Unit-III

- **Bipolar Transistors**
- **Field Effect Transistors**
  - JFET
  - MOSFET
- **Light-Emitting Diodes**

Transistors

- The transistor (transfer resistor) is a multifunction semiconductor device.
- The transistor is integrated with other curicuit element for voltage gain, current gain or signal power gain.
- It is referred as an active device (apply bias).
- The basic transitior action is control of current at one treminal by voltage applied across two other terminals.
- Applications : high speed circuit, analog circuit and power application.
- Three type of transistor :

  a) bipolar transistor (BJT)

  b) junction field-effect transistor (JFET).

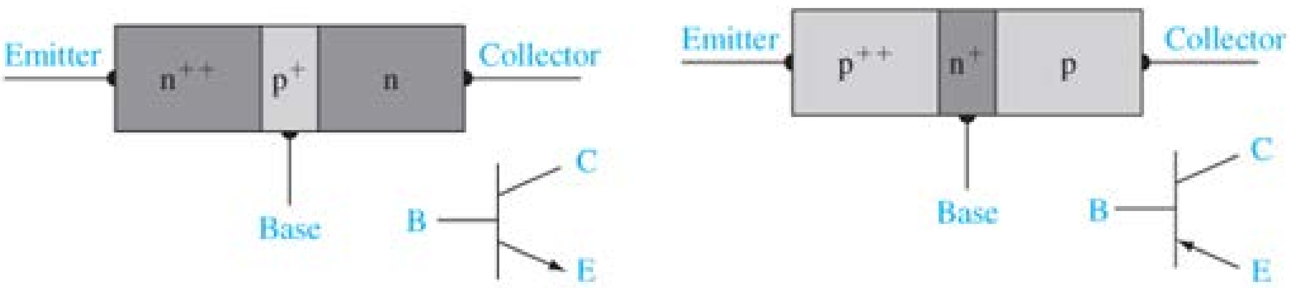
  c) metal-oxide-semiconductor field-effect transistor (MOSFET)

Bipolar junction transistor (BJT)

- ✓ Bipolar junction transistor (BJT) –used extensively in high-speed circuits, analog circuits and power applications.
- ✓ Both electrons & holes participate in the conduction process.
- ✓ The bipolar transistor is a voltage-controlled current source.
- ✓ BJT was invented by a research team at Bell Lab in 1947 (Bardeen, Schokley, Brattain).
- ✓ Modern bipolar transistors –replaced the Ge with Si and replaced the point contacts with two closely coupled p-n junctions in the form of p-n-p & n-p-n structures.

Bipolar junction transistor (BJT)

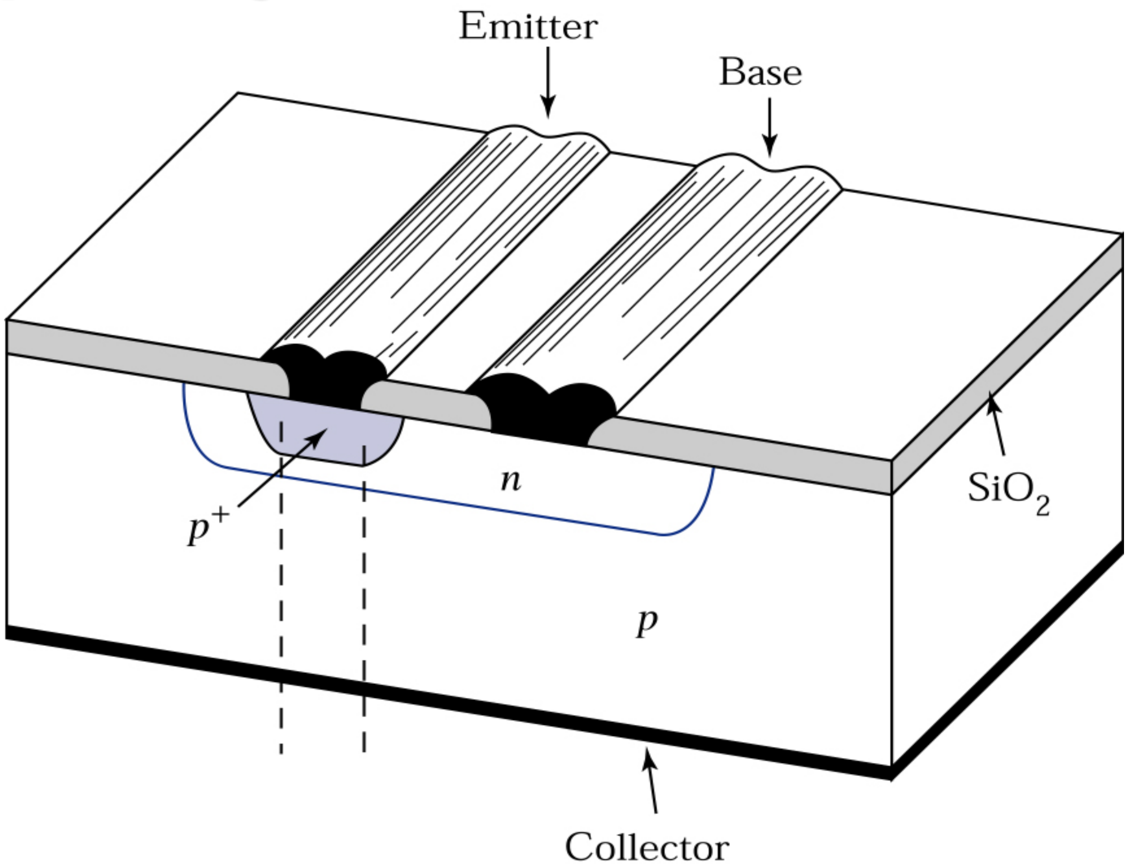
- The term ***Bipolar*** is because two type of charges (electrons and holes) are involved in the flow of electricity.
- There are two p-n junctions
- There are two configurations for this device



(a) (b)

- NPN is more widely used.
- Majority carriers are electrons so it operates more quickly.
- PNP is used for special applications.
- The terminals of the transistor are labeled (Base, Emitter, and Collector)
- The emitter is always drawn with the arrow.

Bipolar junction transistor (BJT)….



Perspective view of a silicon *p-n-p bipolar transistor.*

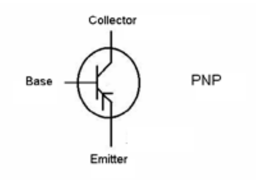
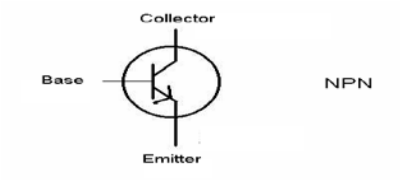
Emitter : heavily doped p^{++} region

Base : moderately doped n^+ region

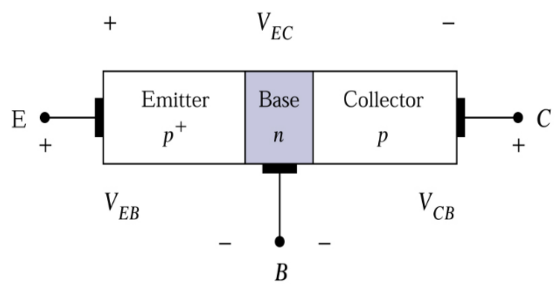
Collector : lightly doped p - region

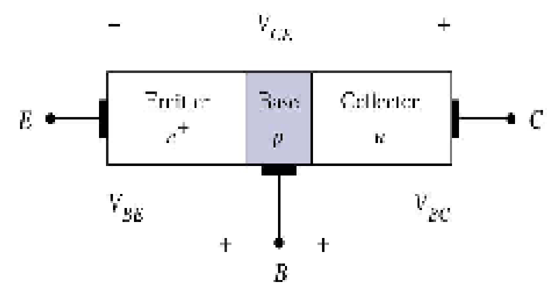
Bipolar junction transistor (BJT)….

Differences between NPN & PNP

PNP	NPN
If the base is at a lower voltage than the emitter, current flows from emitter to collector	If the base is at a higher voltage than the emitter, current flows from collector to emitter.
Small amount of current also flows from emitter to base.	Small amount of current also flows from base to emitter.
Emitter is heavily P-doped compared to collector. So, emitter and collector are not interchangeable.	Emitter is heavily N-doped compared to collector. So, emitter and collector are not interchangeable.
The base width is small compared to the minority carrier diffusion length. If the base is much larger, then this will behave like back-to-back diodes.	The base width is small compared to the minority carrier diffusion length. If the base is much larger, then this will behave like back-to-back diodes.
Voltage at base controls amount of current flow through transistor (emitter to collector).	Voltage at base controls amount of current flow through transistor (collector to emitter).
	
Follow the arrow to see the direction of current flow	Follow the arrow to see the direction of current flow

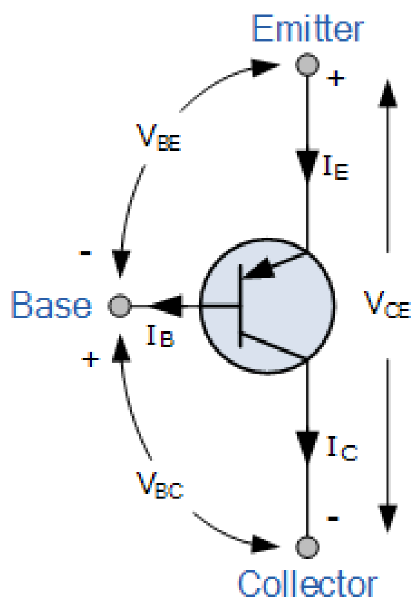
Bipolar Transistor Action

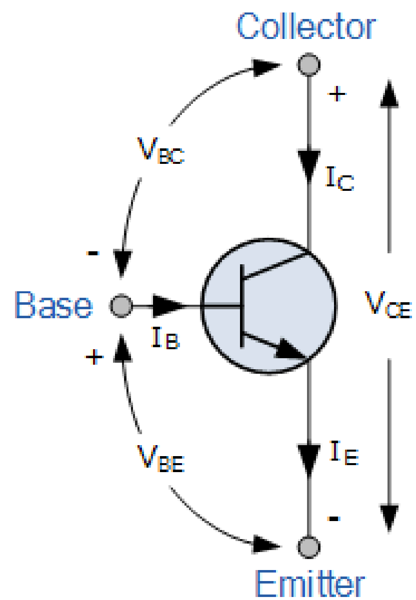




PNP Transistor

NPN Transistor





Idealized one-dimensional schematic of a p-n-p bipolar transistor and its circuit symbol.
Idealized one-dimensional schematic of an n-p-n bipolar transistor and its circuit symbol.

Bipolar Transistor Action….

Principle of Operation

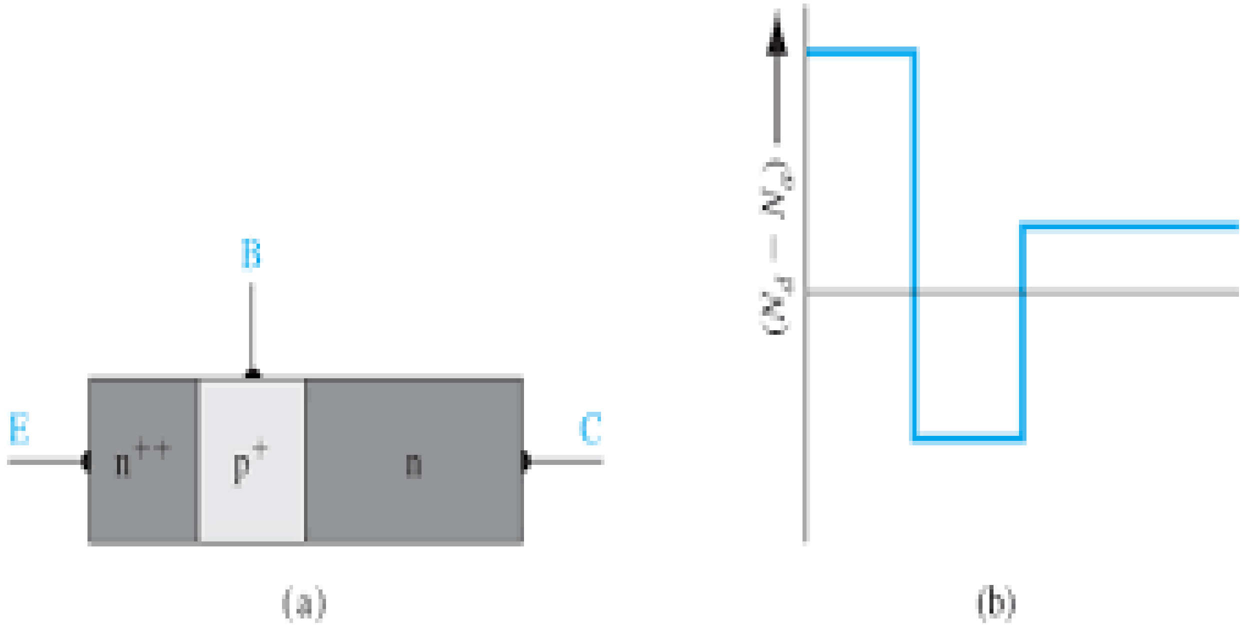
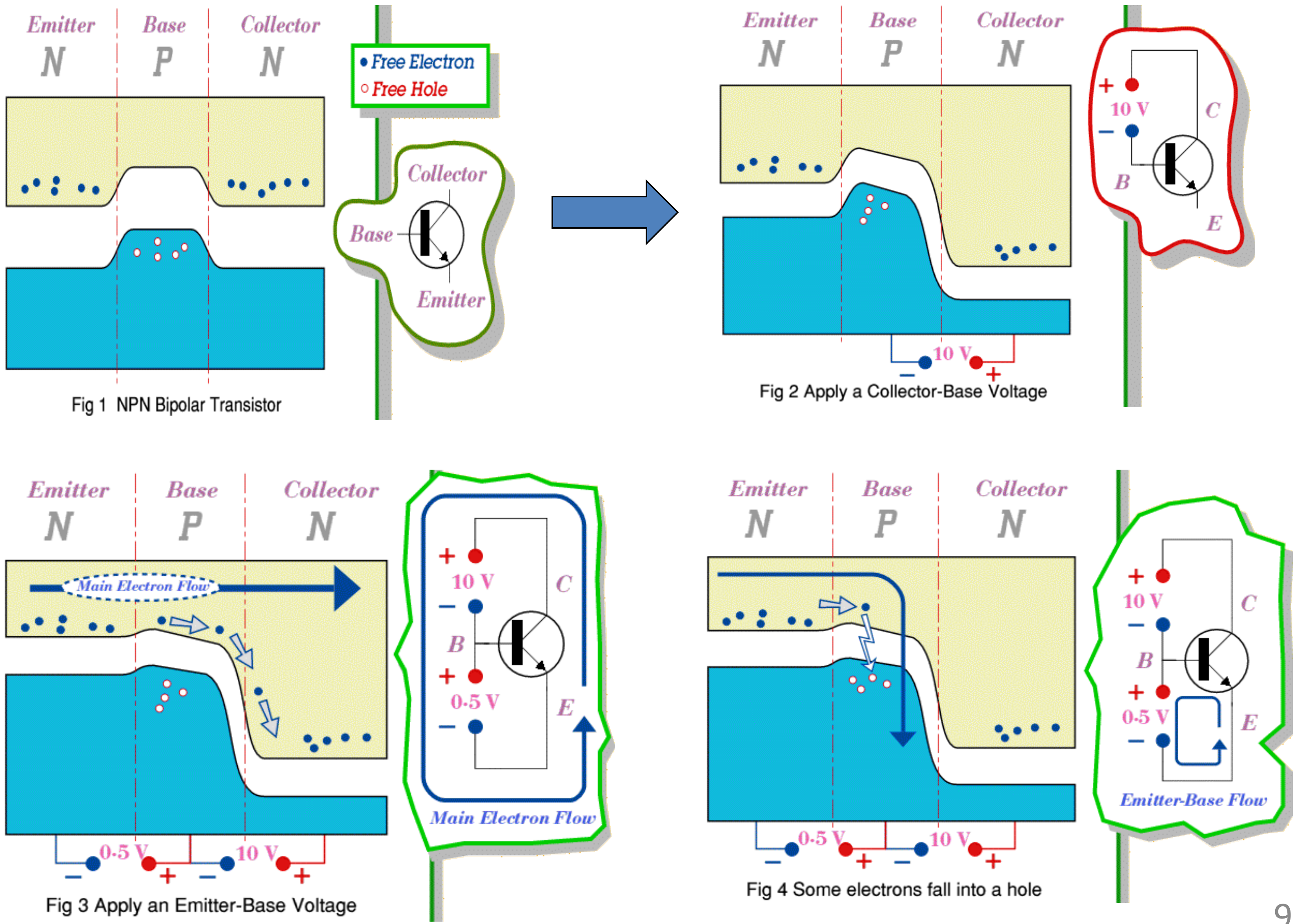


Figure 12.3 | Idealized doping profile of a uniformly doped npn bipolar transistor.

- Each region is uniformly doped.
- Typical impurity doping concentrations in the emitter, base, and collector may be on the order of 10^{19}, $10^{17}$and 10^{15} respectively.

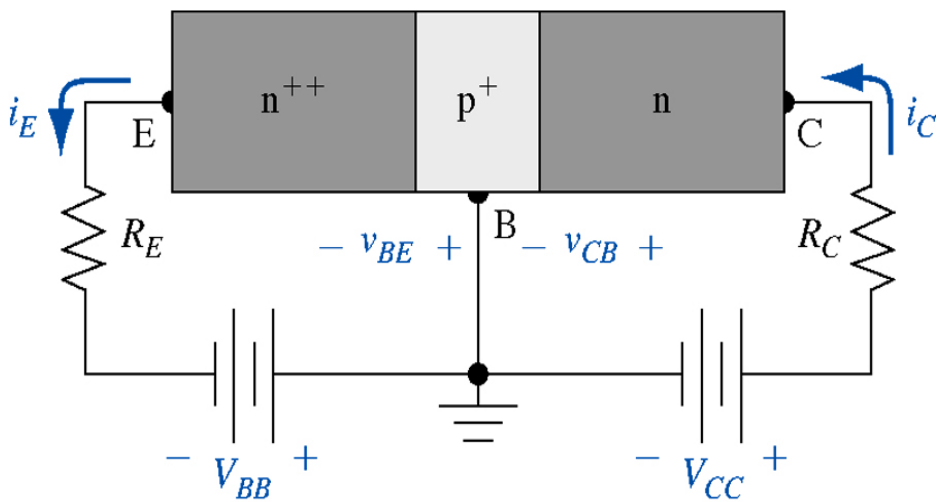
Principle of Operation….



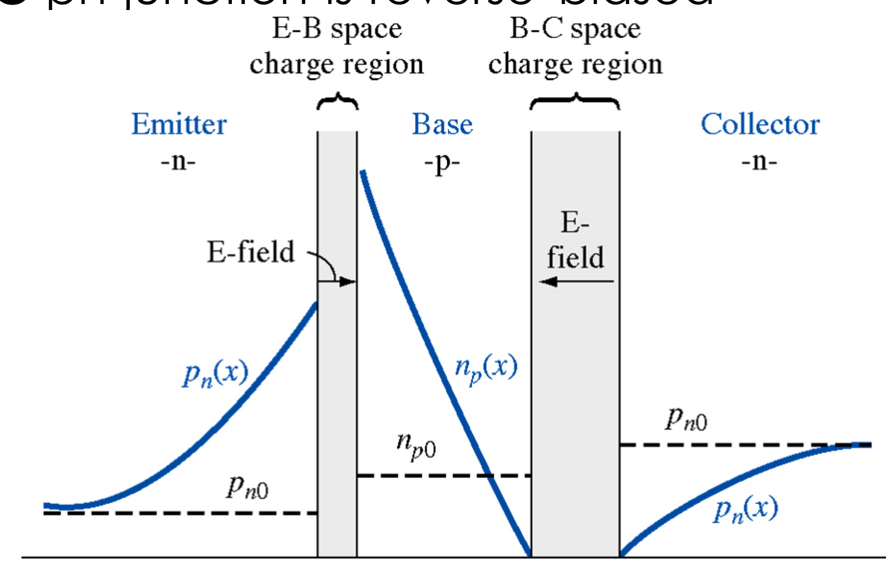
Principle of Operation….

Forward active mode:

- The **B–E** pn junction is forward ,the **B–C** pn junction is reverse–biased



Biasing of an npn bipolar transistor in the forward–active mode



Minority carrier distribution in an npn bipolar transistor in the forward–active mode

- The **B–E** pn junction is forward biased (so electrons from the emitter are injected across the **B–E** junction into the base) while the **B–C** pn junction is reverse–biased (so the minority carrier electron concentration at the edge of B–C junction is ideally zero).

- The width of the base needs to be small compared with minority carrier diffusion length (so that as many electrons as possible to reach the collector without recombining with any majority carrier holes in the base).

Principle of Operation….

Modes operation of Bipolar Transistor.

Active mode:

- **E–B** junction is forward biased, **B–C** junction is reverse –biased

Saturation mode:

- both junctions are forward biased
- corresponds to small biasing V and large output I – transistor is in a conducting state & acts as a closed (or on) switch

Cutoff mode:

- both junctions are reverse–biased
- corresponds to the open (or off) switch

Inverted mode:

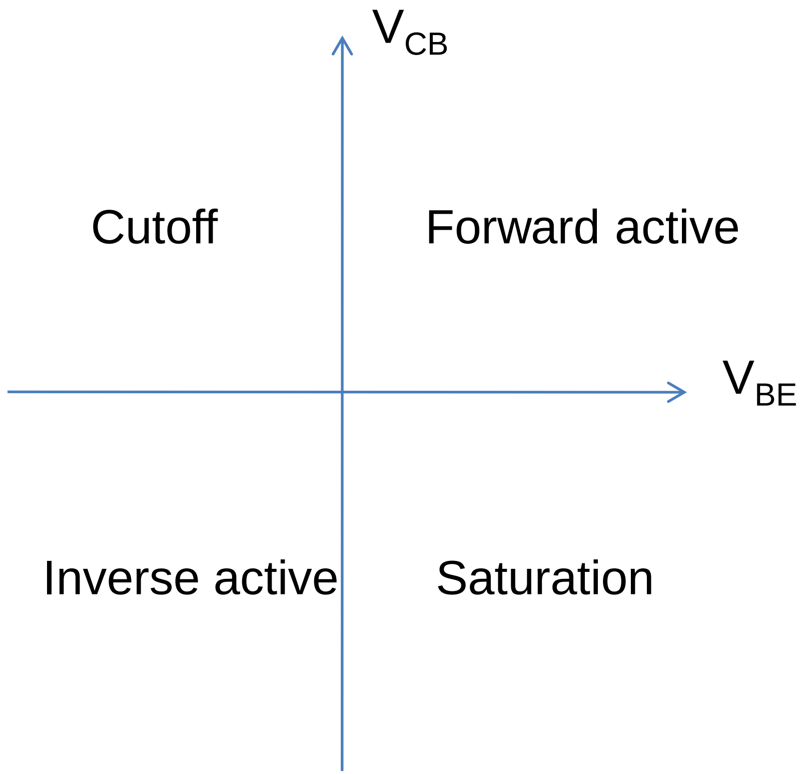
- inverted active mode
- **E–B** junction is reverse–biased, **C–B** junction is forward biased

Principle of Operation….

Bias Mode

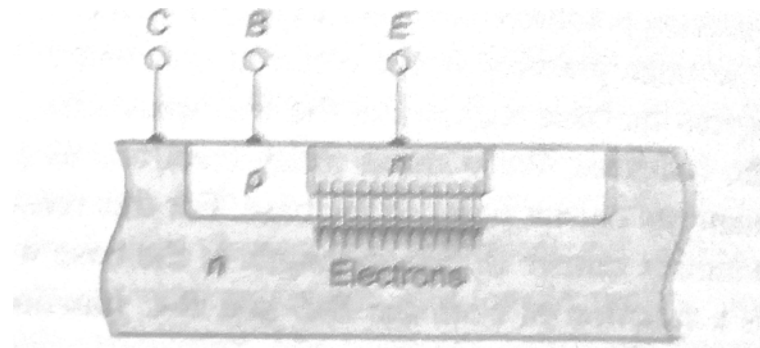
A bipolar transistor has four modes of operation, depending on the voltage polarities on the emitter-base junction and the collector-base junction.

BIASING MODE	BIASING POLARITY E-B JUNCTION	BIASING POLARITY C-B JUNCTION
Saturation	Forward	Forward
Active	Forward	Reverse
Inverted	Reverse	Forward
Cutoff	Reverse	Reverse



Junction voltage conditions for the four operating modes of a <u>npn bipolar transistor</u>

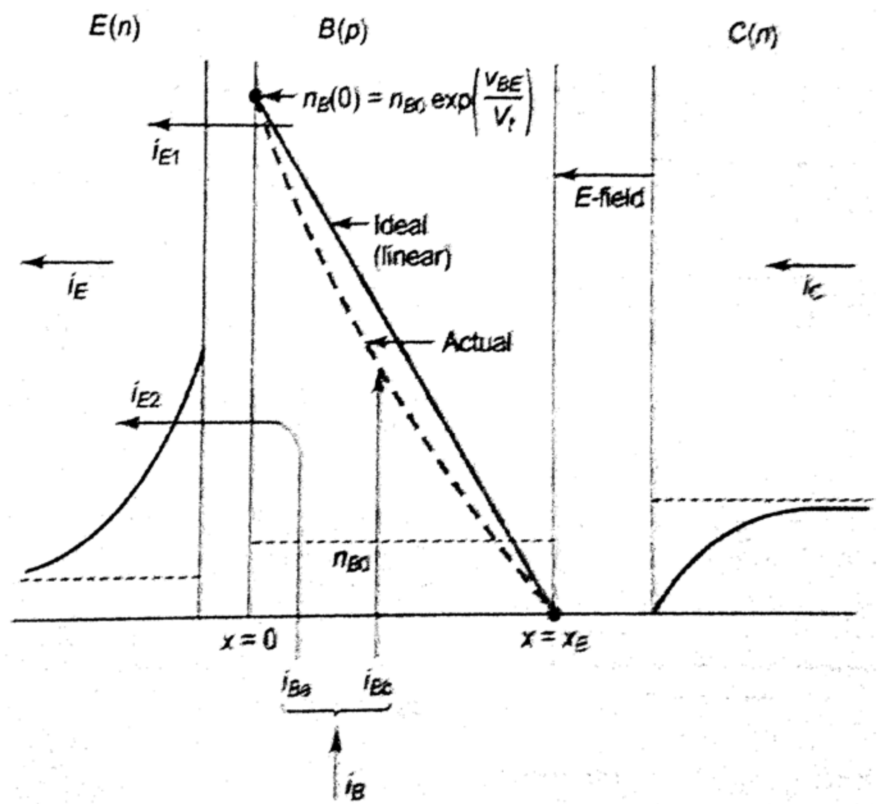
Transistor Current Relations



- The minority concentrations for an bipolar transistor biased in the forward active mode.

- Ideally. the minority electron concentration in the base is a linear function of distance, which implies recombination.

- The electrons diffuse across the base and are swept into the collector by the electric field in the B-C space charge region.



Transistor Current Relations……

Collector Current

Consider linear distribution in base, the collector current as diffusion current is

$$i_C = eD_n A_{BE} \frac{dn(x)}{dx}$$

$$i_C = eD_n A_{BE} \left[\frac{n_B(0) - 0}{0 - x_B} \right]$$

Diffusion electron in +x direction so current in –x direction

$$i_C = \frac{eD_n A_{BE}}{x_B} n_{B0} e^{(\frac{V_{BE}}{V_t})}$$

A_{BE} is the cross section area of B-E junction

n_{B0} is thermal equilibrium electron concentration

$$i_C = I_S e^{(\frac{V_{BE}}{V_t})}$$

Collector current is controlled by the base-emitter voltage

Current at one terminal is controlled by voltage applied to other terminal of device

Emitter Current

- ✓ One component of emitter current, shown in Figure is due to the flow of elections injected from the emitter into the base.
- ✓ This current equals to the collector current

$$i_{E1} = i_C = I_{S1} e^{\left(\frac{V_{BE}}{V_t}\right)}$$

- ✓ The base-emitter junction is forward bias, majority carrier holes in the base are injected across the B-E junction into emitter.
- ✓ These injected holes produce a pn junction current as indicated in Figure. This current is only a B-E junction current so this component of emitter current is not part of the collector current.
- ✓ The forward-biased pn junction current is another component of emitter current

$$i_{E2} = I_{S2} e^{\left(\frac{V_{BE}}{V_t}\right)}$$

I_{s2} involve the minority carrier hole parameter in emitter

Emitter Current.....

Total emitter current

$$i_{E1} = i_{E1} + i_{E2} = i_C + i_{E2} = I_{SE} e^{\left(\frac{V_{BE}}{V_t}\right)}$$

The ratio of collector current and emitter current is

$$\frac{i_C}{i_E} = \alpha$$

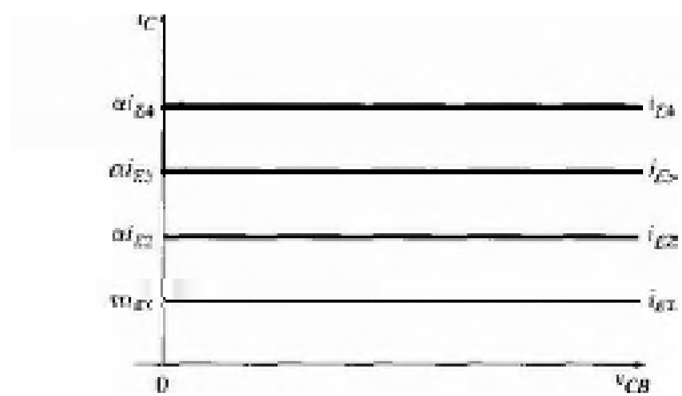


Figure 10.7 | Ideal bipolar transistor common-base current–voltage characteristics.

α is called common base current gain

Since $i_C < i_E$ or $\alpha < 1$

Base Current.....

- component of emitter current, i_{E2} is a B-E junction so this current is also a component of base current i_{E2}

$$i_{Ba} = i_{E2} = I_{S1} e^{\left(\frac{V_{BE}}{V_t}\right)}$$

- There is another component of base current
- Since we considered that in ideal case there is no recombination of minority carrier electrons with carrier holes in the base.
- However, in reality, there will be some recombination. Since majority carrier holes in the base are disappearing, they must be resupplied by a flow of positive charge into the base terminal.
- This flow of charge is indicated as a current i_{Bb}.
- The number of holes per unit time recombining is directly related to the number of minority carrier electrons in the base.
- Therefore, the current i_{Bb} is proportional to exp(V_{BE}/V_t)
- The base current is the sum of and i_{Ba} and i_{Bb} is proportional to exp(V_{BE}/V_t)
- The ratio of collector current to base current is a constant since current, directly proportional to exp.

$$\frac{i_C}{i_B} = \beta$$

β is called common emitter current gain

Modes of Operation

- For given configuration, transistor may be biased in one of three modes of operation.
- If the B-E voltage is zero or reverse biased then majority carrier electrons from the emitter will not be injected into the base.
- The B-C junction is also reverse biased; thus. the emitter and collector currents will be zero for case.
- This condition is referred as cut off (all the current in transistor id zero)
- When the B-E junction becomes forward biased, an emitter current will be generated and the injection of electrons into the base results in a collector current.

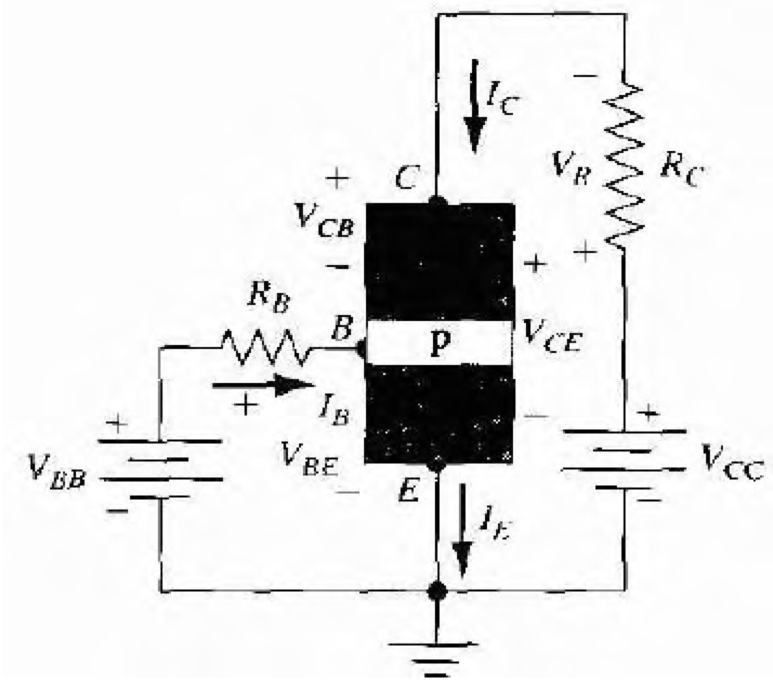


Figure 10.8 | An npn bipolar transistor in a common-emittercircuit configuration.

Modes of Operation……

- Using KVL equations around the collector-emitter loop as we get

$$V_{CC} = I_C R_C + V_{CB} + V_{BE} = V_R + V_{CE}$$

- If V_{CC} is large and V_R is small enough then $V_{CB} > 0$, that means B-C junction is reverse biased and this condition is the forward active region of operation.

- As the B-E voltage increases, I_C and hence V_R will also increase that means the reverse-biased C-B voltage decreases, or $|V_{CB}|$ decreases.

- At some point, I_C may becomes large enough that the combination of V_R and V_{CC} produces zero voltage across the B-C junction.

- A slight increase in I_C beyond this point will cause a slight increase in V_R and B-C junction will become forward biased ($V_{CB} < 0$). This condition is called saturation.

- In the saturation mode of operation, both B-E and B-C junctions are forward biased and the collector current is no longer controlled by the B-E voltage.

Modes of Operation……

$$V_{CE} = V_{CC} - I_C R_C$$

- A linear relation between collector current and collector-emitter voltage is called a load line.
- The load line. superimposed on the transistor characteristics, can be used to visualize the bias condition and operating mode of the transistor.
- The cut off mode occurs when I_C =0,
- Saturation occurs when there is no longer a change in collector current for change in base current,
- The forward-active mode occurs when the relation $I_C = \beta I_B$ is valid.

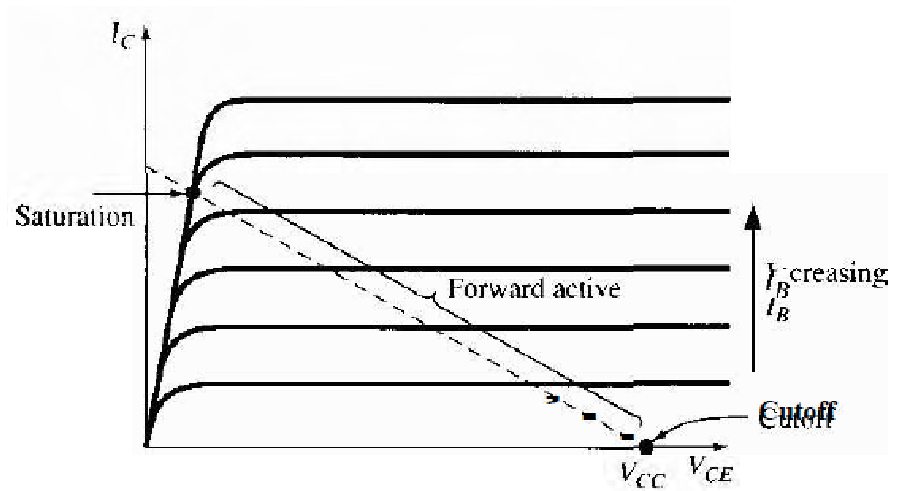
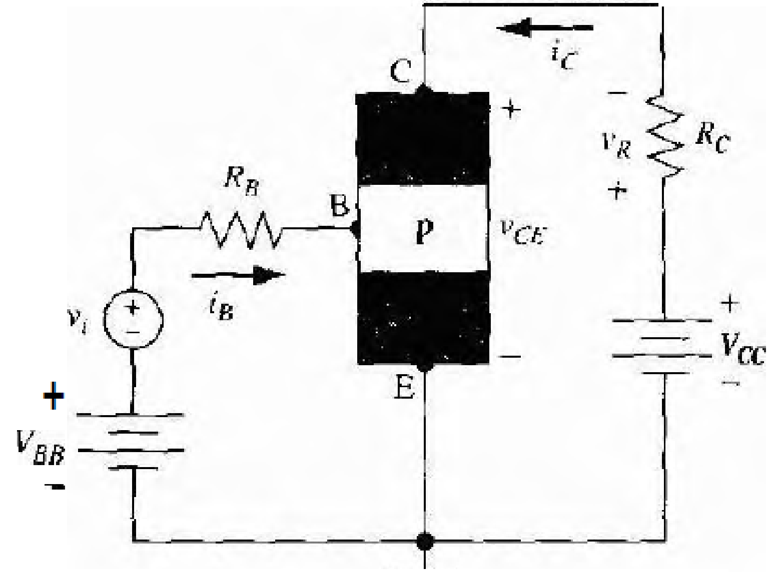


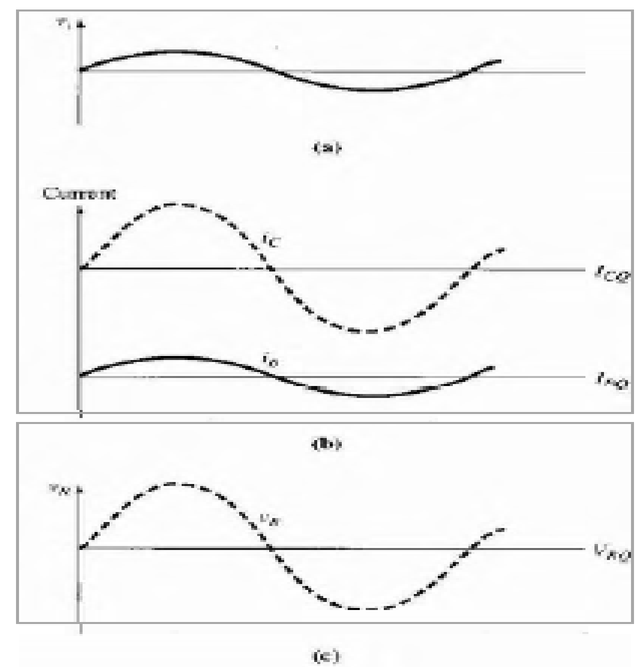
Figure 10.9 | Bipolar transistor common-emittercurrent–voltage characteristics with load line superimposed.

- A fourth mode of operation for the transistor is possible. This mode, known as inverse active, occurs when the B-E junction is reverse biased and the B-C junction forward biased. In this case the transistor is operating "upside down," and the roles of the emitter and collector are reversed.
- The transistor is not a symmetrical device; therefore, the inverse-active characteristics will not be the same as the forward-active

Amplification with Bipolar Transistors

- Voltages and currents can be amplified by bipolar transistors in conjunction with other elements.
- The dc voltage sources, V_{BB} and V_{CC} are used to bias the transistor in the forward-active mode.
- The voltage source represents a time-varying input voltage v_i (sinusoidal form) that needs to be amplified.
- The v_i induces a sinusoidal component of I_B superimposed on a dc quiescent value.
- Since $I_C = \beta I_B$ then a relatively large sinusoidal I_C is superimposed on a dc value of I_C. The time-varying I_C induces a time-varying voltage across the resistor R_C.
- A sinusoidal voltage, superimposed on a dc value, exists between the collector and emitter that are larger than the signal input voltage so that the circuit has produced a voltage gain in the time-varying signals. Hence, the circuit is known as a voltage amplifier.





Minority Carrier Distribution

The current in BJT is calculated under steady state through a simple pn junction theory applying minority carrier diffusion.

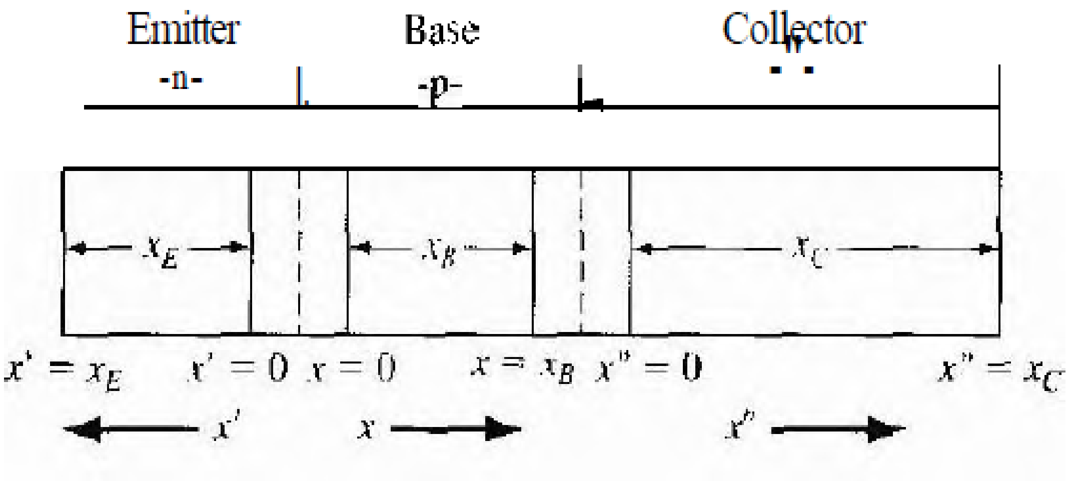
Table 10.1 | Notation used in the analysis of the bipolar transistor

Notation	Definition
For both the npn and pnp transistors	
N_E, N_B, N_C	Doping concentrations in the emitter, base, and collector
x_E, x_B, x_C	Widths of neutral emitter, base, and collector regions
D_E, D_B, D_C	*Minority carrier* diffusion coefficients in emitter, base, and collector regions
L_E, L_B, L_C	*Minority carrier* diffusion lengths in emitter, base, and collector regions
$\tau_{E0}, \tau_{B0}, \tau_{C0}$	*Minority carrier* lifetimes in emitter, base, and collector regions
For the npn	
p_{E0}, n_{B0}, p_{C0}	Thermal equilibrium *minority carrier* hole, electron, and hole concentrations in the emitter, base, and collector
$p_E(x'), n_B(x), p_C(x'')$	Total *minority carrier* hole, electron, and hole concentrations in the emitter base, and collector
$\delta p_E(x'), \delta n_B(x), \delta p_C(x'')$	Excess *minority carrier* hole, electron, and hole concentrations in the emitter, base, and collector
For the pnp	
n_{E0}, p_{B0}, n_{C0}	Thermal equilibrium *minority carrier* electron, hole, and electron concentrations in the emitter, base, and collector
$n_E(x'), p_B(x), n_C(x'')$	Total *minority carrier* electron, hole, and electron concentrations in the emitter, base, and collector
$\delta n_E(x'), \delta p_B(x), \delta n_C(x'')$	Excess *minority carrier* electron, hole, and electron concentrations in the emitter, base, and collector

Minority Carrier Distribution

Forward–active mode

Figure: Geometry of the npn bipolar transistor doped uniformly used to calculate the minority carrier distribution



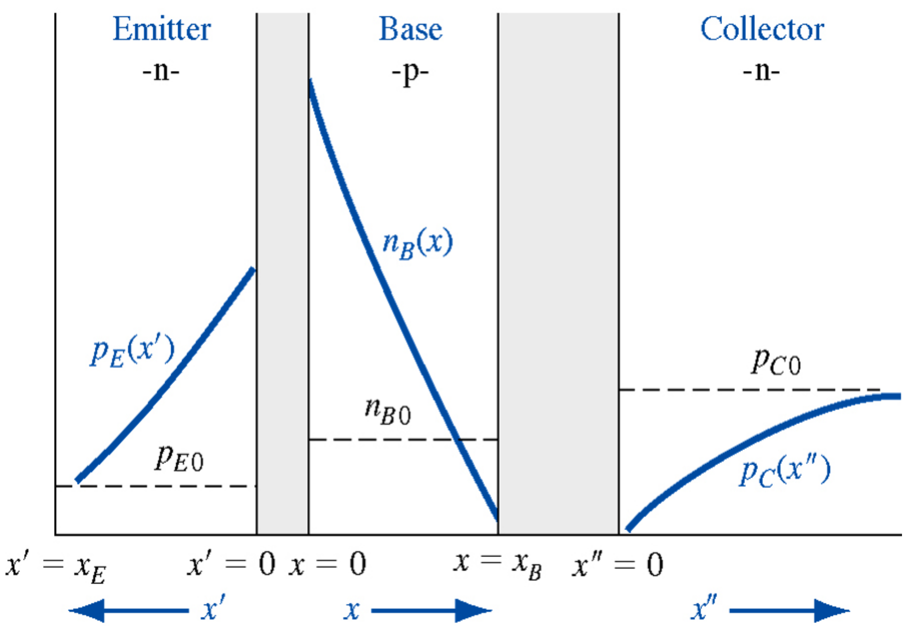


Figure: Minority carrier distribution in an npn bipolar transistor operating in the forward–active mode

$P_E(x,)$, $n_B(x)$ and $P_C(x'')$ are steady state minority carrier concentration in E, B and C respectively.

p_{E0}, n_{B0} and p_{C0} are thermal equilibrium minority carrier concentration in E, B and C respectively.

Consider that $x_C >> L_C$ and $x_E \cong L_C$

Minority Carrier Distribution.....

- In the forward active mode, the **B-E** junction is forward-biased and the **B-C** junction is reverse-biased.
- As there are two n-regions, there will be minority carrier holes in both emitter and collector

Base region

Excess Minority carrier concentration is calculated suing ambipolar transport equation

$$\boxed{D_n \frac{\partial^2(\delta n)}{\partial x^2} + \mu_n E \frac{\partial(\delta n)}{\partial x} + g' - \frac{\delta n}{\tau_{n0}} = \frac{\partial(\delta n)}{\partial t}}$$

For zero electric field in neutral base region and zero generation rate, under steady state above equation becomes

$$\boxed{D_B \frac{\partial^2(\delta n_B(x))}{\partial x^2} - \frac{\delta n_B(x)}{\tau_{B0}} = 0}$$

The excess minority concentration is defined as

$$\boxed{\delta n_B(x) = n_B(x) - n_{B0}}$$

Minority Carrier Distribution…..

General solution is

$$\boxed{\delta n_B(x) = Ae^{\left(\frac{+x}{L_B}\right)} + Be^{\left(\frac{-x}{L_B}\right)}}$$

Where L_{Bn} is minority carrier electron life time is base

$$\boxed{L_B = \sqrt{D_B \tau_{B0}}}$$

The excess minority carrier electron concentration in the base region is given as:

$$\delta n_B(x) = \frac{n_{B0}\left\{\left[exp\left(\frac{eV_{BE}}{kT}\right) - 1\right] sinh\left(\frac{x_B - x}{L_B}\right) - sinh\left(\frac{x}{L_B}\right)\right\}}{sinh\left(\frac{x_B}{L_B}\right)}$$

Using the approximation that sinh(x) ~ x for x<<1, the excess electron concentration in the <u>**base is given by:**</u>

$$\boxed{\delta n_B(x) \approx \frac{n_{B0}}{x_B}\left\{\left[exp\left(\frac{eV_{BE}}{kT}\right) - 1\right](x_B - x) - x\right\}}$$

Minority Carrier Distribution.....

Emitter region

In n-type semiconductor ambipolar transport equation for Excess Minority carrier concentration

$$D_p \frac{\partial^2(\delta p)}{\partial x^2} - \mu_p E \frac{\partial(\delta p)}{\partial x} + g' - \frac{\delta p}{\tau_{p0}} = \frac{\partial(\delta p)}{\partial t}$$

For zero electric field in neutral base region and zero generation rate, under steady state above equation becomes

$$D_E \frac{\partial^2(\delta p_E(x'))}{\partial x'^2} - \frac{\delta p_E(x')}{\tau_{E0}} = 0$$

where D_E and τ_{E0} are minority carrier diffusion coefficient and minority carrier life time.

The excess minority concentration is defined as

$$\boxed{\delta p_B(x') = p_E(x') - p_{E0}}$$

Minority Carrier Distribution…..

General solution is

$$\boxed{\delta p_E(x') = Ce^{(\frac{+x'}{L_E})} + De^{(\frac{-x'}{L_E})}}$$

Where L_E is minority carrier electron life time is base

$$\boxed{L_E = \sqrt{D_E \tau_{E0}}}$$

Assume that neutral emitter length x_E is not long compared to L_E.

The excess minority carrier electron concentration in the emitter region is given as

$$\delta p_E(x') = \frac{p_{E0}\left[exp\left(\frac{eV_{BE}}{kT}\right) - 1\right] sinh\left(\frac{x_E - x'}{L_E}\right)}{sinh\left(\frac{x_E}{L_E}\right)}$$

This excess concentration will vary approximately linearly with distance if x_E is small. Thus:

$$\boxed{\delta p_E(x') \approx \frac{p_{E0}}{x_E}\left[exp\left(\frac{eV_{BE}}{kT}\right) - 1\right](x_E - x')}$$

Minority Carrier Distribution.....

Collector region

Again ambipolar transport equation for Excess Minority carrier concentration at zero electric field in neutral collector region and zero generation rate, under steady state

$$D_C \frac{\partial^2 (\delta p_C(x''))}{\partial x''^2} - \frac{\delta p_C(x'')}{\tau_{C0}} = 0$$

where D_C and τ_{C0} are minority carrier diffusion coefficient and minority carrier life time.

The excess minority concentration (hole) in collector region is

$$\boxed{\delta p_C(x'') = p_C(x'') - p_{C0}}$$

General solution is

$$\boxed{\delta p_C(x'') = Ge^{(\frac{+x''}{L_C})} + He^{(\frac{-x''}{L_C})}}$$

Where L_C is minority carrier electron life time is base

$$\boxed{L_C = \sqrt{D_C \tau_{C0}}}$$

Minority Carrier Distribution…..

Assume that neutral emitter length x_C is long compared to L_C then coefficient G must be zero since the excess concentration must remain finite.

The second boundary condition gives .

$$\boxed{\delta p_C(x''=0) = \delta p_C(0) = p_C(x''=0) - p_{C0} = 0 - p_{C0} = -p_{C0}}$$

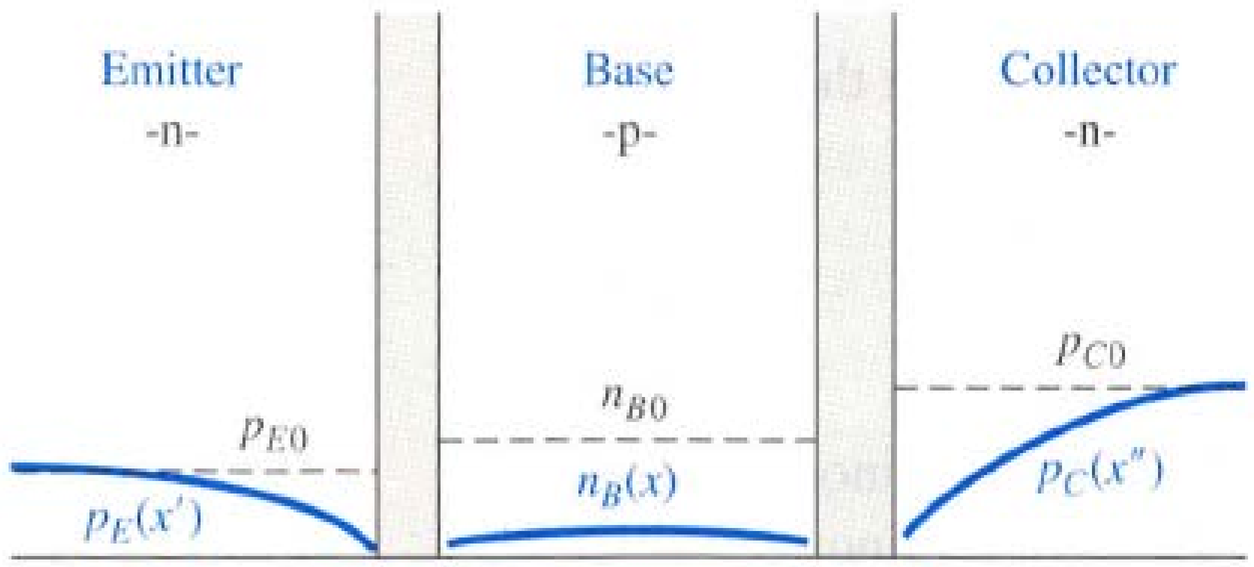
The excess minority carrier hole concentration in the collector is given by:

$$\boxed{\delta p_C(x'') = -p_{C0} exp\left(\frac{-x''}{L_C}\right)}$$

The result is exactly what we expect from the results of a reverse-biased pn junction.

Other Modes of Operation

Cutoff mode



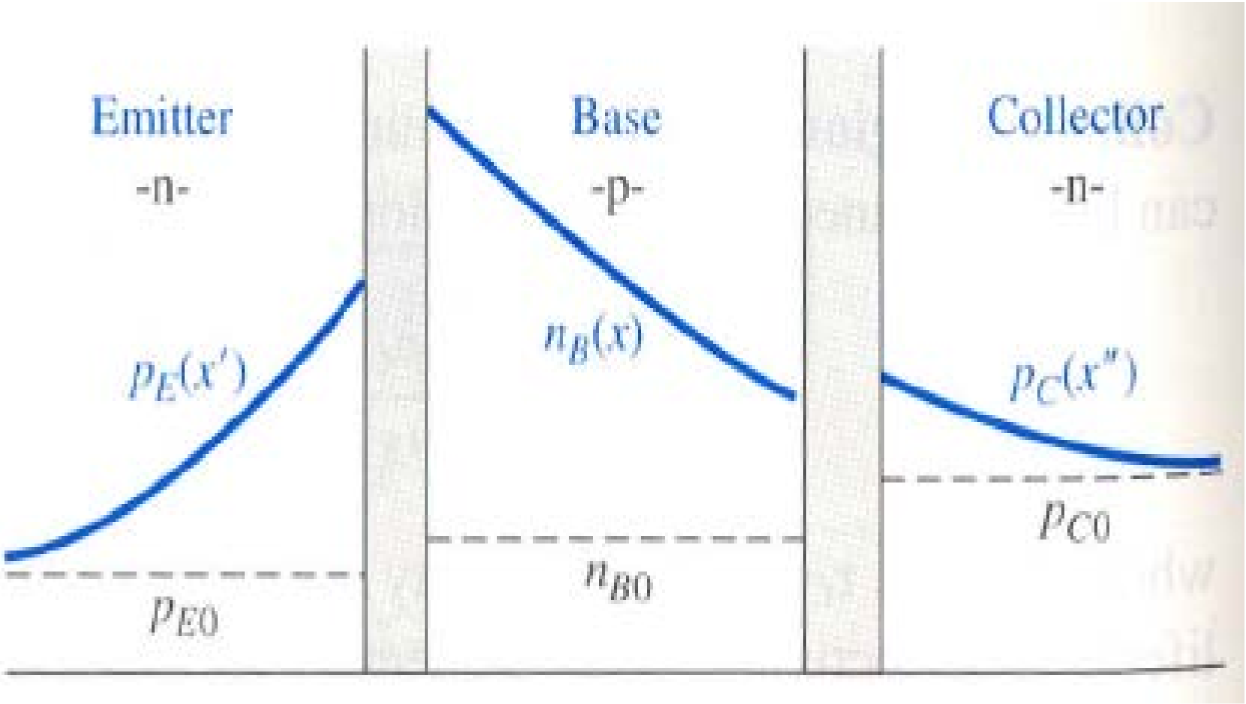
Minority carrier distribution in an npn bipolar transistor operating in cutoff mode

- Both the B-E and B-C junction is reverse-biased in cutoff mode, thus the minority carrier concentrations are zero at each space charge edge.

- The emitter and collector regions are assumed to be long, whereas the base is narrow compared with the minority carrier diffusion length, $X_B << L_B$, essentially all minority carriers are swept out of the base region.

Other Modes of Operation……

Saturation mode



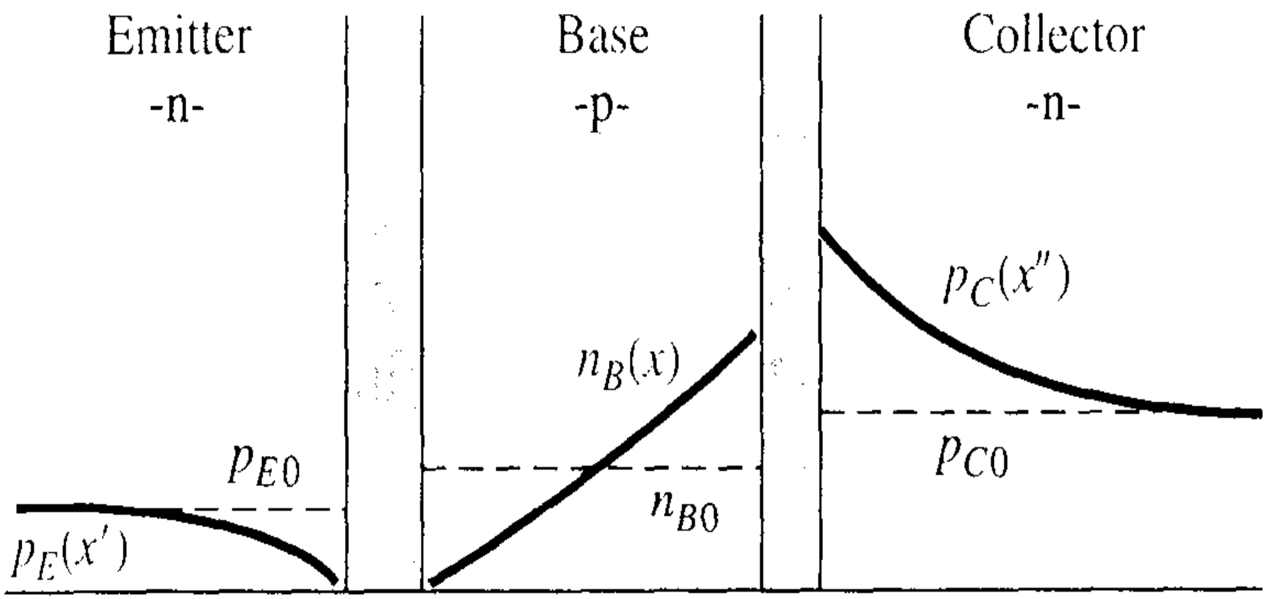
Minority carrier distribution in an npn bipolar transistor operating in saturation mode

- B-E and B-C junction is forward-biased in saturation mode, thus excess minority carriers exist at the edge of each space charge region.

- _Since a collector current still exists when the transistor is in saturation, a gradient will still exist in the minority carrier electron concentration in the base.

Other Modes of Operation……

Inverse–active mode



Minority carrier distribution in an npn bipolar transistor operating in inverse–active mode

- The B-E is reverse-biased and B-C junction is forward-biased in inverse active mode, thus electrons from the collector are now injected into the base.

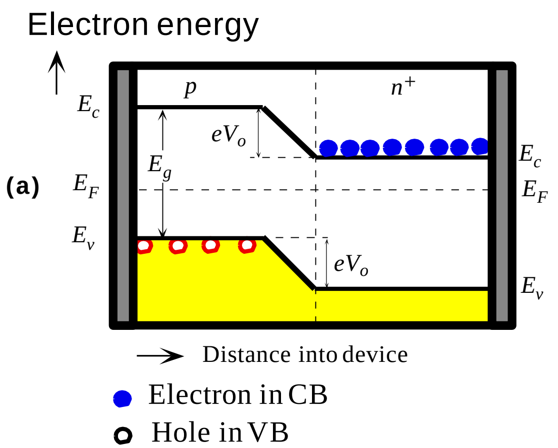
- The gradient in the minority carrier electron concentration in the base is in the opposite directions compared with the forward active mode, so the collector and emitter currents will change direction.

Unit-III

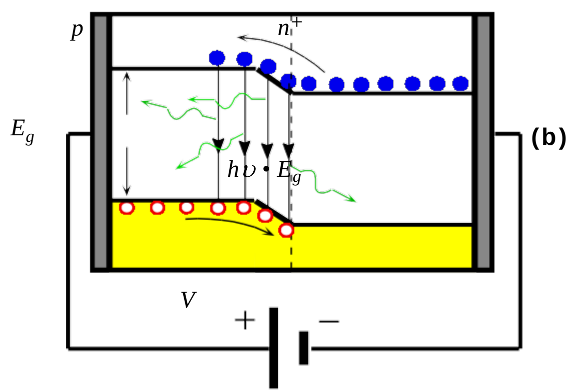
- Bipolar Transistors
- Field Effect Transistors
  - JFET
  - MOSFET
- **Light-Emitting Diodes**

Principles of LED

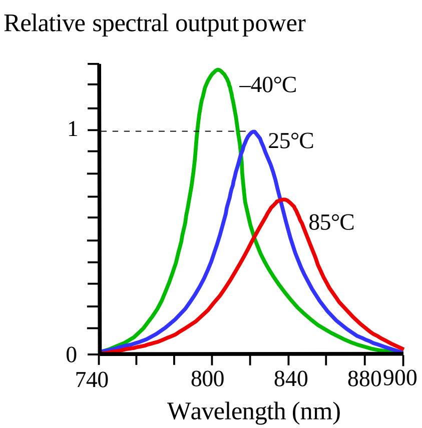
- LEDs are pn junctions usually made from direct band gap semiconductor such as GaAs.
- Direct electron hole pair (EHP) recombination results in emission of a photon. Photon energy is approximately equal to the band gap energy $E_g = h\nu$
- Applied voltage in forward bias drops built-in-voltage allowing more electrons into the p side and increasing the probability of recombination in the depletion region.
- The recombination zone is called the active region and is the volume in which photons are generated.
- Light emission from EHP recombination as a result of minority carrier injection is called injection electroluminescence.
- The statistical nature of this process requires that the p side be sufficiently narrow to prevent reabsorption of the emitted photons



The energy band diagram of a p-n^+ (heavily n-type doped) junction without any bias.



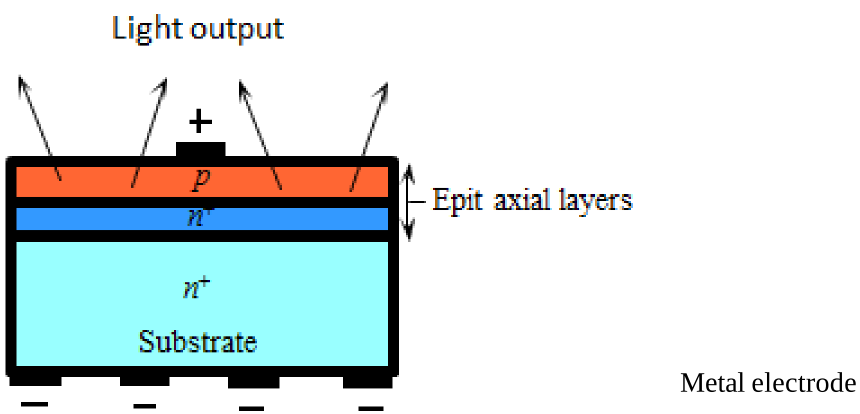
With applied bias



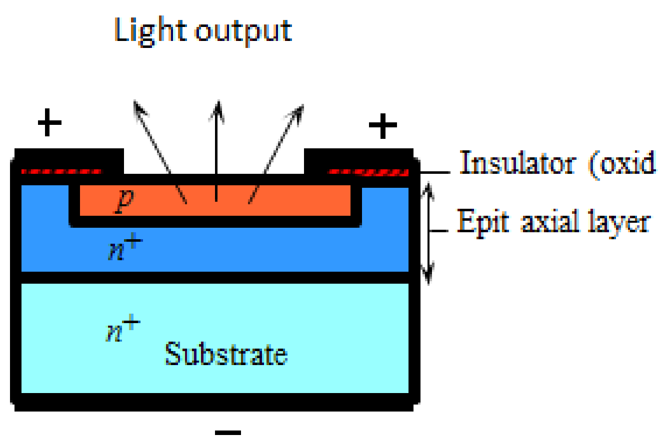
The output spectrum from AlGaAs LED. Values normalized to peak emission at 25°C.

LED Device Structures

- ✓ LED's are typically formed by epitaxially growing doped semiconductors layers on suitable substrate. The substrate is then essentially a mechanical support for the device.
- ✓ However if the epi film and the substrate have mismatched lattice sizes then the lattice strain on the LED leads to crystalline defects that cause indirect recombination of EHPs and a loss of electroluminescence (photon emission). Thus the substrate is usually the same material as the epi layers.
- ✓ To insure that recombination occurs on the p side, the n side is very heavily doped. Photons emitted toward the n side become absorbed or reflected back at the substrate interface.
- ✓ The use of segmented metal electrodes on the back promotes reflections.



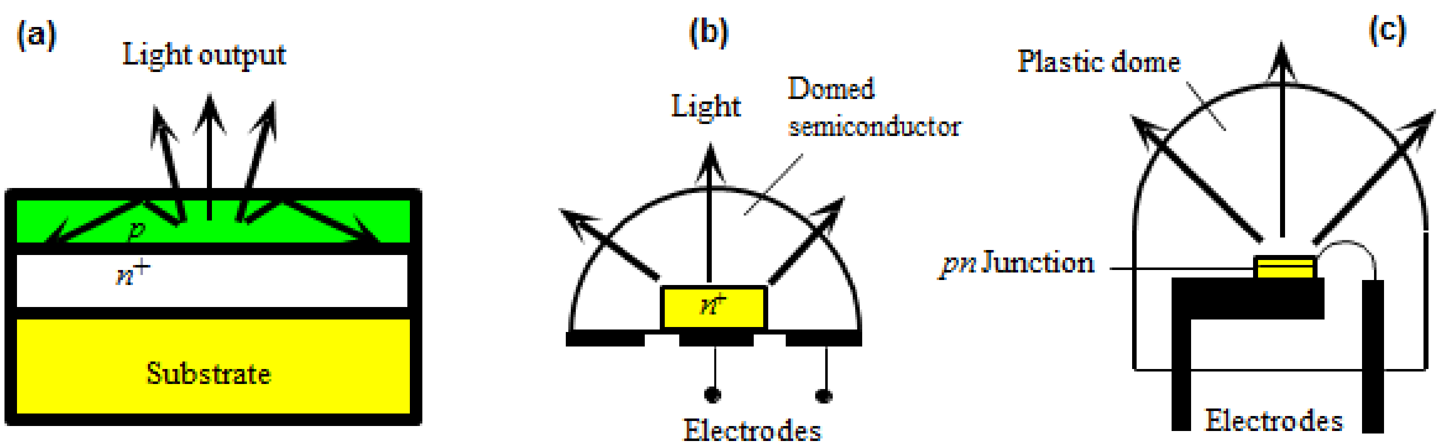
A schematic illustration of typical planar surface emitting LED devices. (a) p-layer grown epitaxially on an n^+ substrate.



(b) First n^+ is epitaxially grown and then p region is formed by dopant diffusion into the epitaxial layer.

Optimizing Light Output vs. TIR

- Not all light reaching the semiconductor air interface escape the surface due to TIR (critical angle for TIR in GaAs-air is only 16º.
- Thus engineers attempt to shape the surface of the semiconductor into a dome or hemisphere so that the light rays strike the surface at angles less than θ_c.
- The main drawback is the additional processing required to achieve these devices.
- The common method is to seal a plastic dome to the LED surface that moderates the index change ($n_{GaAs} > n_{plastic} > n_{air}$) and increases the critical angle for TIR



(a) Some light suffers total internal reflection and cannot escape.

(b) Internal reflections can be reduced and hence more light can be collected by shaping the semiconductor into dome so that the angles of incidence at the semiconductor-air surface are smaller than the critical angle.

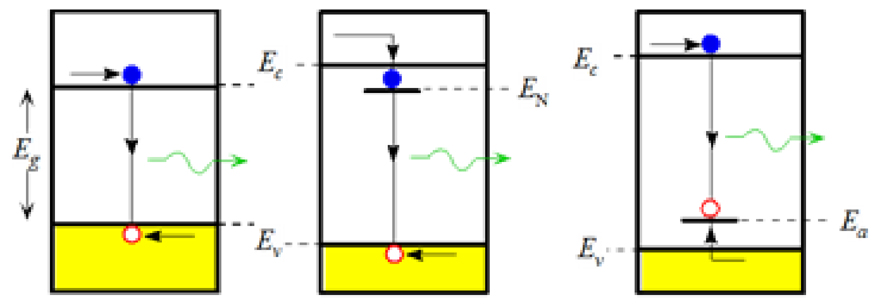
(c) An economic method of allowing more light to escape from the LED is to encapsulate it in a transparent plastic dome.

LED Materials

$GaAs_{1-y}P_y$ — $y = 0.45$ — $\lambda = 870 nm$

$GaAs$ — $y = 0$ — $\lambda = 630 nm$

- Various direct bandgap semiconductor pn junctions can be used to make LEDs that emit in the red and infrared range.
- III-V ternary alloys based on GaAs and GaP allow light in the visible spectrum.
- Doping of Ga materials with different As, P, and Al ratios maintains the lattice constant while allowing for precise control of the bandgap (photon energy emitted)
- GaAsP with As concentrations greater than 0.55% are direct bandgap semiconductors
- GaAsP with As concentrations less than 0.55% are indirect bandgap semiconductors.
- However, adding isoelectronic impurities such as N (same group V as P) into the semiconductor to substitute for P atoms
  - Provides a trap for indirect ECP recombination and generates direct bandgap emission between the trap and the hole.
  - Reduces light efficiency and alters wavelength.



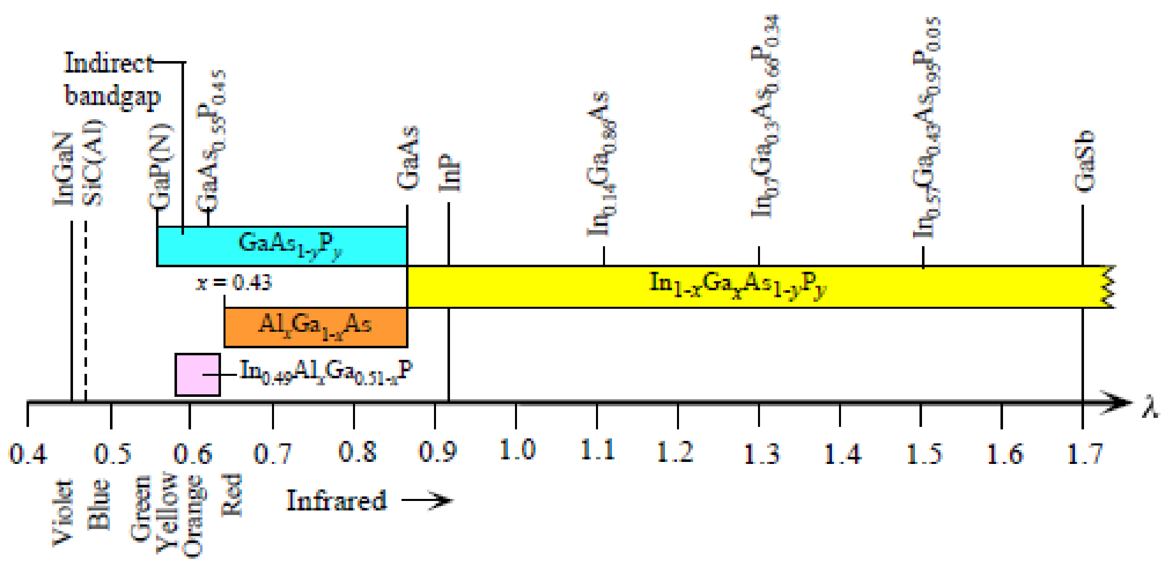
(a) $GaAs_{1-y}P_y$ $y < 0.45$ (b) N doped GaP (c) Al doped SiC

(a) Photon emission in a direct band gap semiconductor
(b) Gap is an indirect band gap semiconductor when doped with nitrogen. Direct recombination between a trapped electron and a hole emits a photon.
(c) In Al doped SiC , EHP recombination is through an accepter level

LED Materials……

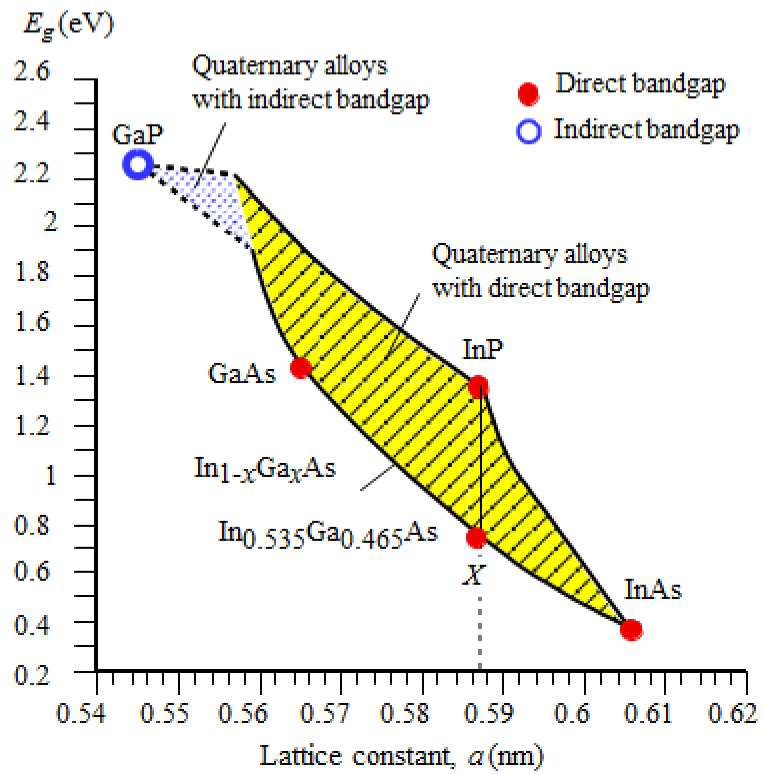
- ✓ Blue LED materials
- ✓ GaN is a direct bandgap with Eg = 3.4 eV
- ✓ InGaN alloy has Eg = 2.7 eV (blue)
- ✓ Less efficient is Al doped SiC (indirect)
  - –Aluminum captures holes and in a similar manner to N in GaAsPN materials and reduces the effective direct emission energy and efficiency of the device
- ✓ II-VI ZnSe semiconductors provide a direct bandgap blue emission

- ➢ Red and Infrared
- ➢ Three to four element alloys.
- ➢ $Al_{1-x}Ga_xAs$ with x<0.43 gives 870 nm
- ➢ Composition variances provide 650 – 870 nm
- ➢ $In_{1-x}Ga_xAl_{1-y}P_y$ can be varied to span 870 nm (GaAs) to 3.5 um (InAs)



Free space wavelength coverage by different LED materials from the visible spectrum to the infrared including wavelengths used in optical communications. Hatched region and dashed lines are indirect E_g materials.

LED Materials……



- Bandgap energy E_g and lattice constant a for various III-V alloys of GaP, GaAs, InP and InAs.
- A line represents a ternary alloy formed with compounds from the end points of the line.
- Solid lines are for direct bandgap alloys whereas dashed lines for indirect bandgap alloys.
- Regions between lines represent quaternary alloys.
- The line from X to InP represents quaternary alloys $In_{1-x}Ga_xAs_{1-y}P_y$ made from $In_{0.535}Ga_{0.465}As$ and InP which are lattice matched to InP.

Light Emitting Materials and Efficiency

- External efficiency
  - Quantifies the efficiency of conversion from electrical energy into emitted external optical energy

$$\eta_{external} = \frac{P_{out}(Optical)}{IV} \times 100\%$$

  - Typically less than 20% for direct bandgap semiconductors
  - Less than 1% for indirect bandgap semiconductors
- Efficiency has been increased by altering the shape, periodicity, and material interfaces within a device

TABLE 3.1 Selected LED semiconductor materials. Optical communication channels are at 850 nm (local network) and at 1.3 and 1.55 μm (long distance). D = Direct, I = Indirect bandgap, DH = Double heterostructure. $\eta_{external}$ is typical and may vary substantially depending on the device structure.

Semiconductor	Substrate	D or I	λ (nm)	$\eta_{external}$ (%)	Comment
GaAs	GaAs	D	870–900	10	Infrared LEDs
$Al_xGa_{1-x}As$ $(0 < x < 0.4)$	GaAs	D	640–870	5–20	Red to IR LEDs. DH
$In_{1-x}Ga_xAs_yP_{1-y}$ $(y \approx 2.20x, 0 < x < 0.47)$	InP	D	1–1.6 μm	>10	LEDs in communications
InGaN alloys	GaN or SiC	D	430–460	2	Blue LED
	Saphire		500–530	3	Green LED
SiC	Si; SiC	I	460–470	0.02	Blue LED. Low efficiency
$In_{0.49}Al_xGa_{0.51-x}P$	GaAs	D	590–630	1–10	Amber, green, red LEDs
$GaAs_{1-y}P_y$ $(y < 0.45)$	GaAs	D	630–870	<1	Red-IR
$GaAs_{1-y}P_y$ $(y > 0.45)$ (N or Zn, O doping)	GaP	I	560–700	<1	Red, orange, yellow LEDs
GaP (Zn-O)	GaP	I	700	2–3	Red LED
GaP (N)	GaP	I	565	<1	Green LED

White light

There are two primary ways of producing high intensity white-light using LEDs.

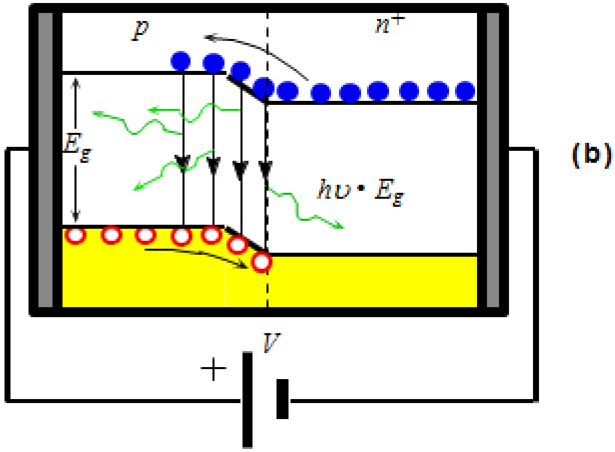
- One is to use individual LEDs that emit three primary colors – red, green, and blue, and then mix all the colors to produce white light.
- The other is to use a phosphor material to convert monochromatic light from a blue or UV LED to broad-spectrum white light, much in the same way a fluorescent light bulb works.

Light Emitting Materials and Efficiency…

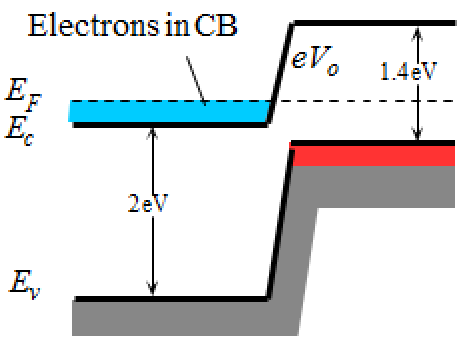
Color	Wavelength [nm]	Voltage [V]	Semiconductor Material
Infrared	λ > 760	ΔV < 1.9	Gallium arsenide (GaAs) Aluminium gallium arsenide (AlGaAs)
Red	610 < λ < 760	1.63 < ΔV < 2.03	Aluminium gallium arsenide (AlGaAs) Gallium arsenide phosphide (GaAsP) Aluminium gallium indium phosphide (AlGaInP) Gallium(III) phosphide (GaP)
Orange	590 < λ < 610	2.03 < ΔV < 2.10	Gallium arsenide phosphide (GaAsP) Aluminium gallium indium phosphide (AlGaInP) Gallium(III) phosphide (GaP)
Yellow	570 < λ < 590	2.10 < ΔV < 2.18	Gallium arsenide phosphide (GaAsP) Aluminium gallium indium phosphide (AlGaInP) Gallium(III) phosphide (GaP)
Green	500 < λ < 570	1.9[29] < ΔV < 4.0	Indium gallium nitride (InGaN) / Gallium(III) nitride (GaN) Gallium(III) phosphide (GaP) Aluminium gallium indium phosphide (AlGaInP) Aluminium gallium phosphide (AlGaP)
Blue	450 < λ < 500	2.48 < ΔV < 3.7	Zinc selenide (ZnSe) Indium gallium nitride (InGaN) Silicon carbide (SiC) as substrate Silicon (Si) as substrate — (under development)
Violet	400 < λ < 450	2.76 < ΔV < 4.0	Indium gallium nitride (InGaN)
Purple	multiple types	2.48 < ΔV < 3.7	Dual blue/red LEDs, blue with red phosphor, or white with purple plastic
Ultraviolet	λ < 400	3.1 < ΔV < 4.4	diamond (C) Aluminium nitride (AlN) Aluminium gallium nitride (AlGaN) Aluminium gallium indium nitride (AlGaInN) — (down to 210 nm[30])
White	Broad spectrum	ΔV = 3.5	Blue/UV diode with yellow phosphor

Homojunction vs. heterojunction LEDS

- pn junctions between two materials doped components of the same material (and thus the same bandgap) are called homojunctions
- Require narrow p type wells to channel photons out of the device prior to absorption
- Narrow channels lead to indirect recombination of electrons that reach defects located at the top surface of the p-type material, thereby reducing efficiency
- Junctions formed by two different bandgap semiconductor materials are called heterojunctions
  - Heterostructure devices (HD) are devices between two different bandgap semiconductors such as AlGaAs and GaAs



homojunction



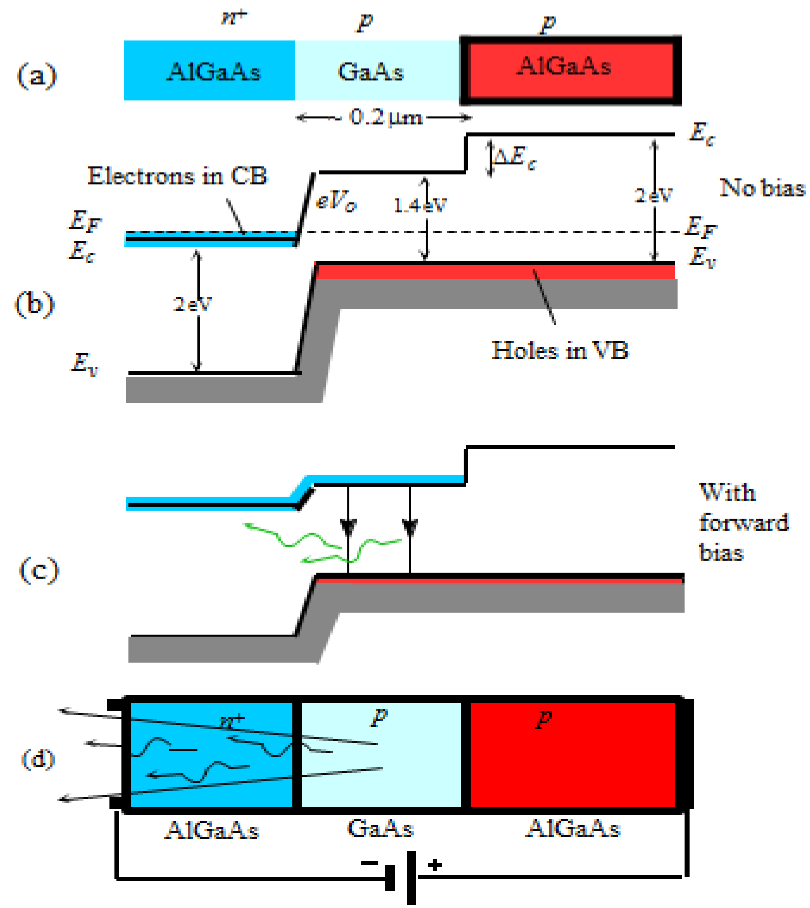
heterojunction

Heterojunction High Intensity LEDS

- The refractive index, n, depends directly on the bandgap.
  - wide bandgap semiconductors have lower refractive indices.
  - we can engineer the dielectric waveguide within the device and channel the photons out from the recombination region

- Adding a double heterostructure (DH) to LEDs reduces radiationless recombination
  - Introduces a higher bandgap behind the pn junction that localizes the optical generation region.
  - The additiona p type region is known as a confining layer.
  - Since the bandgap of AlGaAs is larger than that of GaAs emitted photons cannot get reabsorbed in the AlGaAs regions.
  - Metal reflects light from the back side of the confining layer improving efficiency.
  - n+ layer is used as topside of the device to reduce lattice defects in the active region and improve device efficiency

- DH LEDs are more efficient than homojunction LEDs



(a)A double heterostructure diode has two junctions which are between two different bandgap semiconductors (GaAs and AlGaAs)

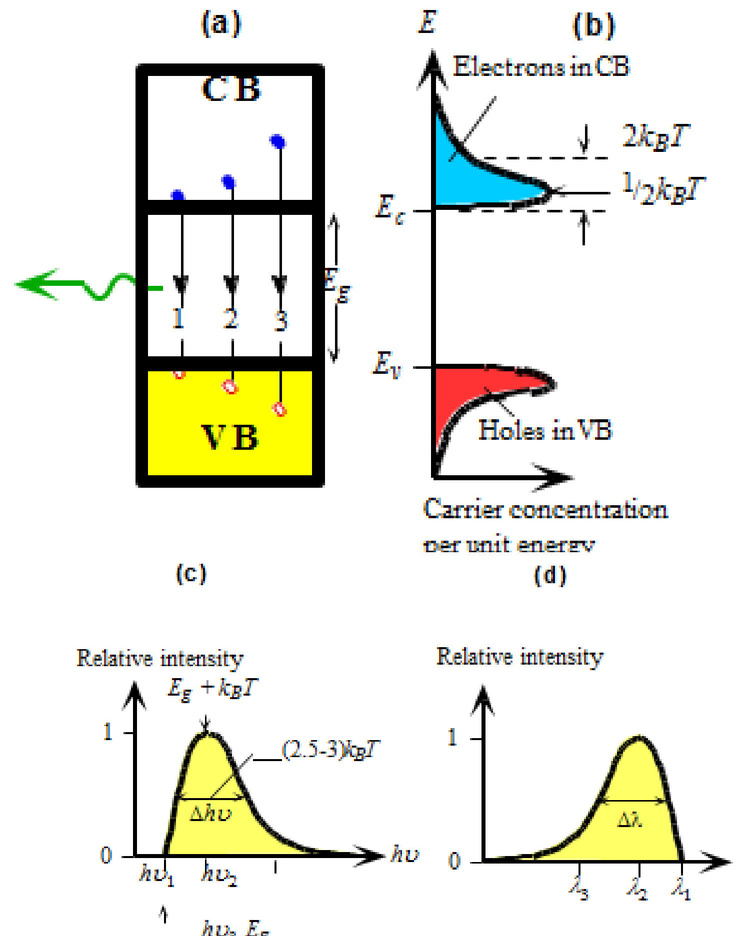
(b)A simplified energy band diagram with exaggerated features. E_F must be uniform.

(c)Forward biased simplified energy band diagram.

(d)Forward biased LED. Schematic illustration of photons escaping reabsorption in the AlGaAs layer and being emitted from the device.

LED Device Characteristics

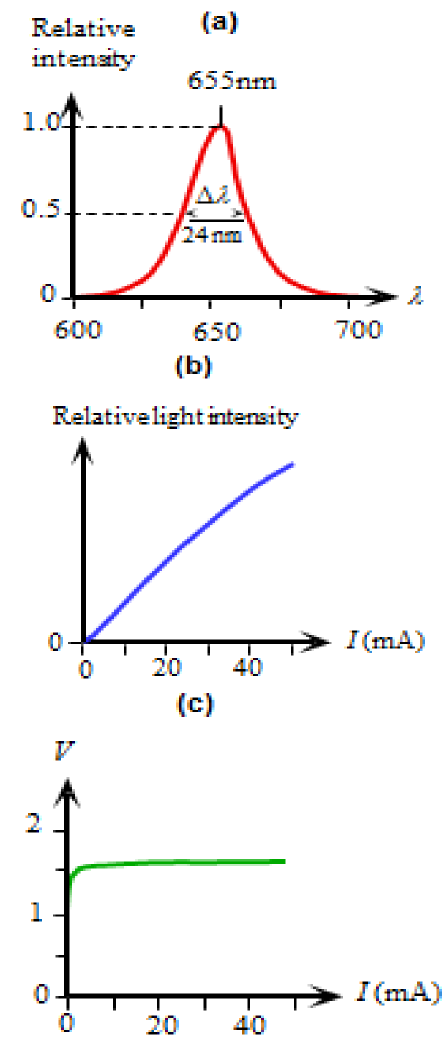
- The energy of emitted photon from LED is not simply equal to the band gap energy since electron in CB are distributed in energy and similarly holes in VC are also.
- The electron concentration as a function of energy is given as g(E)f(E) i.e. product of DOS and Fermi-Dirac function.
- Electron concentration in CB as a function of energy is asymmetrical with a peak at $1/2k_BT$ above E_c.
- The energy spread of electrons is typically $2k_BT$ from E_c.
- Similar observation is made in the VB for holes.
- The rate of direct recombination is proportional to both electron and hole concentration at the energy involved.
- Highest energy photon emissions have small probability
- Highest intensity comes from largest carrier concentration.
- Intensity falls off again with carrier concentration near the CB band edge



(a) Energy band diagram with possible recombination paths. (b) Energy distribution of electrons in the CB and holes in the VB. The highest electron concentration is $(1/2k)_BT$ above E_c. (c) The relative light intensity as a function of photon energy based on (b). (d) Relative intensity as a function of wavelength in the output spectrum based on (b) and (c)

LED Device Characteristics…..

- Spread of available carrier recombination probabilities generates a spread in optical wavelength emitted.
- Linewidth of the spectral output is typically between 2.5 and $3.5k_BT$.
- Notice in figure a that the relative intensity does not match the probabilistic intensity.
- This is due to the fact that as heavily doped n type semiconductors used to create efficiency in active p-type regions create a donor band that overlaps the conduction band and lowers the effective output wavelength.
- Turn on voltage is achieved at low operating currents and remains flat as current is increased.
- Below the turn on voltage, no light is emitted.
- The number of populated electrons in the p- type region increases and thus the relative light intensity also increases with increasing current.



(a)A typical output spectrum (relative intensity vs wavelength) from a red GaAsP LED.
(b)Typical output light power vs. forward current.
(c)(c) Typical I-V characteristics of a red LED. The turn-on voltage is around 1.5V.