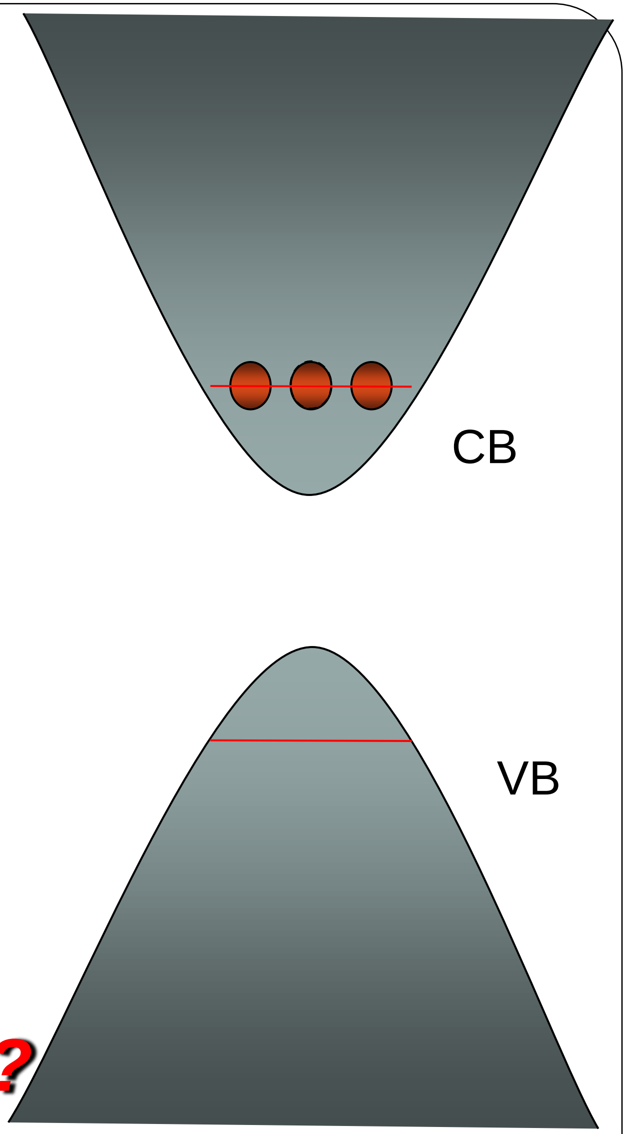
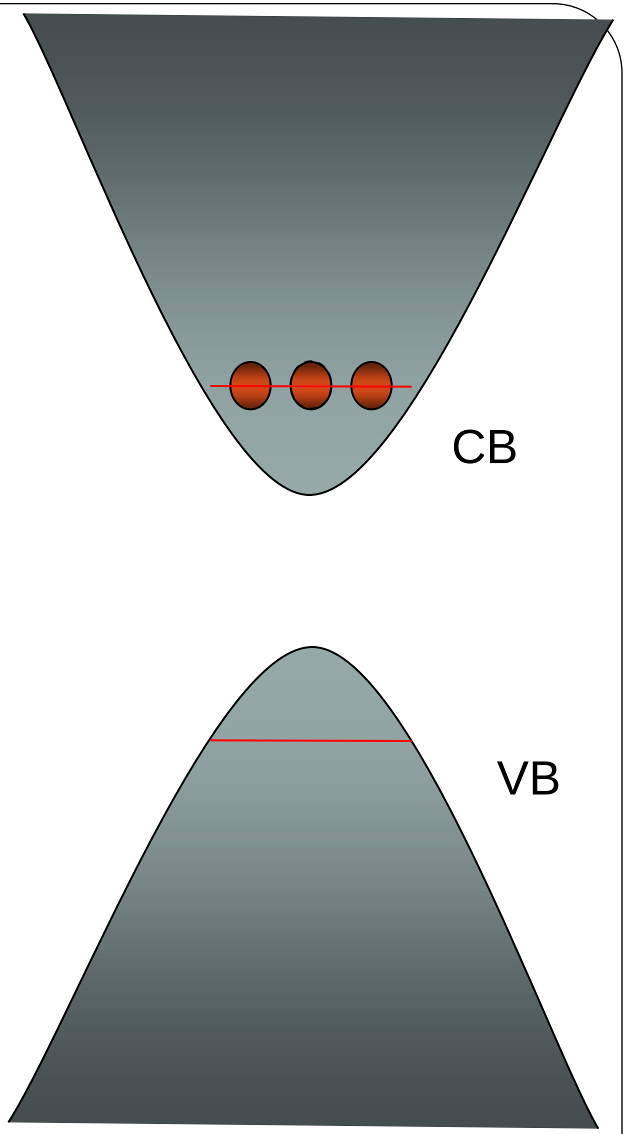


The question is;

where does that energy go?



The question is;

what is the mechanism

behind photon emission in LEDs?

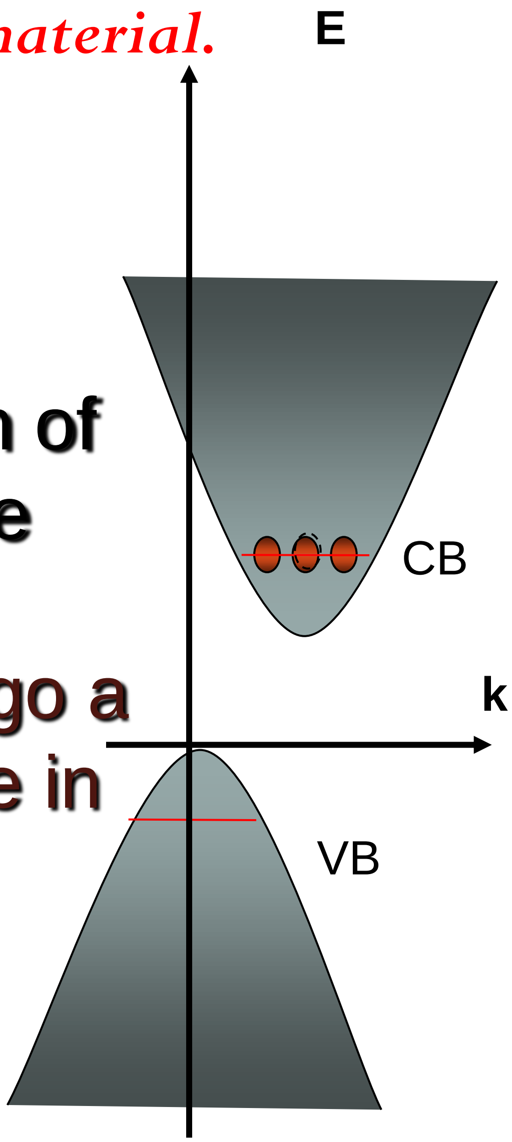
For example;

Silicon is known as an *indirect band-gap material.*

What this means is that

as an electron goes from the bottom of the conduction band to the top of the valence band;

it must also undergo a significant change in momentum.



- As we all know, whenever something changes state, one must conserve not only energy, but also momentum.
- In the case of an electron going from conduction band to the valence band in silicon, both of these things can only be conserved:

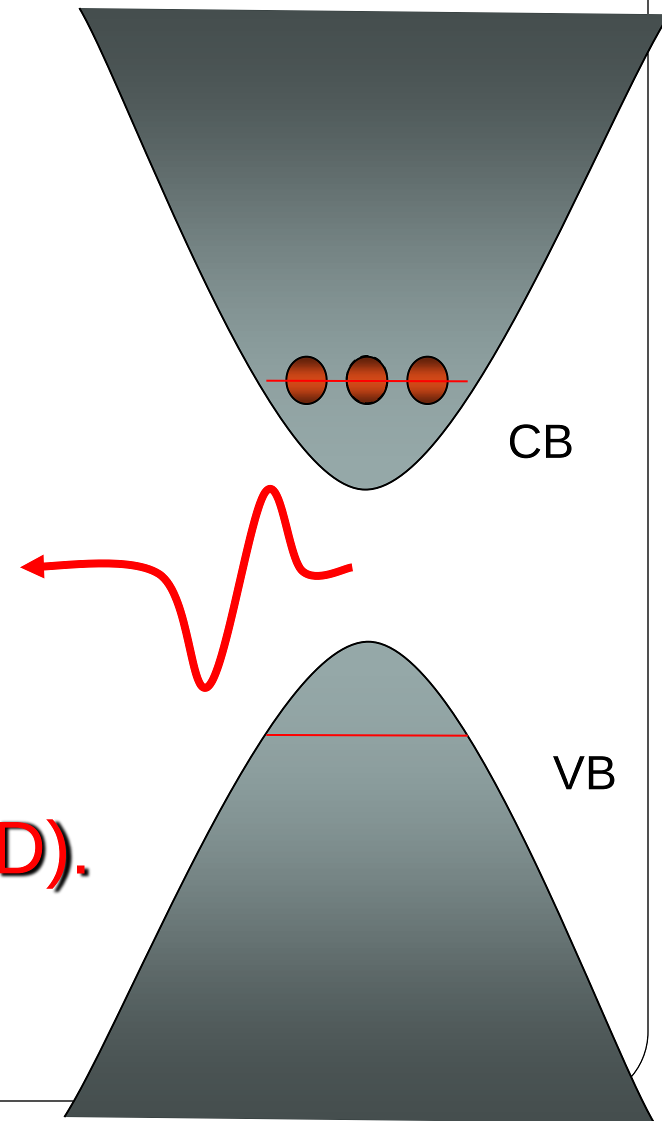
The transition also creates a quantized set of lattice vibrations, called phonons, or "heat“ .

- Phonons possess both energy and momentum.
- Their creation upon the recombination of an electron and hole allows for complete conservation of both energy and momentum.
- All of the energy which the electron gives up in going from the conduction band to the valence band (1.1 eV) ends up in phonons, which is another way of saying that the electron heats up the crystal.

In a class of materials called ***direct band-gap semiconductors***;

- the transition from conduction band to valence band involves essentially no change in momentum.
- Photons, it turns out, possess a fair amount of energy (several eV/photon in some cases) but they have very little momentum associated with them.

- Thus, for a direct band gap material, the excess energy of the electron-hole recombination can either be taken away as heat, or more likely, as a photon of light.
- This radiative transition then conserves energy and momentum by giving off light whenever an electron and hole recombine.

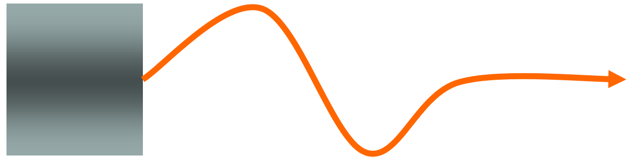


This gives rise to (for us) a new type of device;

the light emitting diode (LED).

Mechanism behind photon emission in LEDs?

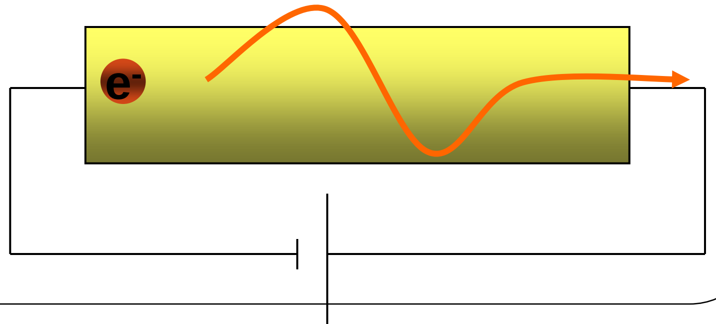
Mechanism is “injection Electroluminescence”.



Luminescence part tells us that we are producing photons.

Electro part tells us that the photons are being produced by an electric potential.

Injection tells us that photon production is by the injection of charge carriers.

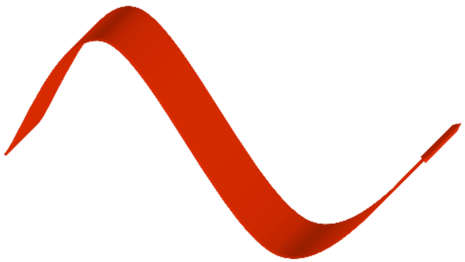


Producing photon

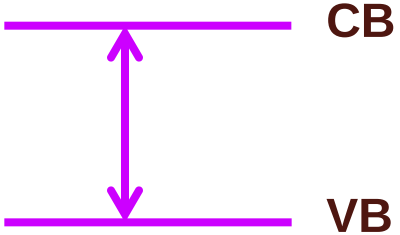
Electrons recombine with holes.

e^-

h

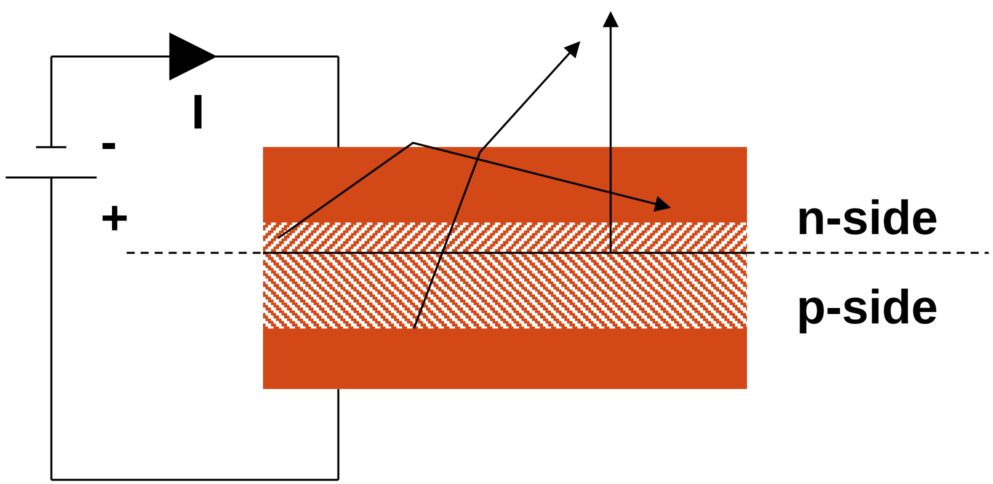


Energy of photon is the energy of band gap.



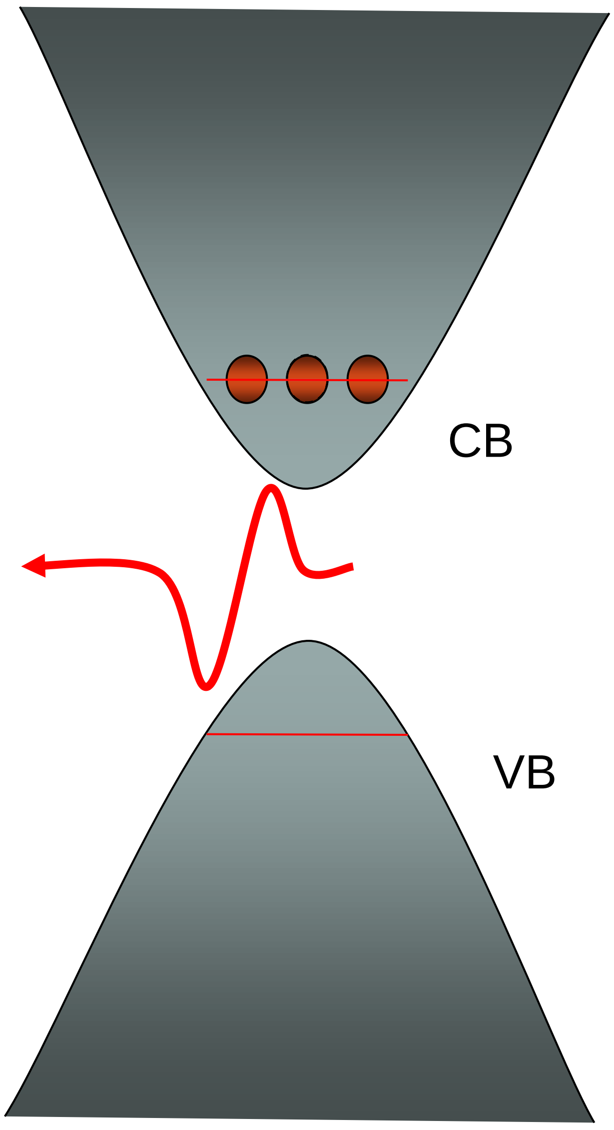
Method of injection

- We need putting a lot of e^{-}'s where there are lots of holes.
- So electron-hole recombination can occur.
- Forward biasing a p-n junction will inject lots of e^{-}'s from n-side, across the depletion region into the p-side where they will be combine with the high density of majority carriers.



MATERIALS FOR LEDS

- The semiconductor bandgap energy defines the energy of the emitted photons in a LED.
- To fabricate LEDs that can emit photons from the infrared to the ultraviolet parts of the e.m. spectrum, then we must consider several different material systems.
- No single system can span this energy band at present, although the 3-5 nitrides come close.



- Unfortunately, many of potentiallly useful II-VI group of direct band-gap semiconductors (ZnSe, ZnTe, etc.) come naturally doped either p-type, or n-type, but they don't like to be type-converted by overdoping.

- The material reasons behind this are complicated and not entirely well-known.

- The same problem is encountered in the III-V nitrides and their alloys InN, GaN, AlN, InGaN, AlGaN, and InAlGaN. The amazing thing about III-V nitride alloy systems is that appear to be direct gap throughout.

- When we talk about light, it is conventional to specify its wavelength, λ, instead of frequency.
- Visible light has a wavelength of the order of nanometers.

$$\lambda(nm) = \frac{hc}{E(eV)}$$

$$\lambda(nm) = \frac{1240}{E(eV)}$$

- Thus, a semiconductor with a 2 eV band-gap should give a light at about 620 nm (in the red). A 3 eV band-gap material would emit at 414 nm, in the violet.
- The human eye, of course, is not equally responsive to all colors.

Color Name	Wavelength (Nanometers)	Semiconductor Composition
Infrared	880	GaAlAs/GaAs
Ultra Red	660	GaAlAs/GaAlAs
Super Red	633	AlGaInP
Super Orange	612	AlGaInP
Orange	605	GaAsP/GaP
Yellow	585	GaAsP/GaP
Incandescent White	4500K (CT)	InGaN/SiC
Pale White	6500K (CT)	InGaN/SiC
Cool White	8000K (CT)	InGaN/SiC
Pure Green	555	GaP/GaP
Super Blue	470	GaN/SiC
Blue Violet	430	GaN/SiC
Ultraviolet	395	InGaN/SiC

Material	Wavelength (μm)	Material	Wavelength (μm)
ZnS	0.33	GaAs	0.84-0.95
ZnO	0.37	InP	0.91
GaN	0.40	GaSb	1.55
ZnSe	0.46	InAs	3.1
CdS	0.49	Te	3.72
ZnTe	0.53	PbS	4.3
GaSe	0.59	InSb	5.2
CdSe	0.675	PbTe	6.5
CdTe	0.785	PbSe	8.5

Laser Diode

- Basic mechanism for light emission is the recombination of electrons and holes at p-n junction when current is passed through the diode
- Any laser system has 3 possible interaction process

  a) excitation from VB to CB by absorbing energy from incident radiation

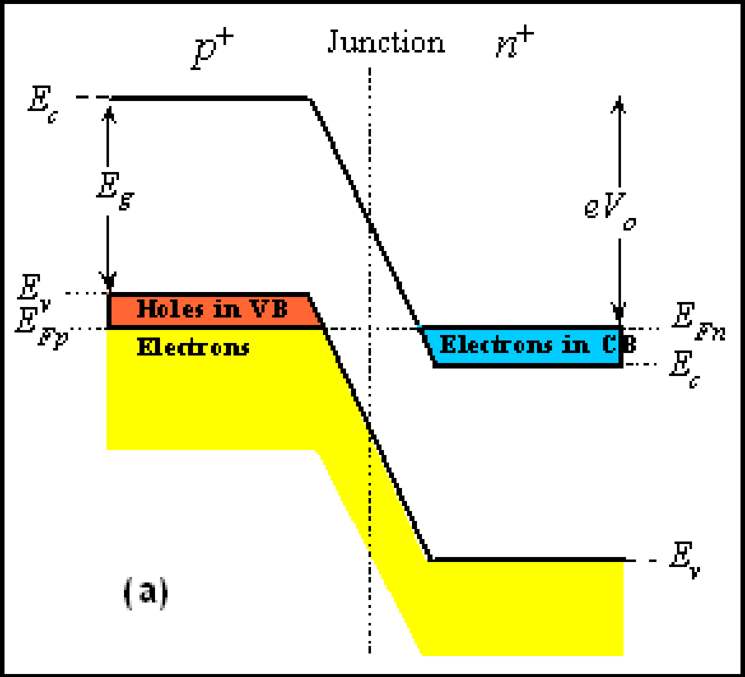
  b) spontaneous transition from CB to VB with the emission of radiation

  c) stimulated emission from CB to VB by the stimulation of incident radiation

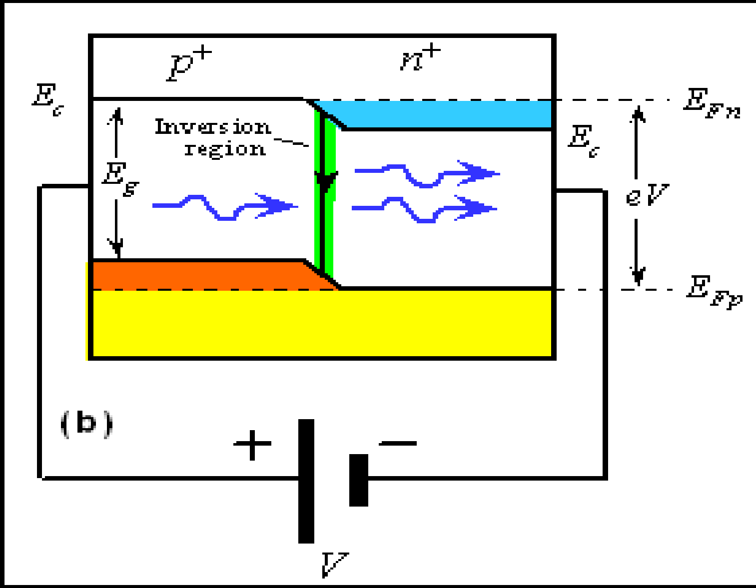
- If we can have large number of electrons in the bottom of CB and large number of holes in the upper part of the valance band, then semiconductor can amplify optical radiation at frequency which corresponds to energy slightly greater than the band gap energy.

- When current is passed through the p-n junction it will increase the carrier concentration in the CB and the VB close to the junction.
- For some value of current stimulated emission will exceed the absorption rate and amplification will begin.
- On further increase of current (threshold value of current) the amplification will overcome the losses in the cavity and laser will begin to emit coherent radiation.

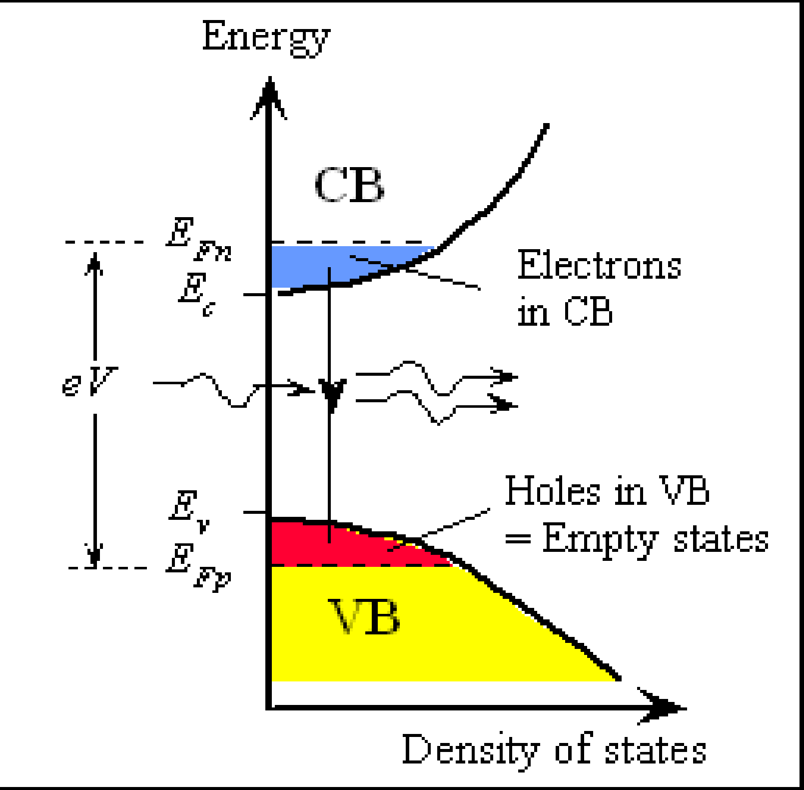
- Consider a degenerately doped direct band gap semiconductor p-n junction



- **Degenerate doping** – Fermi level of p side is in its VB and Fermi level of n side is in its CB, all the energy levels can be considered to be occupied in the absence of applied voltage
- Fermi level is continuous across the diode
- Depletion region or the space charge region in such p-n junction is very narrow.
- There is a built in voltage V_0 which give rise to a potential energy barrier eV_0 that prevents the electron in CB of n side to diffuse into CB of p and the hole diffusion too.
- If this junction is forward biased by a voltage V greater than the band gap voltage

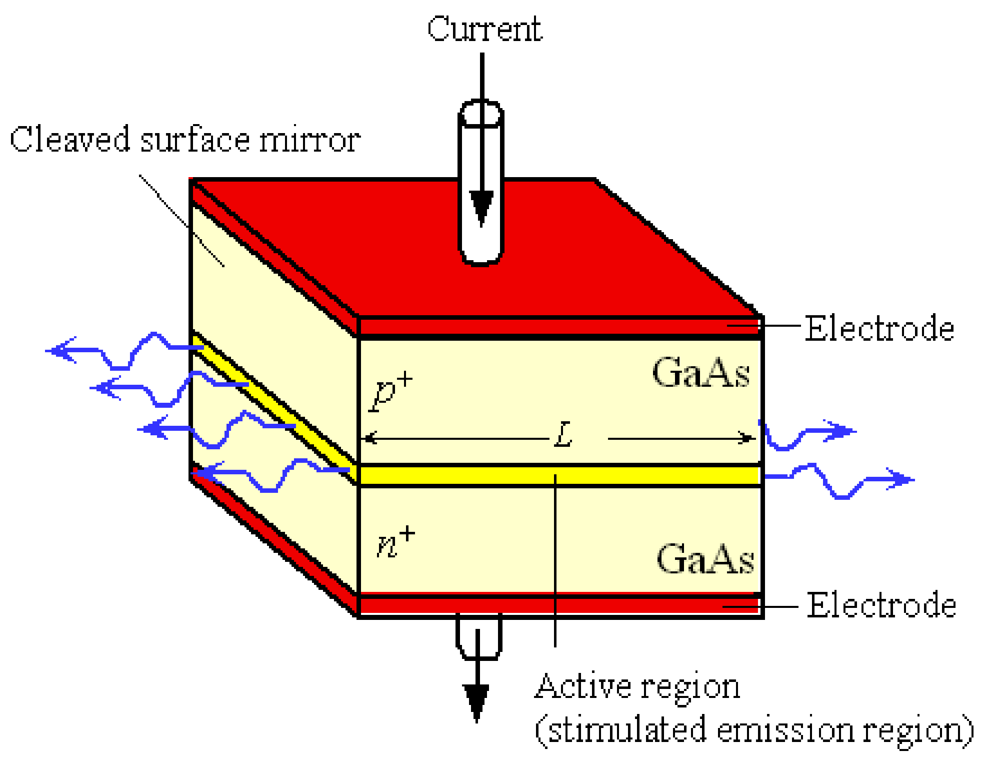


- Now the separation between E_{Fn} and E_{Fp} is the applied voltage.
- This applied voltage reduces the built-in potential barrier almost to zero- which ensues flow of carriers.
- There are more number of electrons in CB when compared to VB which could be assumed as population inversion stage
- The region where the population inversion occurs develops a layer along the junction called an ***inversion layer*** or ***active region***



- An incoming photon with energy of (E_c – E_v) will not see electrons to excite from E_v due to the absence of electrons at E_v.
- The photon can cause an electron to fall down from E_c to E_V.
- The incoming photon is stimulating ***direct recombination***.

- Figure shows a schematic diagram of homo junction laser
- Laser action - only in the active region
- Optical feedback obtained by reflections from cleaved end faces of the semiconductor
- Amount of population inversion and the gain is determined by the current flowing through the junction.



- Beyond a particular value of current (threshold current) lasing commences and radiative output then increases very rapidly with increasing current
- The outrageous difference between semiconductor laser and other lasers is their exceedingly small size.

Photo-detectors

- Convert an optical signal into an electrical signal.
- Photodetectors made up of semiconductor materials absorb incident photons and produce electrons/holes
- Basic requirements of a photodetector:
  - Sensitivity at the required wavelength
  - Efficient conversion of photons to electrons/holes
  - Fast response to operate at high frequencies
  - Low noise for reduced errors
  - Sufficient area for efficient coupling to optical fibers
  - Low cost

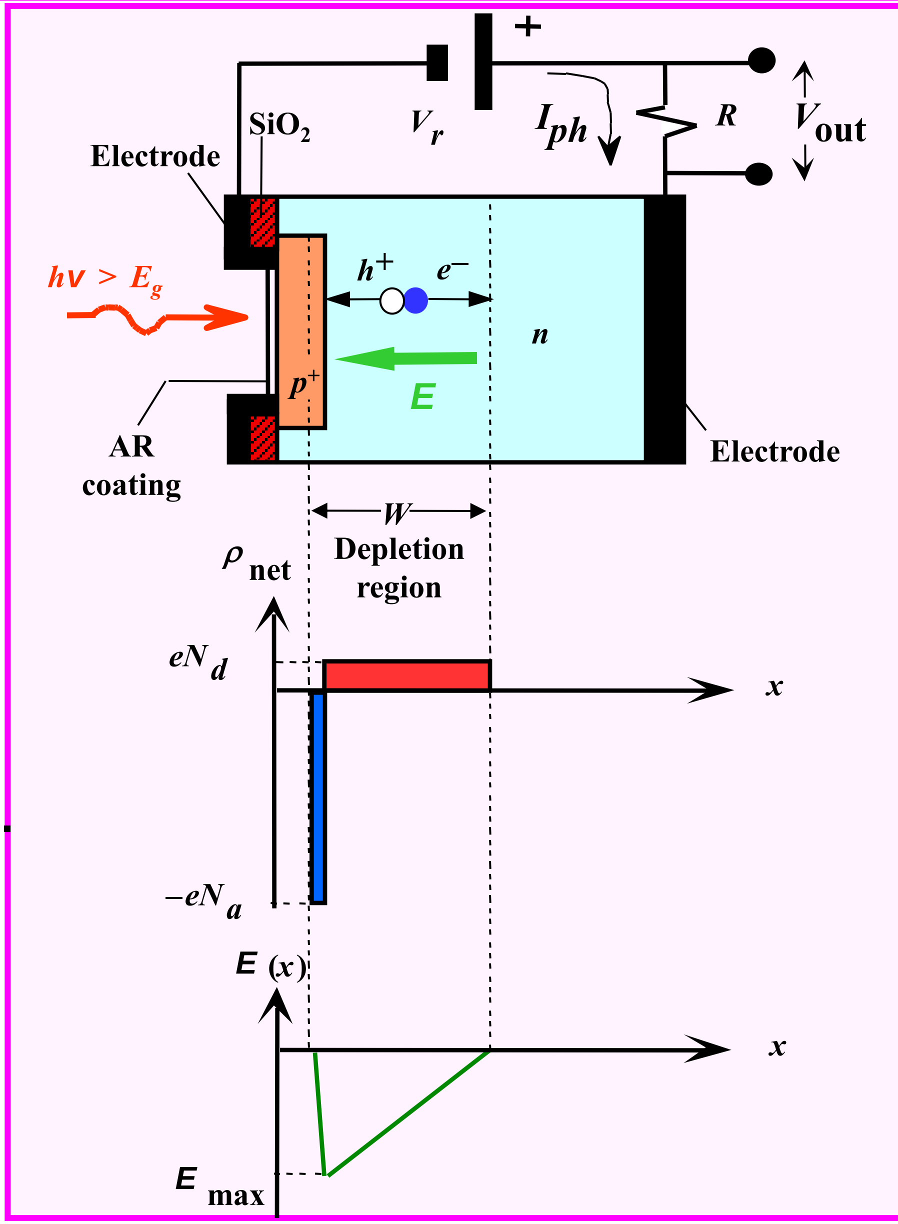
Photodetectors

Principle of the p-n junction Photodiode

- ❑ **Schematic diagram of a reverse biased p-n junction photodiode**
  - ➢ **Photocurrent is depend on number of EHP and drift velocity.**
  - ➢ **The electrode do not inject carriers but allow excess carriers in the sample to leave and become collected by the battery.**

- ❑ **Net space charge across the diode in the depletion region. N_d and N_a are the donor and acceptor concentrations in the p and n sides.**

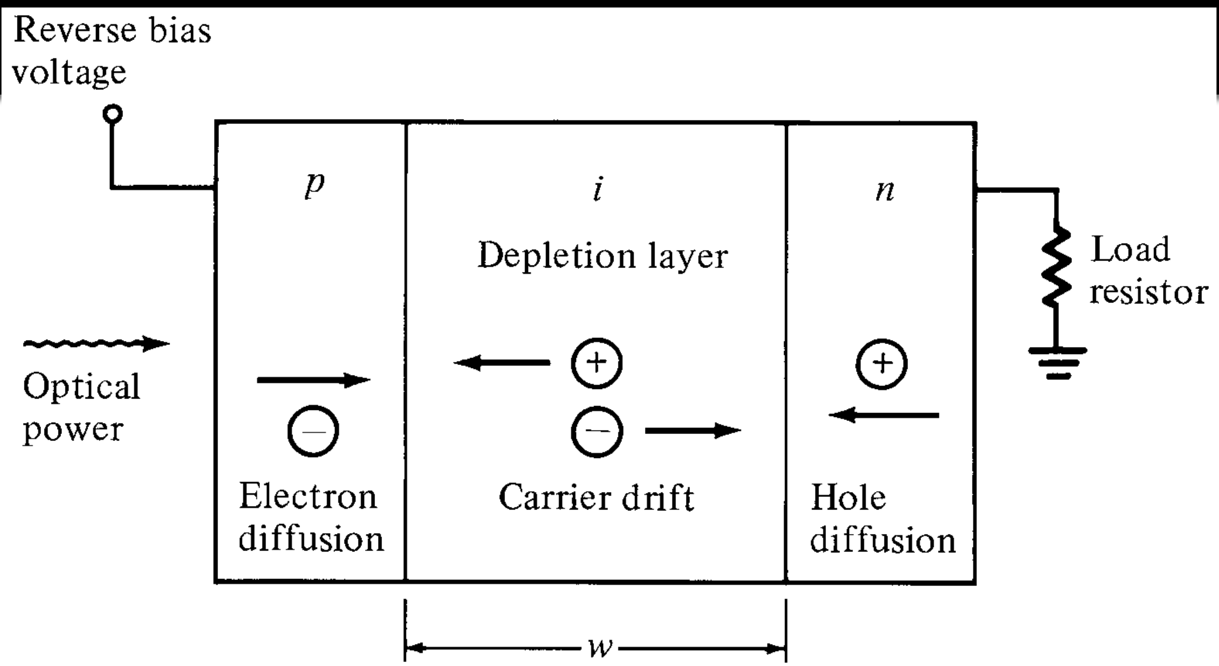
- ❑ **The field in the depletion region.**



- **REVERSE BIASING**
  - 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.

P-I-N Photodiode

- ✓ 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 carrier charges, this action results in **high quantum efficiency** of this device.
- ✓ As it is **reverse biased** the carriers produced are driven by the respective terminals.



Responsivity (R) and Quantum Efficiency (η)

- Responsivity is a measure of the conversion efficiency of a photodetector.
- Current produced is proportional to the number of incident photon

$$I_p \propto P \text{ (input power)}$$

$$I_p = RP$$

R is a constant called responsivity, measured in Amp/Watt

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

$$I_p = (N_e e)/t$$

Light power – light energy per unit time

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

$$P = (N_p E_p)/t$$

Substituting, $E_p = hc/\lambda$, $P = (N_p\, hc)/t\lambda$

But $I_p/P = R$

Substituting for P, and I_p we get

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

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

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.

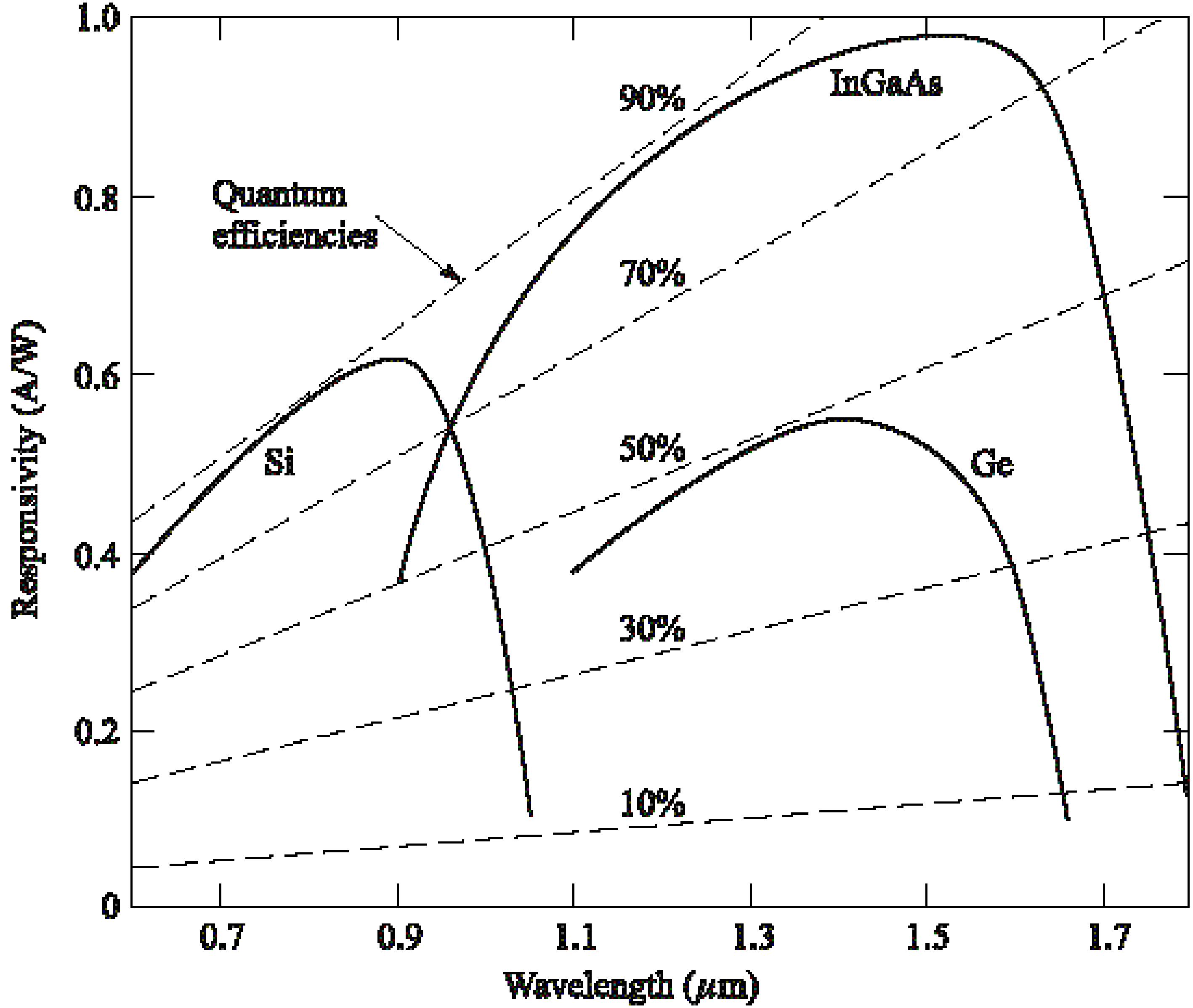
This ratio is called as quantum efficiency η of a photo diode

$$\eta = N_e / N_p$$

hence $$R = \eta\,(e\lambda/hc)$$

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

Responsivity of various P-I-N photodiodes



Quantum efficiency vs. wavelength for various photodetectors