-JUNCTION

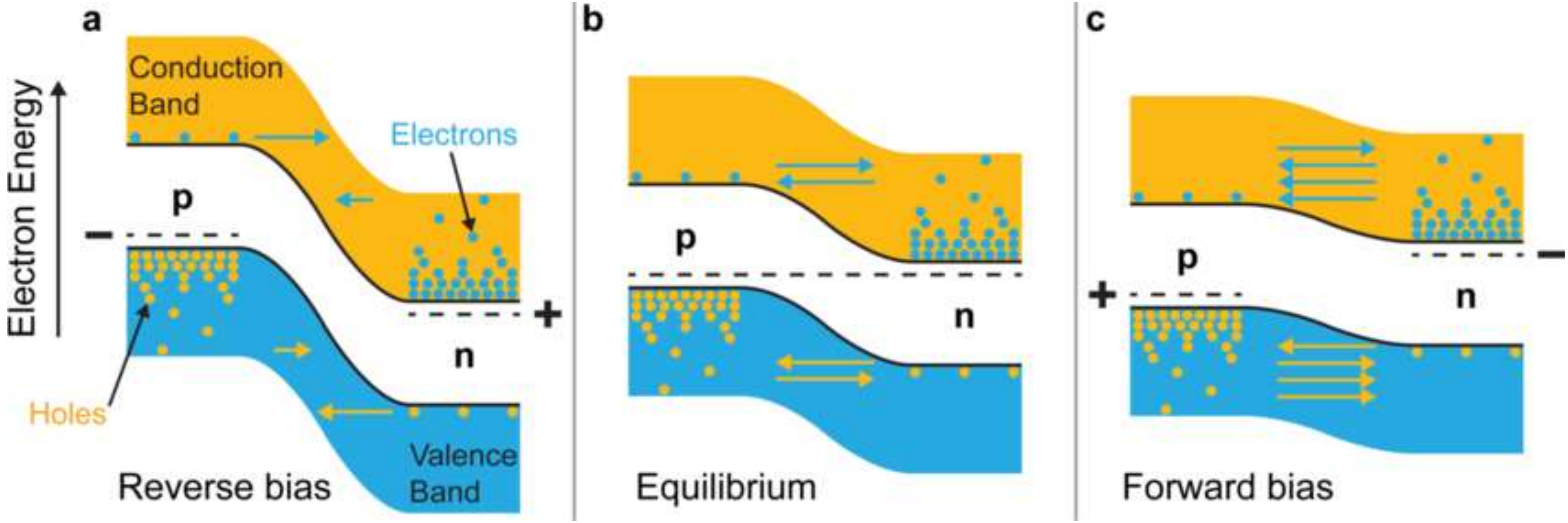


Depletion region formation



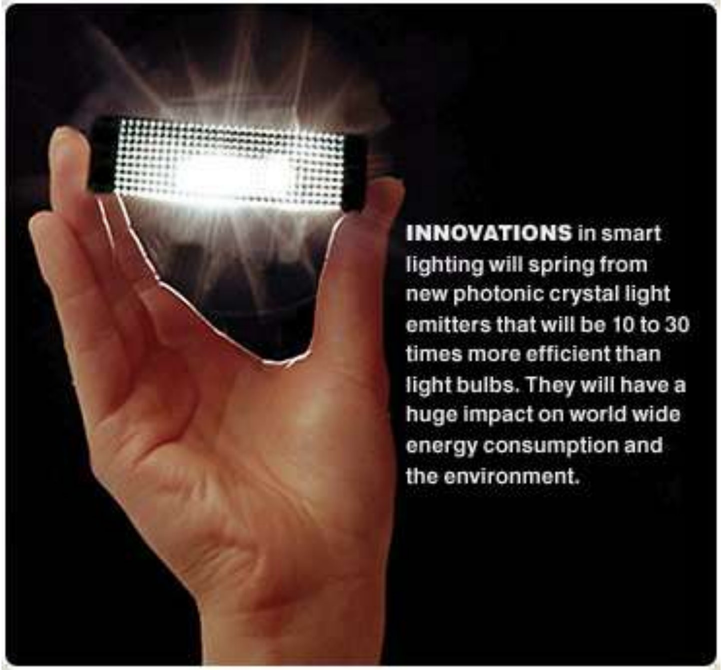
Depletion region becomes narrower under forward biasing

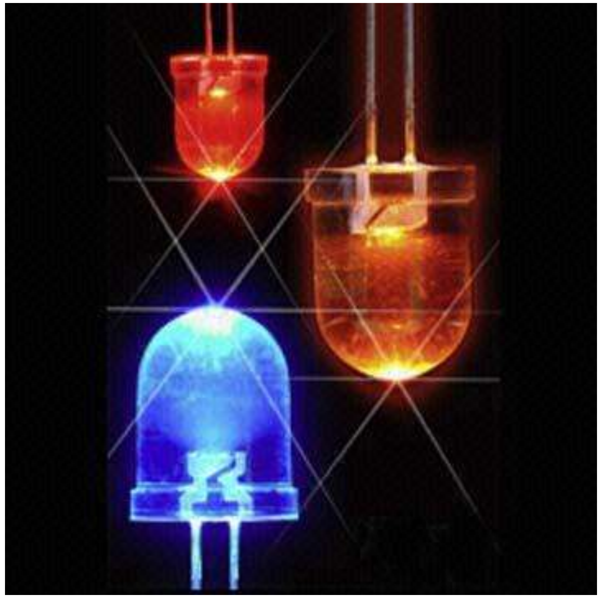
ENERGY BAND DIAGRAM OF PN-JUNCTION



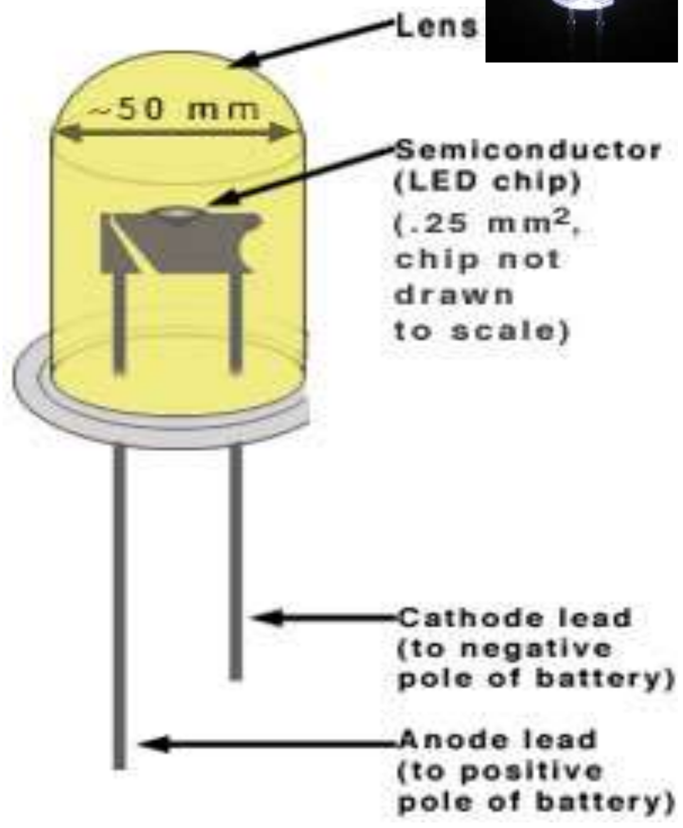
WHAT IS AN LED?

- LED are semiconductor p-n junctions that <u>under forward bias condition</u> can emit radiation by electro-luminescence in the UV, visible or infrared regions of the electromagnetic spectrum.
- The quantum of light energy released is approximately proportional to the band gap of the semiconductor.





GETTING TO KNOW LED



<u>Advantages of Light Emitting Diodes (LEDs)</u>

Longevity:

The light emitting element in a diode is a small conductor chip rather than a filament which greatly extends the diode's life in comparison to an incandescent bulb (10 000 hours life time compared to ~1000 hours for incandescence light bulb)

Efficiency:

Diodes emit almost no heat and run at very low amperes.

Greater Light Intensity:

Since each diode emits its own light

Cost:

Not too bad

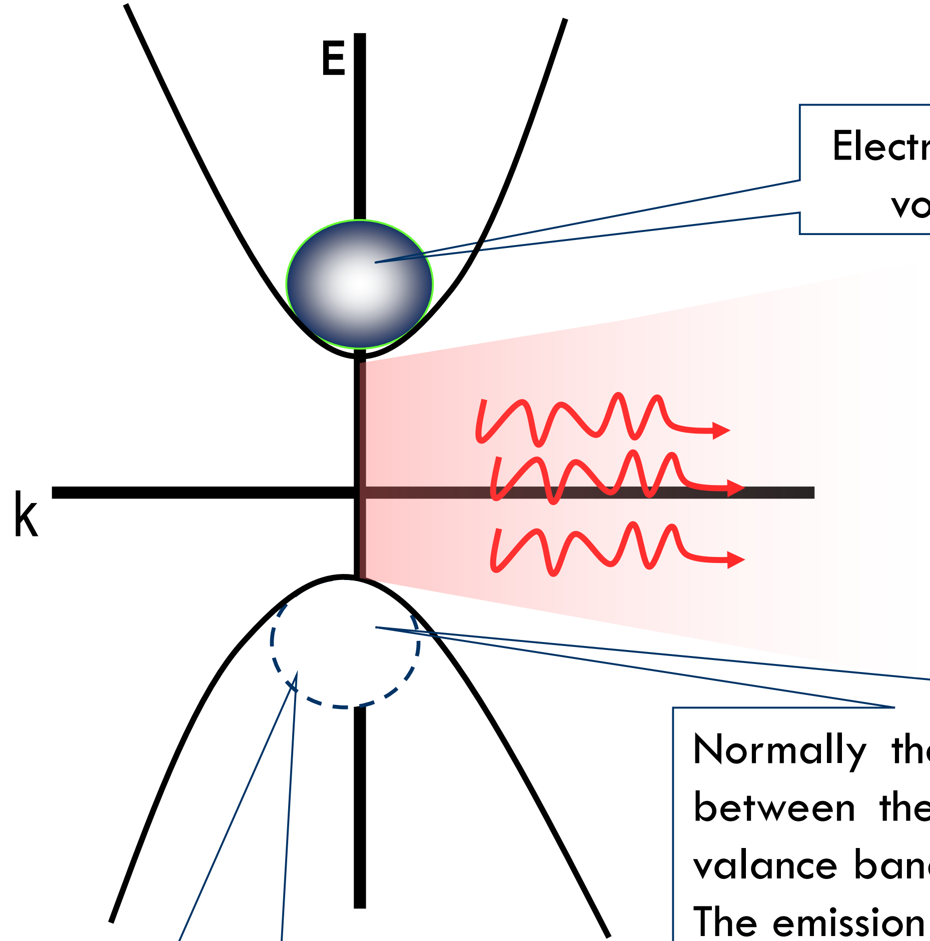
Robustness:

Solid state component, not as fragile as incandescence light bulb

LUMINESCENCE IS THE PROCESS BEHIND LIGHT EMISSION

- Luminescence is a term used to describe the emission of radiation from a solid when the solid is supplied with some form of energy.
- Electroluminescence → excitation is resulted from the application of an electric field
- In a p-n junction diode injection electroluminescence occurs resulting in light emission when the junction is forward biased
- Under forward bias – majority carriers from both sides of the junction can cross the depletion region and entering the material at the other side.
- Upon entering, the majority carriers become minority carriers. For example, electrons in n-type (majority carriers) enter the p-type to become minority carriers
- The minority carriers will be larger → minority carrier injection.
- Minority carriers will diffuse and recombine with the majority carrier. For example, the electrons as minority carriers in the p-region will recombine with the holes. Holes are the majority carrier in the p-region.
- The recombination causes light to be emitted. Such process is termed radiative recombination.

LIGHT EMISSION MECHANISM

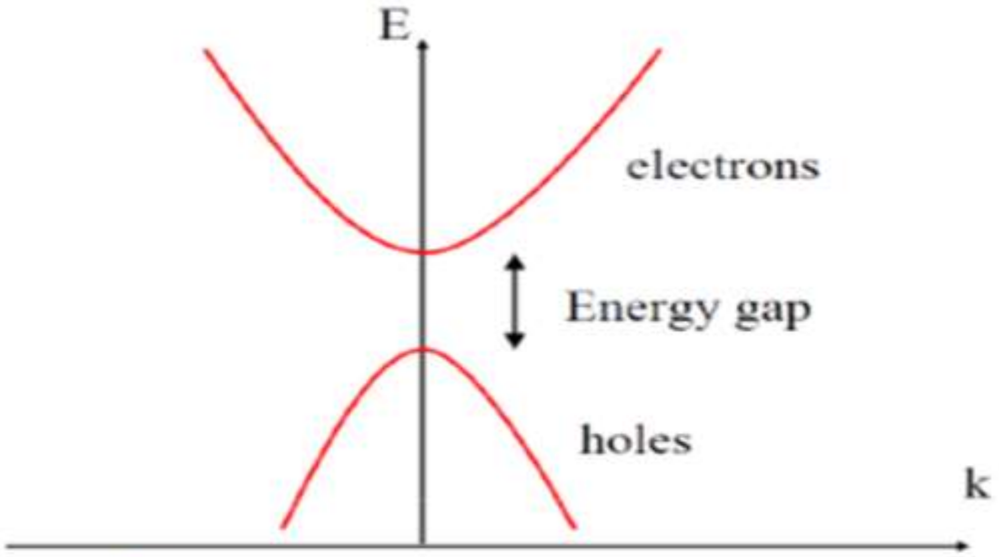


Electron (excited by the biased forward voltage) is in the conduction band

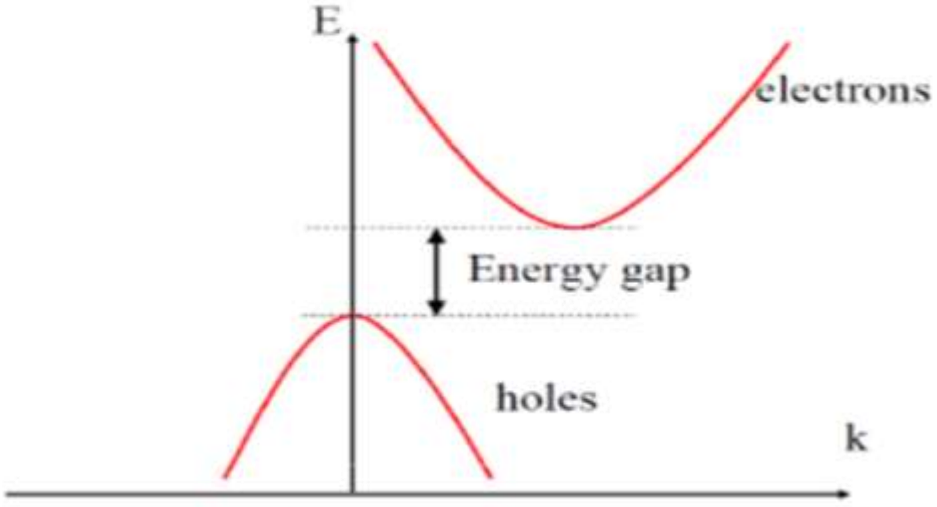
Normally the recombination takes place in transition of electrons between the bottom of the conduction band and the top of the valance band (band exterma).
The emission of light is therefore;
$hc/\lambda = E_c\text{-}E_v = E_g$(only direct band gap allows radiative transition)

Hole is in valance band

DIRECT AND INDIRECT BAND GAP SEMICONDUCTORS



Direct bandgap semiconductors



Indirect bandgap semiconductors

- The materials for which maximum of valence band and minimum of conduction band lie at the same value of k, are called direct band gap materials e.g. GaAs, InP, CdS etc.
- The materials for which maximum of valence band and minimum of conduction band do not lie at the same value of k, are called indirect band gap materials e.g. Si and Ge

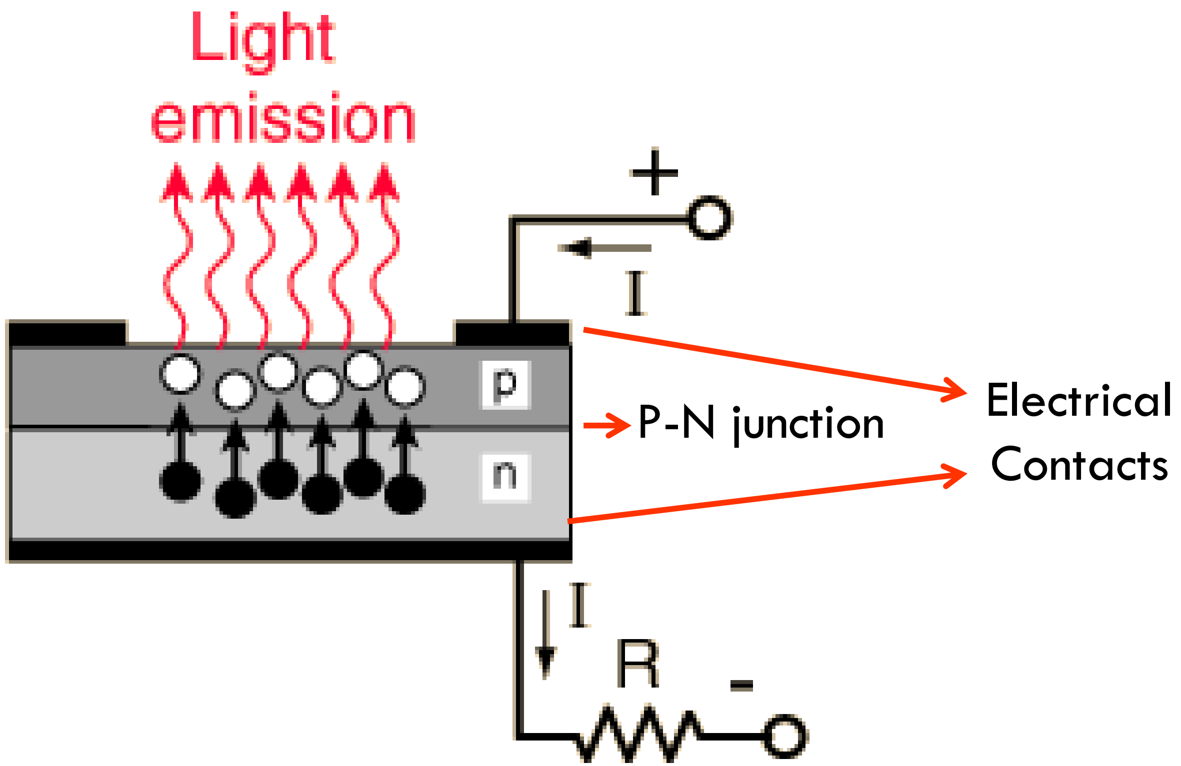
HOW DOES AN LED WORK?

A typical LED needs a p-n junction

There are a lot of electrons and holes at the junction due to excitations

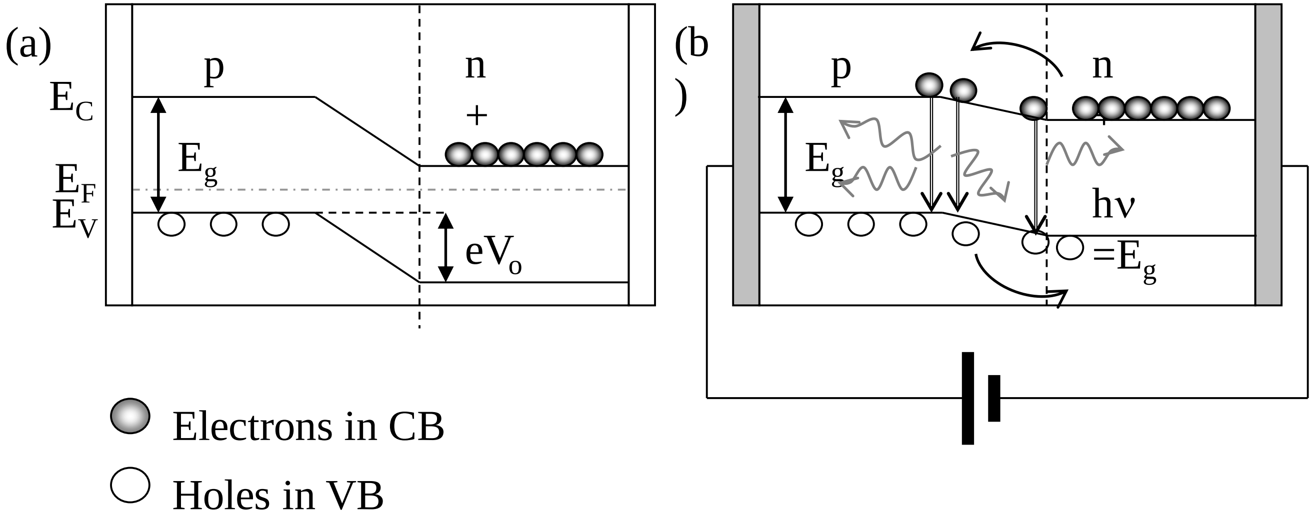
Electrons from n need to be injected to p to promote recombination

Junction is biased to produce even more e-h and to inject electrons from n to p for recombination to happen



Recombination produces light!!

CONT'D....

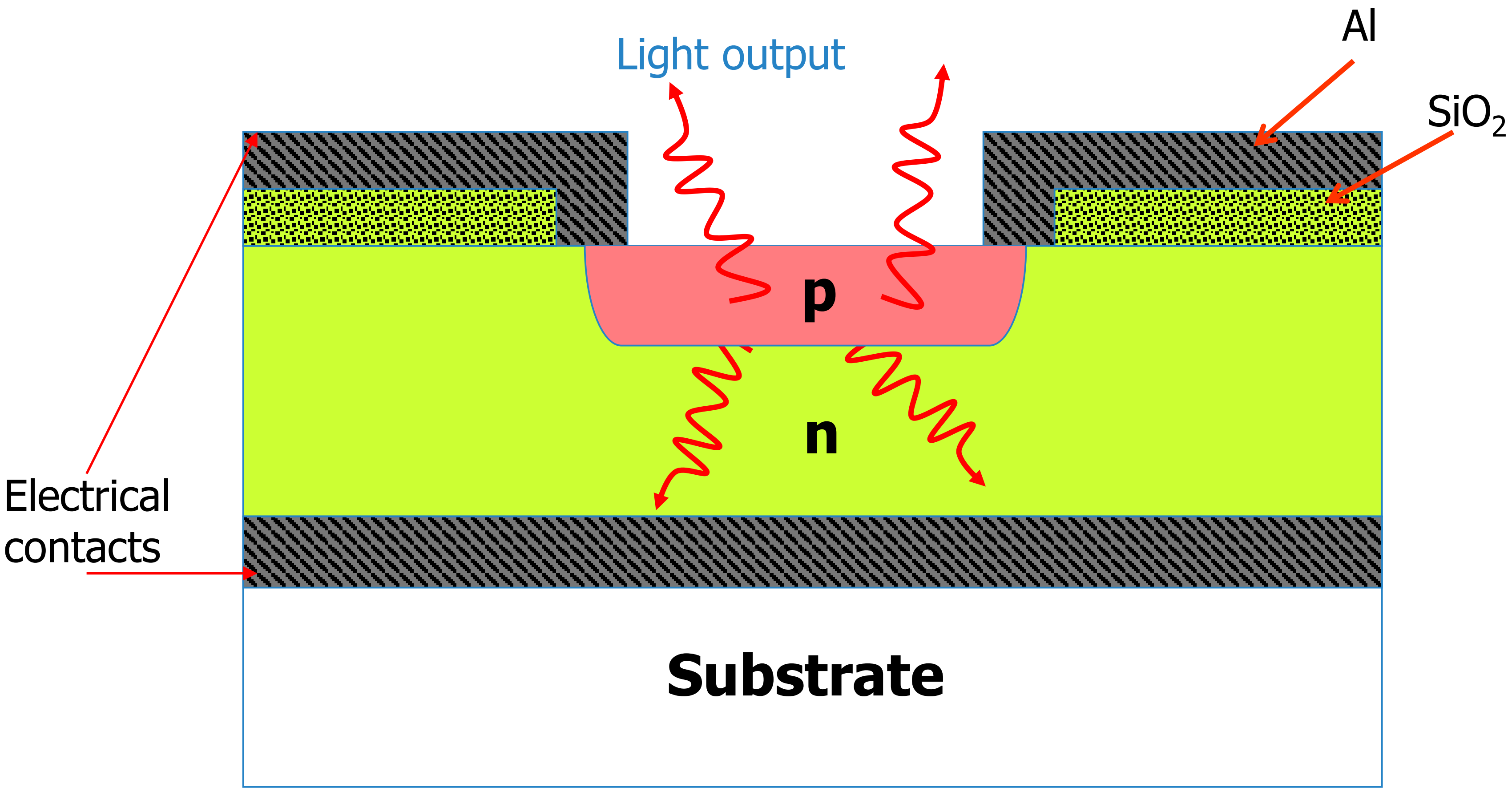


- ❖ Ideal LED will have all injection electrons to take part in the recombination process
- ❖ In a real device not all the electrons will recombine with the holes to radiate light
- ❖ Sometimes recombination occurs but no light is being emitted (non-radiative)
- ❖ Efficiency of the device therefore can be described
- ❖ Efficiency is the rate of photon emission over the rate of supply electrons

EMISSION WAVELENGTH, λ_g

- The number of radiative recombination is proportional to the carrier injection rate
- Carrier injection rate is related to the current flowing in the junction
- If the transition take place between states (conduction and valance bands) the emission wavelength, $\lambda_g = hc/(E_C-E_V)$
- $E_C-E_V = E_g$
- $\lambda_g = hc/E_g$

CONSTRUCTION OF A TYPICAL LED



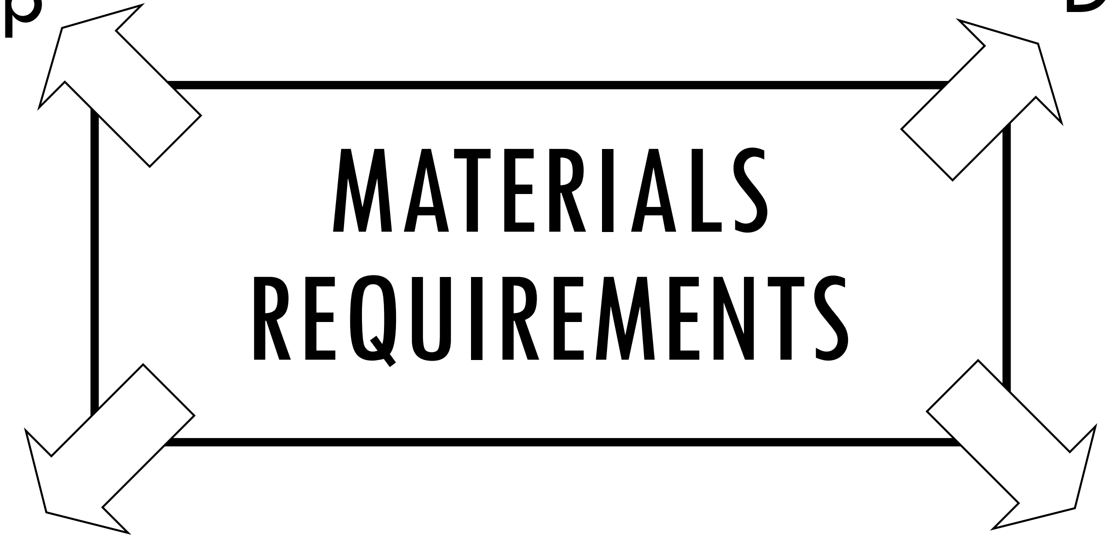
EFFICIENT LED

- Need a **p-n junction** (preferably the same semiconductor material only different dopants)
- **Recombination must occur** → Radiative transmission to give out the 'right coloured LED'
- 'Right coloured LED' → **$hc/\lambda = E_c - E_v = E_g$ → so choose material with the right E_g**
- **Direct band gap** semiconductors to allow efficient recombination
- All photons created must be able to leave the semiconductor
- Little or **no reabsorption** of photons

MATERIALS REQUIREMENTS

Correct band gap

Direct band gap



Efficient radiative pathways must exist

Material could be made p and n-type both

CANDIDATE MATERIALS

CANDIDATE MATERIALS

Direct band gap materials e.g. GaAs not Si

→ UV-ED λ ~0.5-400nm, $E_g > 3.25eV$
→ LED - λ ~450-650nm,E_g = 3.1eV to 1.6eV
→ IR-ED- λ ~750nm- 1nm, E_g = 1.65eV

Materials with refractive index that could allow light to 'get out'

Readily doped n or p-types

VISIBLE LIGHT EMITTING DIODE

Definition:

LED which could emit visible light, the band gap of the materials that we use, must be in the region of visible wavelength = 390- 770 nm. This coincides with the energy value of 3.18 eV- 1.61 eV which corresponds to colours as stated below:

Violet	~ 3.17 eV
Blue	~ 2.73 eV
Green	~ 2.52 eV
Yellow	~ 2.15 eV
Orange	~ 2.08 eV
Red	~1.62 eV

The band gap, E_g that the semiconductor must possess to emit each light

PHOTO-DETECTORS

- Convert an optical signal into an electrical signal.
- Photo detectors are made up of semiconductor materials, absorb incident photons and produce electrons/holes
- <u>Basic requirements of a photo detector:</u>
  - Sensitivity at the required wavelength
  - Efficient conversion of photons to electrons/holes
  - Fast response to operate at high frequencies
  - Low noise
  - Sufficient area for efficient coupling to optical fibers
  - Low cost

MODES OF OPERATION OF PHOTO DIODE

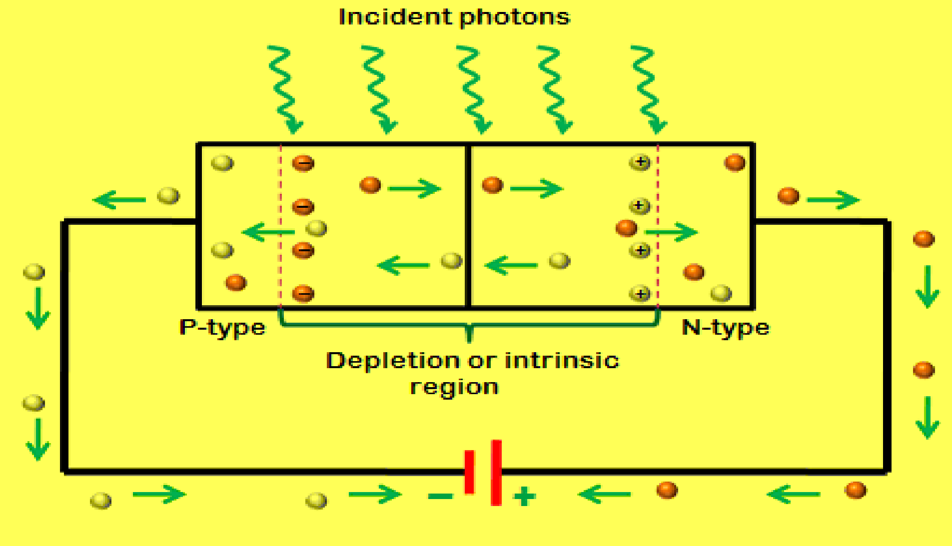
A photo sensitive diode can be operated mainly in two modes:

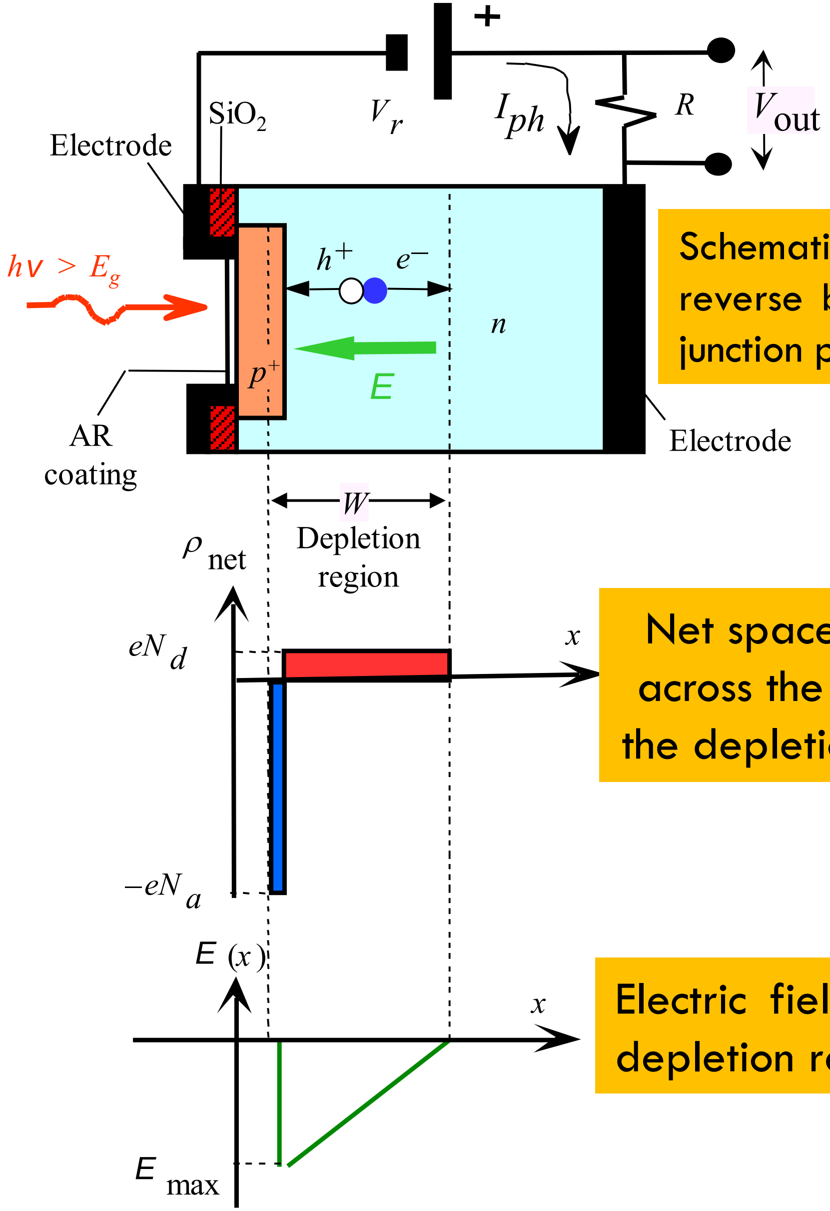
- Photo conductive mode
- Photo voltaic mode

- ❖ The photo diodes used as photo detectors are optimized (in the physical construction of the device itself) to have fast response times.
- ❖ whereas the photo diodes used in electrical energy generation are optimized to have high efficiency of energy conversion.
- ❖ The photo detectors are operated in photo conductive mode.
- ❖ Solar cells are operated in Photo voltaic mode.

WORKING PRINCIPLE OF THE PHOTODIODE

- Photocurrent depends on number of Electron-Hole pair and drift velocity.
- The electrodes do not inject carriers but allow excess carriers in the sample to leave and get collected by the battery.
- N_d and N_a are the donor and acceptor concentrations in the *n* and *p* sides.





Schematic of a reverse biased p-n junction photodiode

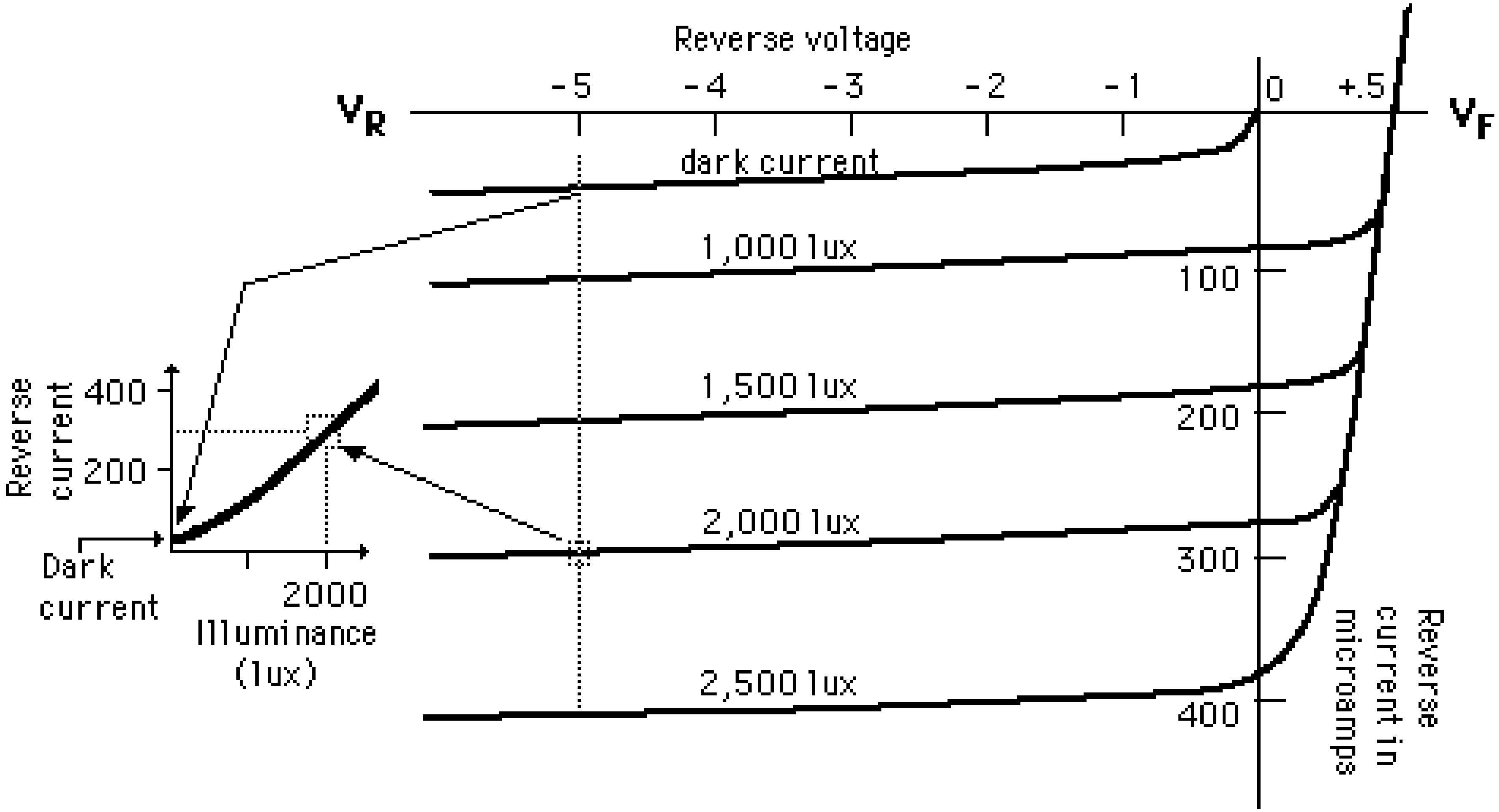
Net space charge across the diode in the depletion region

Electric field in the depletion region

CONT'D….

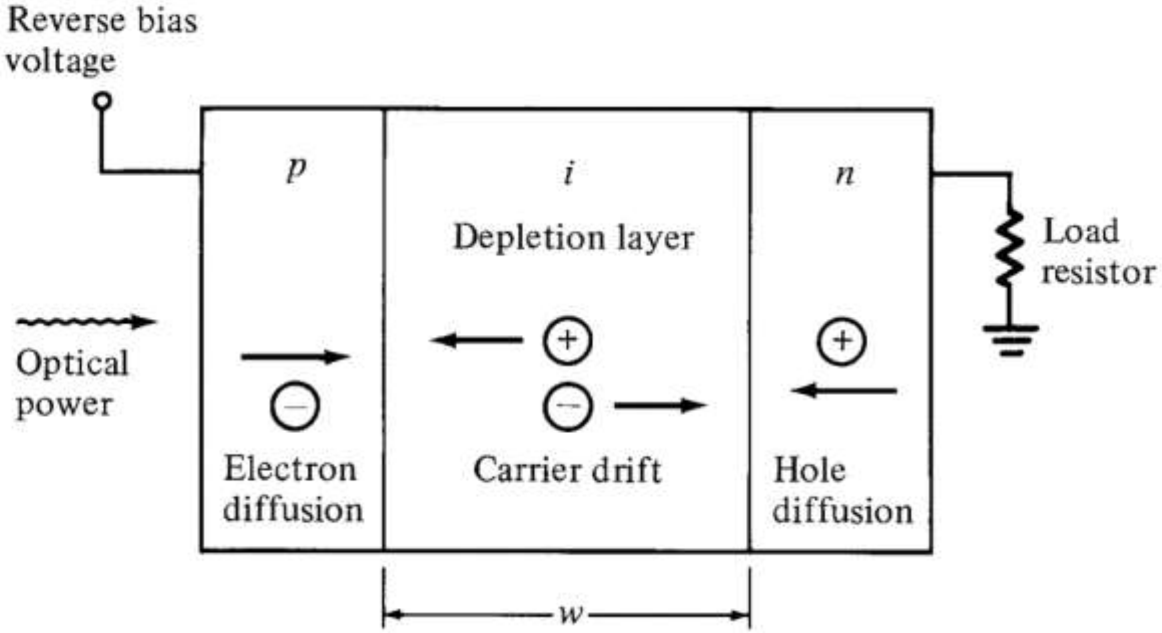
- Depletion region is devoid of any charge carriers.
- Width of depletion region increases upon reverse biasing the p-n junction leading to higher quantum efficiency.
- The carriers produced due to photons are driven by the potential applied generating photocurrent.
- Reverse biasing also helps in eliminating dark current.

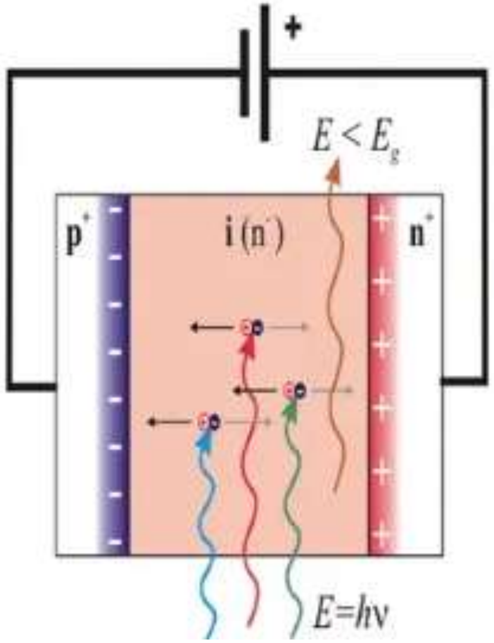
I-V CHARACTERISTICS OF PHOTO DIODE



PIN PHOTO DIODE

- It is positive – intrinsic – negative photodiode, it consist of a thick, lightly doped intrinsic layer sandwiched between thin p and n regions.
- Intrinsic layer is the depletion layer where the absorption of photons occurs.
- Photons entering these layer produces charge carriers, this action results in high quantum efficiency of this device.
- As it is reverse biased the carriers produced are driven by the respective terminals.





DARK CURRENT, RESPONSIVITY (R) AND QUANTUM EFFICIENCY (η)

- Dark current is the current through the diode for zero illumination. It will be non zero due to back ground radiation and thermally excited minority saturation current.
- Responsivity is a measure of the conversion efficiency of a photo detector.
- Current produced in a photo diode is proportional to the number of incident photon,

$$I_p \, \alpha \, P \qquad \text{(input power)}$$

$$I_p = RP \qquad \text{———— (1)}$$

R is a constant called responsivity, is measured in A/W.

- Photocurrent is number of electrons (N_e) times the electron charge (e) per unit time

$$I_p = (Nee)/t \qquad \text{———— (2)}$$

CONT'D....

Light energy – energy of photons E_p times the number of photons (N_p).

Therefore Incident power, $P = \frac{N_p E_p}{t}$ Substituting, $E_p = hc/\lambda$, we get $P = \frac{N_p hc}{t\lambda}$ ——— (3)

However from eqn. (1) $R = \frac{I_p}{P}$

Substituting for P, and I_p we get

$$R = \frac{N_e e/t}{N_p hc/t\lambda}$$

or

$$R = \left(\frac{N_e}{N_p}\right)\left(\frac{e\lambda}{hc}\right)$$

CONT'D....

- The ratio of number of electrons produced (N_e) to the number of photons falling (N_p) shows the efficiency of the semiconductor material to convert light into current.
- This ratio is called as quantum efficiency, η of a photo diode.

$$\eta = \frac{N_e}{N_p}$$

Hence,

$$R = \eta \frac{e\lambda}{hc}$$

- The above relation shows the connection between the responsivity and quantum efficiency of a photo diode.

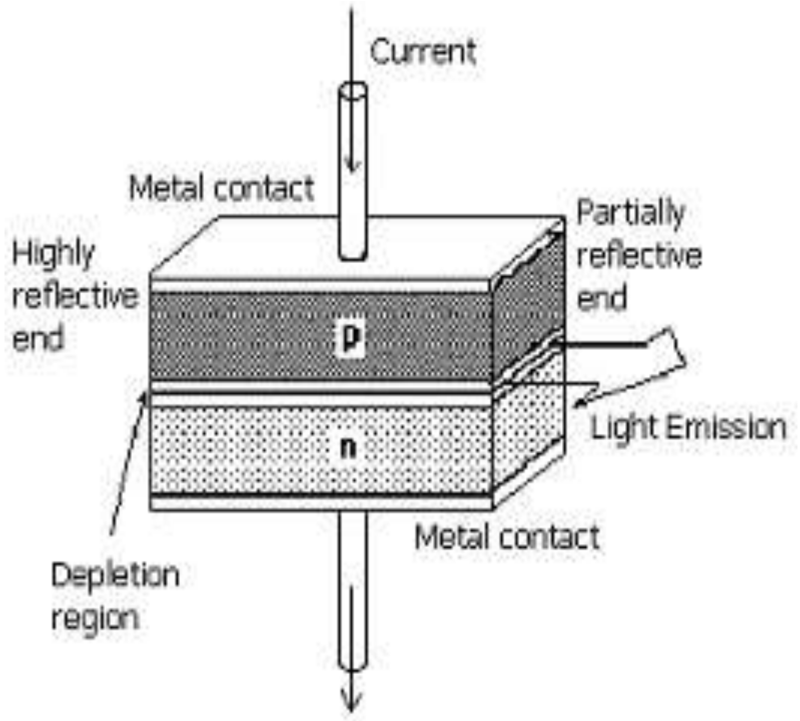
APPLICATIONS OF PHOTODIODE

The applications of photodiodes involve in similar applications of photo detectors like charge-coupled devices, photoconductors, and photomultiplier tubes.

- These diodes are used in consumer electronics devices like smoke detectors, compact disc players, and televisions.
- Photodiodes are frequently used for exact measurement of the intensity of light in science & industry. Generally, they have an enhanced, more linear response than photoconductors.
- Photodiodes are also widely used in numerous medical applications like instruments to analyse samples, detectors for computed tomography and also used in blood gas monitors.
- These diodes are much faster & more complex than normal PN junction diodes and hence are frequently used for lighting regulation and in optical communications.

SEMICONDUCTOR DIODE LASER/LASER DIODE

- A Laser Diode is a semiconductor device similar to a light-emitting diode (LED).
- It uses a p-n junction to emit coherent light in which all the waves are of the same frequency and phase.
- This coherent light is produced by the laser diode using a process termed as "Light Amplification by Stimulated Emission of Radiation", which is abbreviated as LASER.
- And since a p-n junction is used to produce laser light, this device is named as a laser diode.
- Semiconductor lasers can be made to emit light in the spectrum from UV to IR using different semiconductor materials e.g. InGaAs, AlGaAs etc.



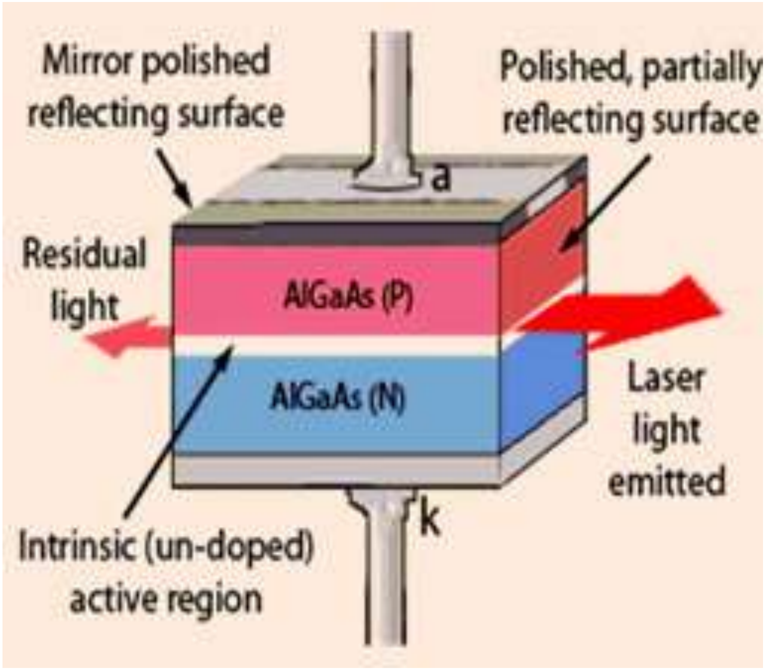
Schematic of a diode laser

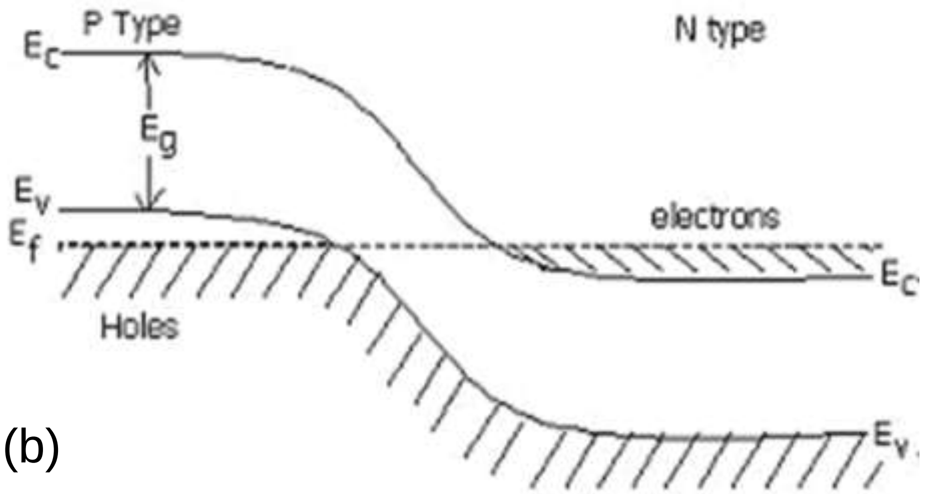
- These lasers are of very small size (□0.1m long), efficient, portable and can operate at low power.
- These are widely used in Optical fibre communications, in CD players, CD-ROM Drives, optical reading, laser printing etc.

CONSTRUCTION

- A pn-junction is formed from highly doped p and n regions
- P and N regions are made from the same semiconductor material.
- Equilibrium is attained only when the equalization of Fermi level takes place in both the regions(see Fig. (b))
- In this case, the Fermi level is pushed inside the conduction band in n-region and inside the valence band in the p-region.
- The diode chip is about 500 µm long and 100 µm wide and thick.
- The top and bottom faces has metal contacts to pass the current.
- The front and rare faces are polished to constitute the optical resonator (Fig. (a)).

(a)





(b)

Heavily doped P-N junction in Equilibrium

WORKING MECHANISM

The basic mechanism responsible for light emission from a semiconductor is the recombination of electrons and holes in a p-n junction when a current is passed through it.

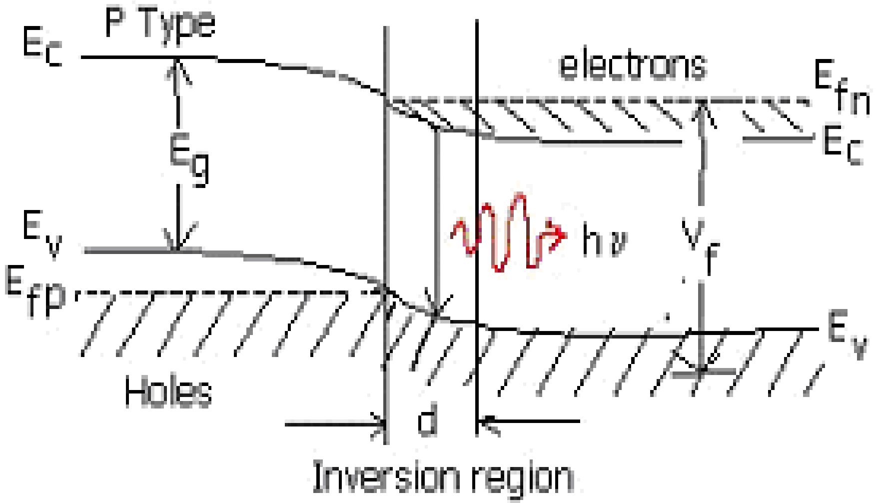
There can be three interaction processes under forward bias of a p-n junction device:

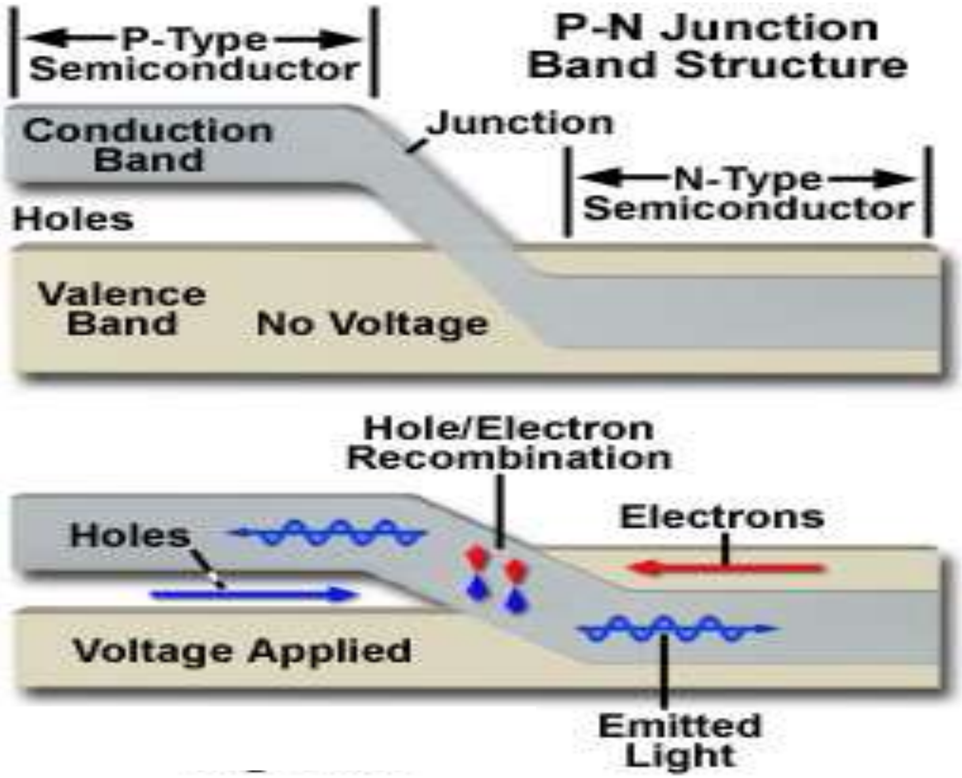
- An electron in the valence band can get excited to the conduction band due to applied forward bias leading to the generation of electron-hole pair.
- An electron can make a spontaneous transition from conduction band to valence band and combines with a hole to emit radiation spontaneously.
- Stimulated emission may occur in which the spontaneously emitted radiation stimulates an electron in the conduction band to make a transition to the valence band and in the process emit radiation.

CONT'D...

- For amplification of this stimulated emitted photon optical feedback should be provided
- This is done by cleaving or polishing the ends of the p-n junction diode at right angles to the junction.

POPULATION INVERSION IN SEMICONDUCTOR LASER





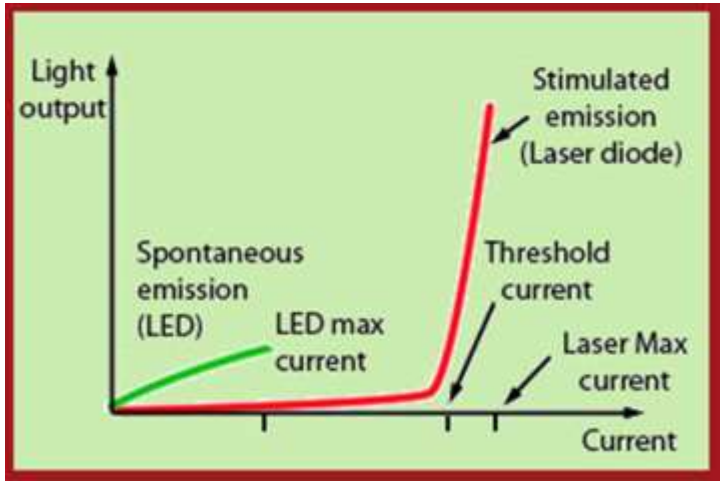
Population inversion is achieved by direct conversion method of pumping

CONT'D....

- When the junction is forward biased, at low voltage the electron and hole recombine and cause spontaneous emission
- But when the forward voltage reaches a threshold value, the carrier concentration rises to very high value.
- As a result, the depletion region ("d") contains large number of electrons in the conduction band and at the same time large number of holes in the valence band. <u>Thus the population inversion is achieved.</u>
- The recombination of electron and hole leads to spontaneous emission and it stimulate the others to emit radiation.
- A GaAs based diode laser produces light of 9000 Å in IR region.

COMPARISON OF A DIODE LASER AND AN LED

- Semiconductor Diode Laser
  - Stimulated radiation
  - narrow line width
  - coherent
  - higher output power
  - a threshold device
  - strong temperature dependence
  - higher coupling efficiency to a fiber



- Light Emitting Diode
  - Spontaneous radiation
  - broad spectral
  - incoherent
  - lower output power
  - no threshold current
  - weak temperature dependence
  - lower coupling efficiency