MODULE III
(Syllabus)

PN junctions : Contact potential, Electrical Field, Potential and Charge distribution at the junction, Biasing and Energy band diagrams, Ideal diode equation.

Metal Semiconductor contacts, Electron affinity and work function, Ohmic and Rectifying Contacts, current voltage characteristics.

Bipolar junction transistor, current components, Transistor action, Base width modulation.

Bipolar junction transistor

- Two types of BJTs- NPN & PNP
- Three terminals each – Emitter, Base, Collector
- Two pn junctions each – Emitter-Base junction &
- Base-Collector junction.
- In NPN Tr- all terminal currents($I_{E,}$ $I_{B,}I_C$) are constituted by electrons.
- While in PNP all terminal currents are constituted by holes.
- Since 3 terminals only (not 4) - one terminal is common to both i/p &o/p, three configurations.
- CB (Common Base), CE, CC.

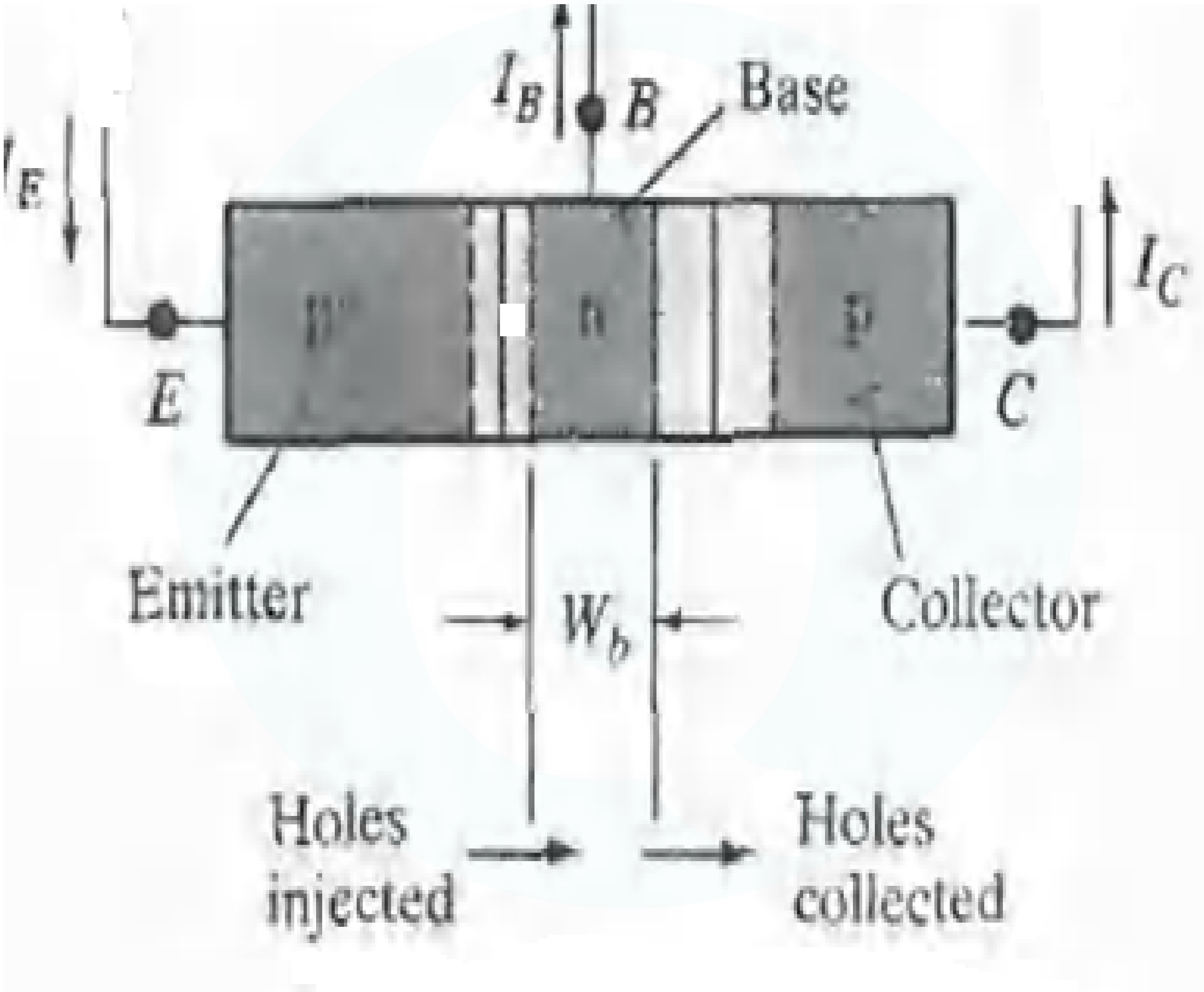
Bipolar junction transistor

- Three regions of operation- Cut off, Active , Saturation.
- Cut off- The two pn junctions are in reversre biased condition
- Active– Emitter-Base junction is forward biased & Base-Collector junction is reverse biased.
- Saturation– Both pn junctions are in forward biased condition.

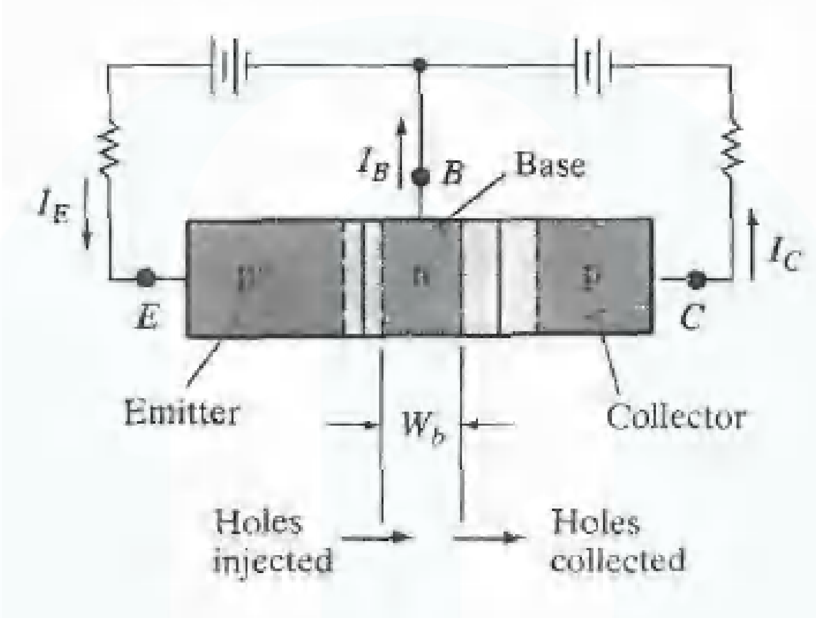
Bipolar junction transistor

- Two types of application- as a Switch & as an Amplifier.
- As a Switch- Tr operates between Cut off & Saturation or Active region.
- As an Amplifier- Tr operates in Active region.

Bipolar junction transistor- PNP



Bipolar junction transistor



A convenient hole injection device is a forward-biased p^+-n junction. The current is primarily due to holes injected from the p+ region into the n material.

With this configuration, injection of holes from the p^+-n junction into the center n region supplies the minority carrier holes to participate in the reverse current through the n-p junction.

The injected holes do not recombine in the n region before they can diffuse to the depletion layer of the reverse biased junction.

Thus n region must be narrow compared with a hole diffusion length.

The forward-biased junction which injects holes into the center n region is called the **emitter junction**

The reverse-biased junction which collects the injected holes is called the **collector junction**

The p+ region, which serves as the source of injected holes, is called the **emitter**

The p region into which the holes are swept by the reverse-biased junction is called the **collector**

The center n region is called the **base**

The biasing arrangement is called the **common base configuration**, since the base electrode B is common to the emitter and collector circuits.

A good p-n-p transistor - Almost all the holes injected by the emitter into the base be collected.

Thus the n-type base region should be narrow, and the hole lifetime τ_p should be long. i.e. $W_b << L_p$,

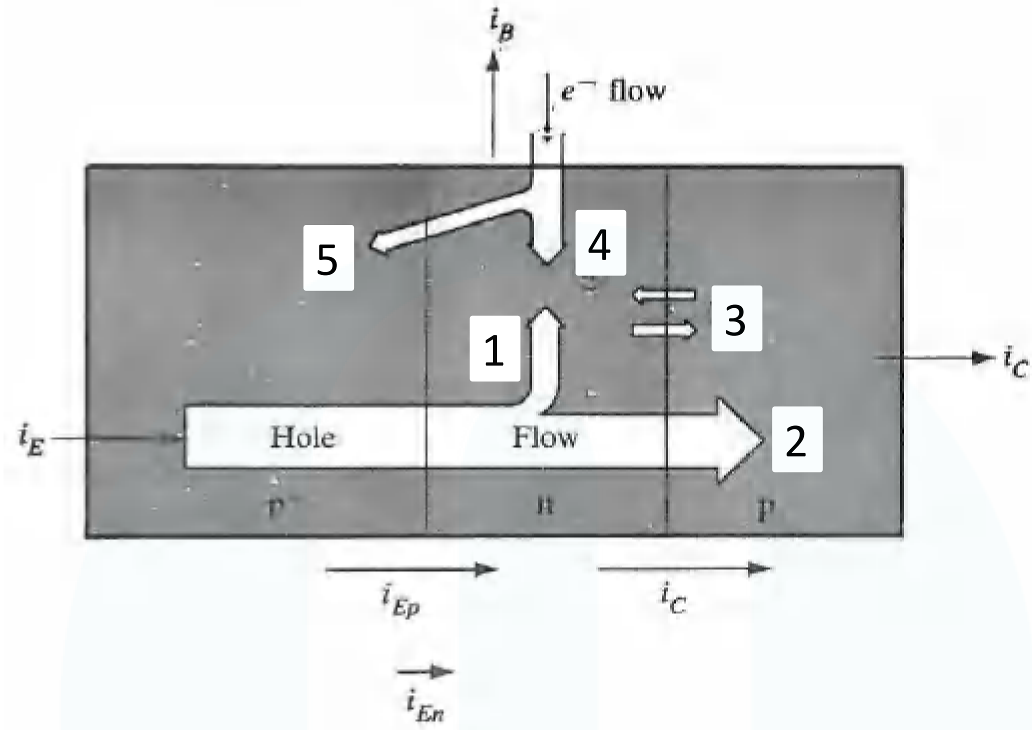
where W_b is the length of the neutral n material of the base

L_p is the diffusion length for holes in the base

With this requirement satisfied, an average hole injected at the emitter junction will diffuse to the depletion region of the collector junction without recombination in the base.

A second requirement is that the current I_E crossing the emitter junction should be composed almost entirely of holes injected into the base, rather than electrons crossing from base to emitter.

This requirement is satisfied by doping the base region lightly compared with the emitter



(1) Injected holes lost to recombination in the base

(2) Holes reaching the reverse-biased collector junction

(3) Thermally generated electrons and holes making up the reverse saturation current of the collector junction

(4) Electrons supplied by the base contact for recombination with holes

(5) Electrons injected across the forward-biased emitter junction.

I_E flows into the emitter of a properly biased p-n-p transistor

I_c flows out at the collector, since the direction of hole flow is from emitter to collector

I_B will be very small since I_E is essentially hole current, and the collected hole current I_c is almost equal to I_E

However, there must be some base current, due to requirements of electron flow into the n-type base region

We can account for I_B physically by three dominant mechanisms:

(a) There must be some recombination of injected holes with electrons in the base, even with $W_b << L_p$. The electrons lost to recombination must be resupplied through the base contact

(b) Some electrons will be injected from n to p in the forward-biased emitter junction, even if the emitter is heavily doped compared to the base. These electrons must also be supplied by I_B.

(c) Some electrons are swept into the base at the reverse-biased collector junction due to thermal generation in the collector. This small current reduces I_B by supplying electrons to the base.

The dominant sources of base current are

(a) Recombination in the base
(b) injection into the emitter region

Both of these effects can be greatly reduced by device design

In a well-designed transistor, I_B will be a very small fraction of I_E

In an **n-p-n transistor** the three current directions are reversed, since electrons flow from emitter to collector and holes must be supplied to the base.

The physical mechanisms for operation of the n-p-n can be understood simply by reversing the roles of electrons and holes in the p-n-p discussion.

Amplification with BJT

The transistor is useful in amplifiers because the currents at the emitter and collector are controllable by the relatively small base current.

The essential mechanisms are easy to understand if various secondary effects are neglected
Neglect the saturation current at the collector and such effects as recombination in the transition regions.

Under these assumptions, the collector current is made up entirely of those holes injected at the emitter which are not lost to recombination in the base.

Thus i_c is proportional to the hole component of the emitter current i_{Ep}

$$i_C = Bi_{Ep}$$

The proportionality factor B = fraction of injected holes which make it across the base to the collector, B is called the **base transport factor**

The total emitter current i_E is made up of the hole component i_{Ep} and the electron component i_{En} due to electrons injected from base to emitter

The **emitter injection efficiency** $$\boxed{\gamma = \frac{i_{Ep}}{i_{En} + i_{Ep}}}$$

For an efficient transistor : B and ϒ to be very near unity

The emitter current should be due mostly to holes (ϒ≈1)

Most of the injected holes should eventually participate in the collector current (B ≈ 1)

The relation between the collector and emitter currents is

$$\frac{i_C}{i_E} = \frac{Bi_{Ep}}{i_{En} + i_{Ep}} = B\gamma \equiv \alpha$$

α - current transfer ratio, which represents the **emitter-to-collector current amplification**.

There is no real amplification between these currents, since **α is smaller than unity.**

The relation between i_c and i_B is more promising for amplification

In accounting for the base current, we must include the rates at which electrons are lost from the base by injection across the emitter junction (i_{En}) and the rate of electron recombination with holes in the base.

In each case, the lost electrons must be resupplied through the base current i_B.

If the fraction of injected holes making it across the base without recombination is B, then it follows that (1 - B) is the fraction recombining in the base.

Thus the base current neglecting the collector saturation current is

$$i_B = i_{En} + (1 - B)i_{Ep}$$

The relation between the collector and base currents is

$$\frac{i_C}{i_B} = \frac{B i_{Ep}}{i_{En} + (1 - B) i_{Ep}}$$

$$= \frac{B[i_{Ep}/(i_{En} + i_{Ep})]}{1 - B[i_{Ep}/(i_{En} + i_{Ep})]}$$

$$\boxed{\frac{i_C}{i_B} = \frac{B\gamma}{1 - B\gamma} = \frac{\alpha}{1 - \alpha} \equiv \beta}$$

The factor **β** relating the collector current to the base current is the **base-to collector current amplification factor**

Since α is near unity, **β can be large** for a good transistor, and the collector current is large compared with the base current.

Transit time, τ_t – Time taken by average excess hole from emitter to collector.

Since $W_b << L_p$, $\tau_t << \tau_p$ in the base.

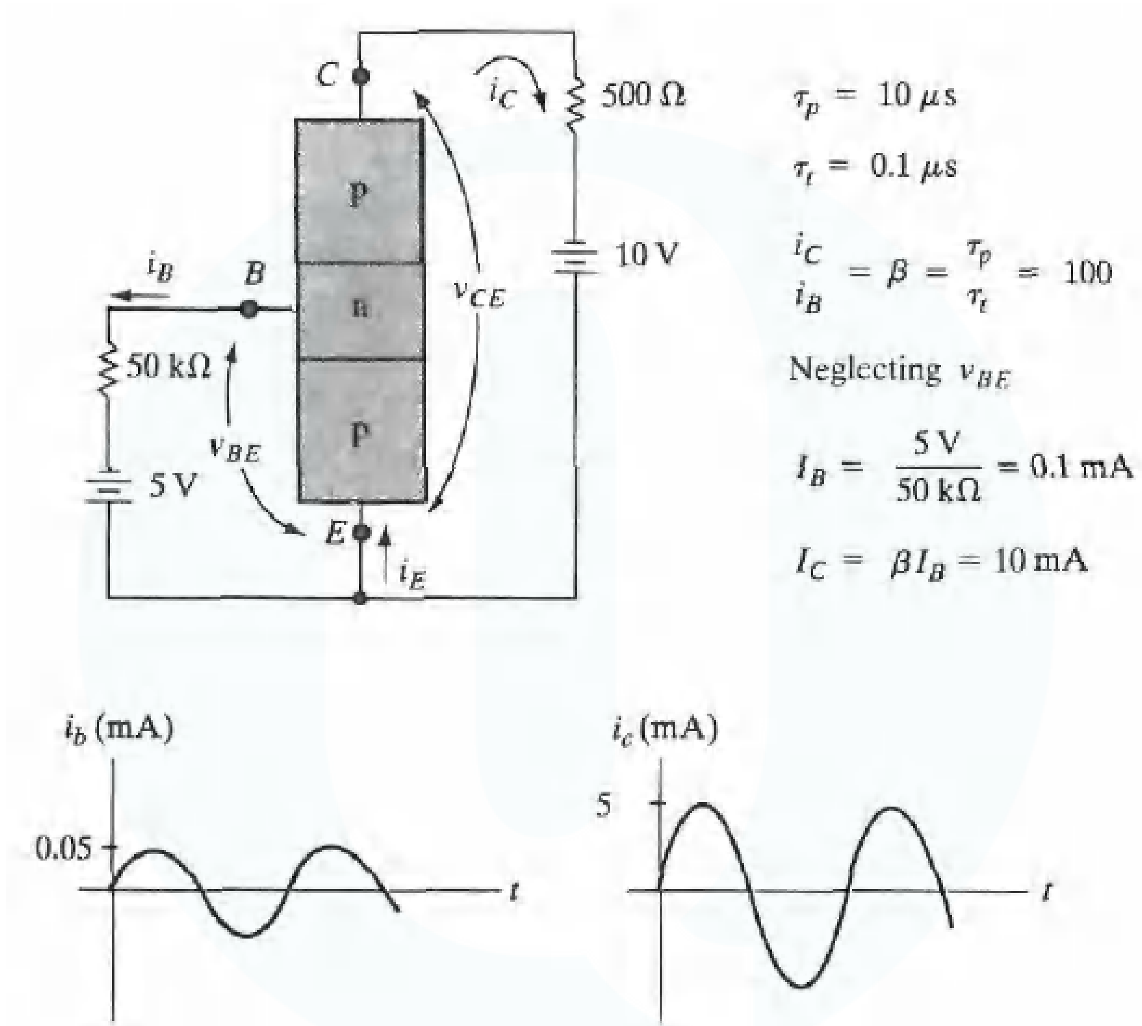
An average excess electron supplied from the base contact spends τ_p seconds in the base supplying space charge neutrality during the lifetime of an average excess hole.

While the average electron waits τ_p seconds for recombination, many individual holes can enter and leave the base region, each with an average transit time τ_t .

For each electron entering from the base contact, τ_p / τ_t holes can pass from emitter to collector while maintaining space charge neutrality.

Thus for $\Upsilon = 1$ and negligible collector saturation current,

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



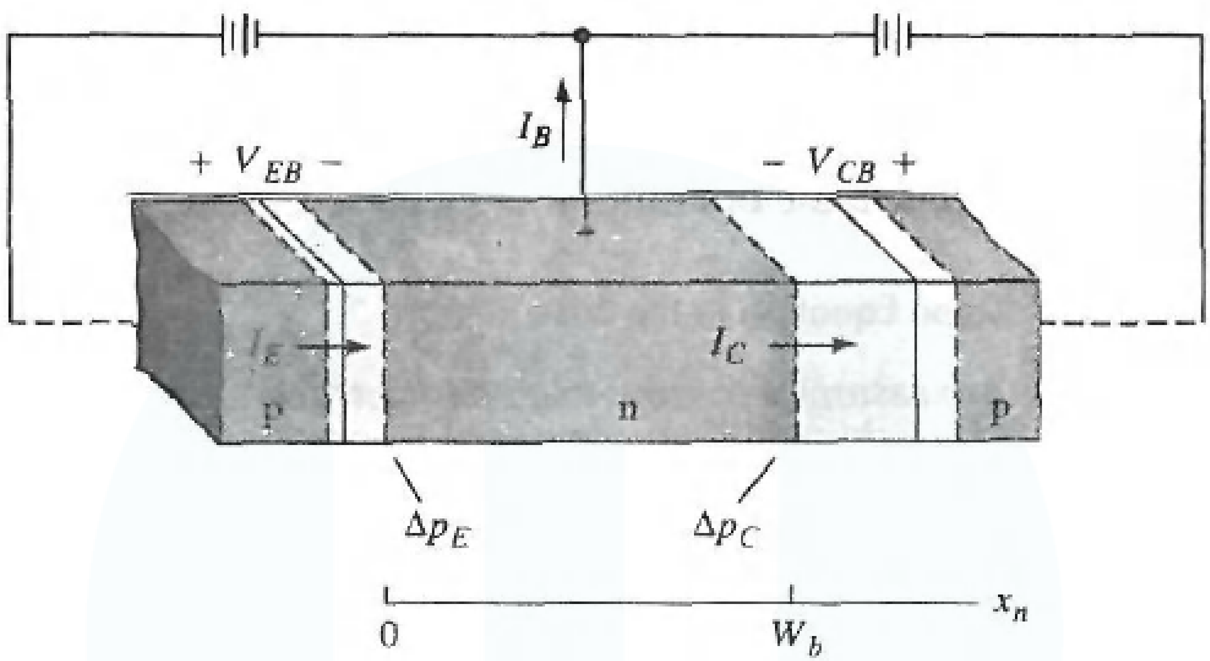
Assume unity emitter injection efficiency and negligible collector saturation current

Common Emitter (CE) configuration

Terminal Currents

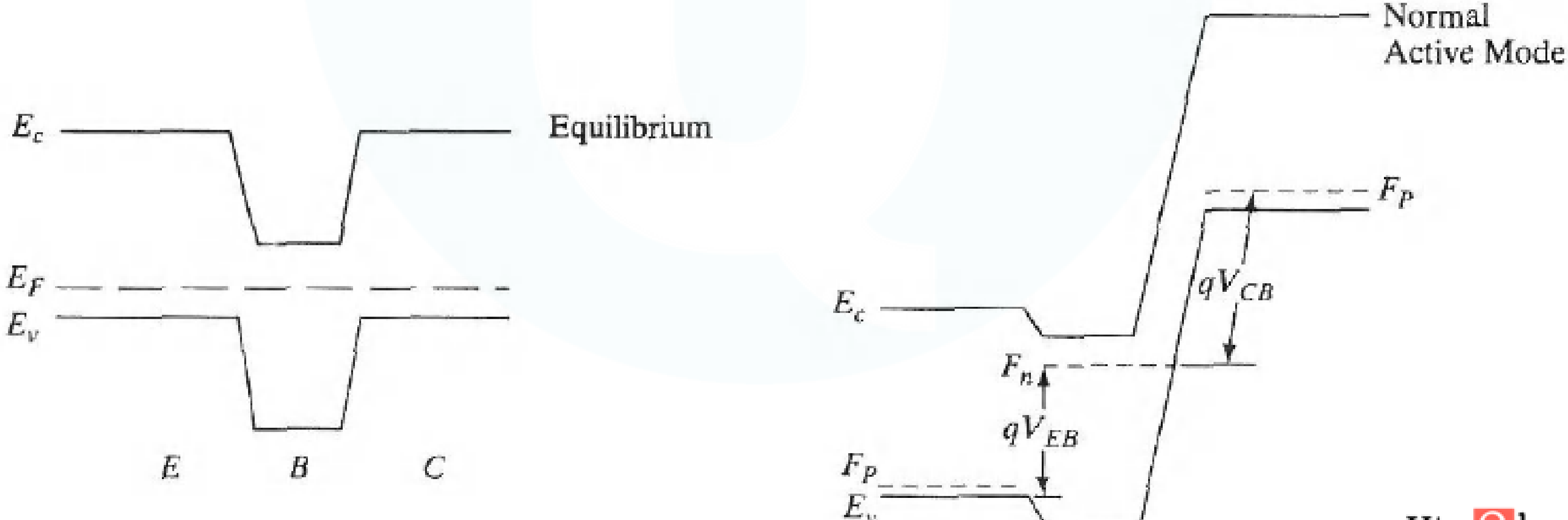
Simplifying the calculations by making several assumptions:

1. Holes diffuse from emitter to collector; drift is negligible in the base region
2. The emitter current is made up entirely of holes; the emitter injection efficiency is $\gamma = 1$
3. The collector saturation current is negligible
4. The active part of the base and the two junctions are of uniform cross sectional area A; current flow in the base is essentially one-dimensional from emitter to collector
5. All currents and voltages are steady state



- Injected holes are assumed to flow from emitter to collector by diffusion
- Recombination in the two depletion regions is neglected
- I_E : Hole current entering the base at the emitter junction
- I_c : Hole current leaving the base at the collector
- W_b : Base width is between the two depletion regions
- A : Uniform cross-sectional area

- In equilibrium, the Fermi level is flat, and the band diagram corresponds to that for two back-to-back p-n junctions.
- For a forward-biased emitter and a reverse-biased collector (normal active mode), the Fermi level splits up into quasi-Fermi levels
- The barrier at the emitter-base junction is reduced by the forward bias, and that at the collector-base junction is increased by the reverse bias



The excess hole concentration at the edge of the emitter depletion region Δp_E and the corresponding concentration on the collector side of the base Δp_C

$\Delta p_E = ?$

$\Delta p_C = ?$

$$\Delta p_E = p_n(e^{qV_{EB}/kT} - 1)$$
$$\Delta p_C = p_n(e^{qV_{CB}/kT} - 1)$$

Emitter junction is strongly forward biased ($V_{EB} >> kT/q$)
Collector junction is strongly reverse biased ($V_{CB} << 0$)

$\Delta p_E = ?$

$\Delta p_C = ?$

$$\Delta p_E \simeq p_n e^{qV_{EB}/kT}$$
$$\Delta p_C \simeq -p_n$$

We can solve for the excess hole concentration as a function of distance in the base $\delta p(x_n)$ by using the proper boundary conditions in the diffusion equation

$$\frac{d^2\delta p(x_n)}{dx_n^2} = \frac{\delta p(x_n)}{L_p^2}$$

The solution of this equation is

$$\delta p(x_n) = C_1 e^{x_n/L_p} + C_2 e^{-x_n/L_p}$$

where L_p is the diffusion length of holes in the base region

The appropriate boundary conditions are

$$\delta p(x_n = 0) = C_1 + C_2 = \Delta p_E$$

$$\delta p(x_n = W_b) = C_1 e^{W_b/L_p} + C_2 e^{-W_b/L_p} = \Delta p_C$$

Solving for the parameters C_1 and C_2

$$C_1 = \frac{\Delta p_C - \Delta p_E e^{-W_b/L_p}}{e^{W_b/L_p} - e^{-W_b/L_p}}$$

$$C_2 = \frac{\Delta p_E e^{W_b/L_p} - \Delta p_C}{e^{W_b/L_p} - e^{-W_b/L_p}}$$

Substituting in $\delta p(x_n) = C_1 e^{x_n/L_p} + C_2 e^{-x_n/L_p}$

$$\delta p(x_n) = \Delta p_E \frac{e^{W_b/L_p} e^{-x_n/L_p} - e^{-W_b/L_p} e^{x_n/L_p}}{e^{W_b/L_p} - e^{-W_b/L_p}} \quad (\text{for } \Delta p_C \simeq 0)$$

We have $$I_p(x_n) = -qAD_p\frac{d\delta p(x_n)}{dx_n}$$

This expression evaluated at $x_n = 0$ gives the hole component of the emitter current,

$$I_{Ep} = I_p(x_n = 0)$$

$$= qA\frac{D_p}{L_p}(C_2 - C_1)$$

If we neglect the electrons crossing from collector to base in the collector reverse saturation current, I_C is made up entirely of holes entering the collector depletion region from the base. Evaluating at $x_n = W_b$ we get the collector current

$$I_C = I_p(x_n = W_b)$$

$$= qA\frac{D_p}{L_p}(C_2e^{-W_b/L_p} - C_1e^{W_b/L_p})$$

When the parameters C_1 and C_2 are substituted

$$I_{Ep} = qA\frac{D_p}{L_p}\left[\frac{\Delta p_E(e^{W_b/L_p} + e^{-W_b/L_p}) - 2\Delta p_C}{e^{W_b/L_p} - e^{-W_b/L_p}}\right]$$

Similarly, $I_C = ?$

Emitter and collector currents take a form that is most easily written in terms of hyperbolic functions

Hyperbolic Functions

$\sinh(x) = \frac{e^x - e^{-x}}{2}$	$\operatorname{csch}(x) = \frac{1}{\sinh(x)} = \frac{2}{e^x - e^{-x}}, x \neq 0$
$\cosh(x) = \frac{e^x + e^{-x}}{2}$	$\operatorname{sech}(x) = \frac{1}{\cosh(x)} = \frac{2}{e^x + e^{-x}}$
$\tanh(x) = \frac{\sinh(x)}{\cosh(x)} = \frac{e^x - e^{-x}}{e^x + e^{-x}}$	$\coth(x) = \frac{1}{\tanh(x)} = \frac{e^x + e^{-x}}{e^x - e^{-x}}, x \neq 0$

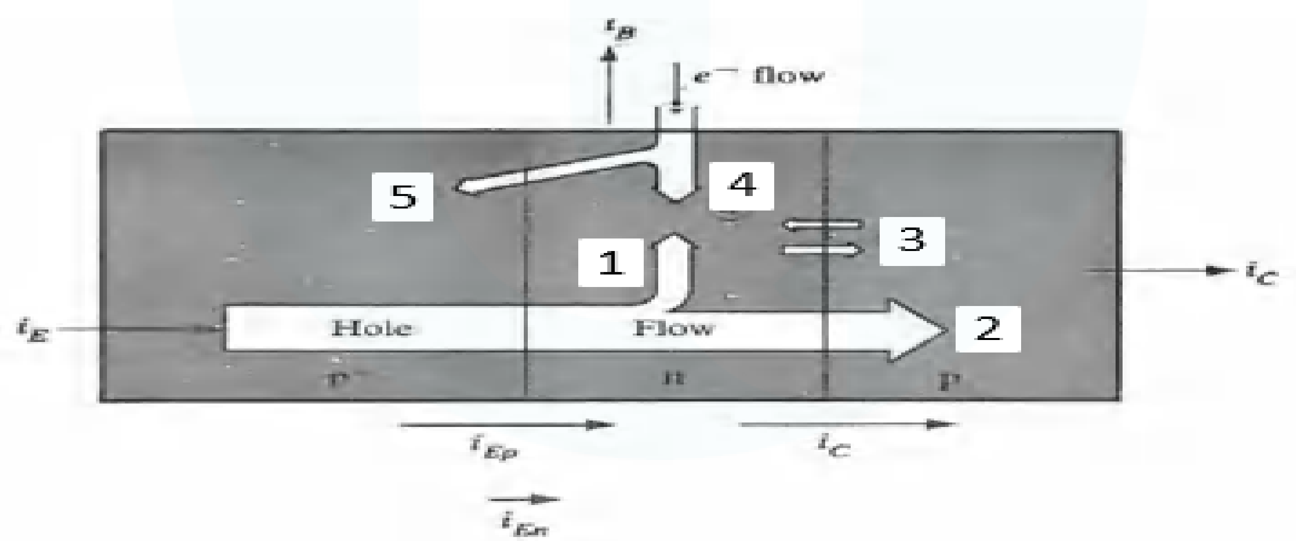
$$\boxed{\begin{aligned} I_{Ep} &= qA\frac{D_p}{L_p}\left(\Delta p_E \operatorname{ctnh}\frac{W_b}{L_p} - \Delta p_C \operatorname{csch}\frac{W_b}{L_p}\right) \\ I_C &= qA\frac{D_p}{L_p}\left(\Delta p_E \operatorname{csch}\frac{W_b}{L_p} - \Delta p_C \operatorname{ctnh}\frac{W_b}{L_p}\right) \end{aligned}}$$

If $I_E = I_{Ep}$

$$I_B = I_E - I_C = qA\frac{D_p}{L_p}\left[(\Delta p_E + \Delta p_C)\left(\operatorname{ctnh}\frac{W_b}{L_p} - \operatorname{csch}\frac{W_b}{L_p}\right)\right]$$

$$\boxed{I_B = qA\frac{D_p}{L_p}\left[(\Delta p_E + \Delta p_C)\tanh\frac{W_b}{2L_p}\right]}$$

For a p-n-p BJT with $N_E > N_B > N_C$, show the dominant current components, with proper arrows, for directions in the normal active mode. If $I_{Ep} = 10$ mA, $I_{En} = 100\ \mu$A, $I_{Cp} = 9.8$ mA, and $I_{Cn} = 1\ \mu$A, calculate the base transport factor, emitter injection efficiency, common-base current gain, common-emitter current gain, and I_{CBO}. If the minority stored base charge is 4.9×10^{-11} C, calculate the base transit time and lifetime.



$$i_C = B i_{Ep}$$

The **emitter injection efficiency** $\boxed{\gamma = \frac{i_{Ep}}{i_{En} + i_{Ep}}}$

$$\frac{i_C}{i_E} = \frac{B i_{Ep}}{i_{En} + i_{Ep}} = B\gamma \equiv \alpha$$

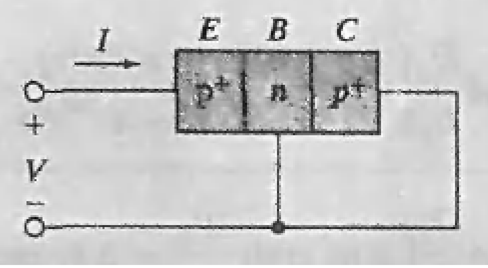
$$i_B = i_{En} + (1 - B) i_{Ep}$$

$$\boxed{\frac{i_C}{i_B} = \frac{B\gamma}{1 - B\gamma} = \frac{\alpha}{1 - \alpha} \equiv \beta}$$

- $I_{CBo} = I_{cn} = ?$
- $i_B = \frac{Q_n}{\tau_p}$
- $\tau_t = ?$
- $i_C = \frac{Q_p}{\tau_t}$
- Due to space charge neutrality $Q_n = Q_p$

(a) Find the expression for the current I for the transistor connection shown if $\gamma = 1$.

(b) How does the current I divide between the base lead and the collector lead?



(a) Since $V_{CB} = 0$,

$\Delta p_C = ?$

$$\Delta p_C = p_n(e^{qV_{CB}/kT} - 1)$$

$$\Delta p_C = 0$$

$I_{Ep} = ?$

$$I_{Ep} = qA\frac{D_p}{L_p}\left(\Delta p_E \operatorname{ctnh}\frac{W_b}{L_p} - \Delta p_C \operatorname{csch}\frac{W_b}{L_p}\right)$$

$I_E = ?$

$$I_E = I = \frac{qAD_p}{L_p}\Delta p_E \operatorname{ctnh}\frac{W_b}{L_p}$$

(b) $I_C = ?$

$$I_C = \frac{qAD_p}{L_p}\Delta p_E \operatorname{csch}\frac{W_b}{L_p}$$

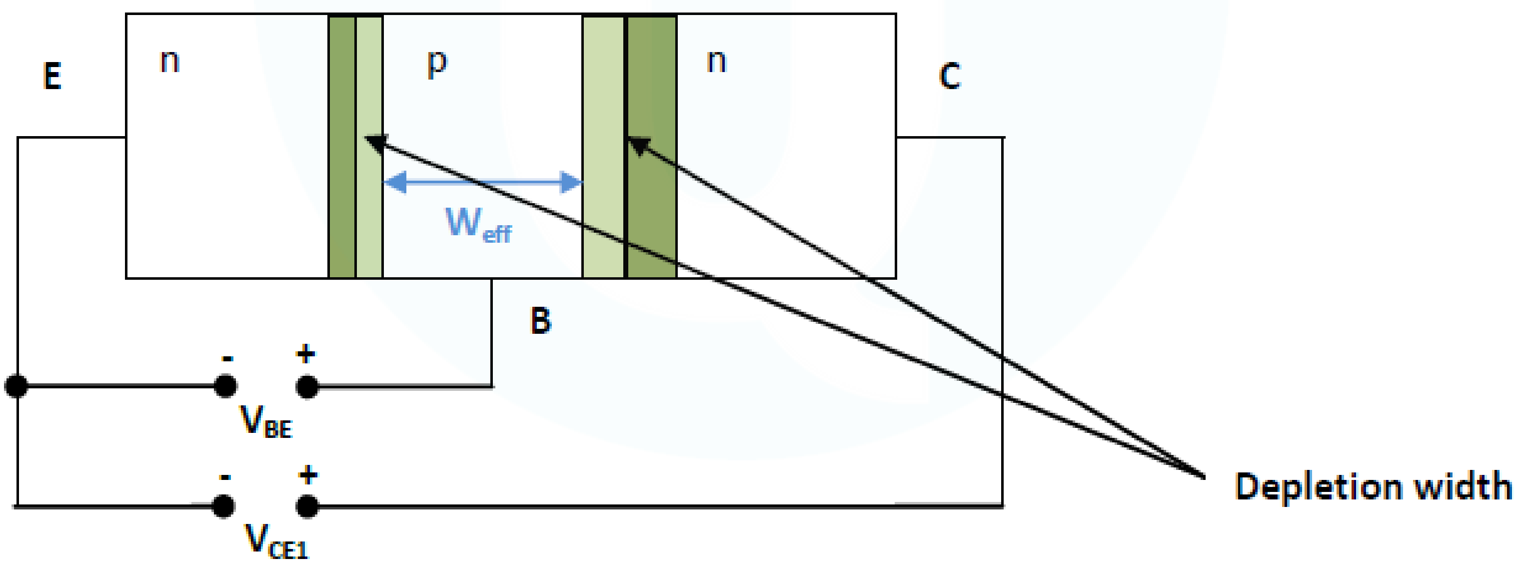
$I_B = ?$

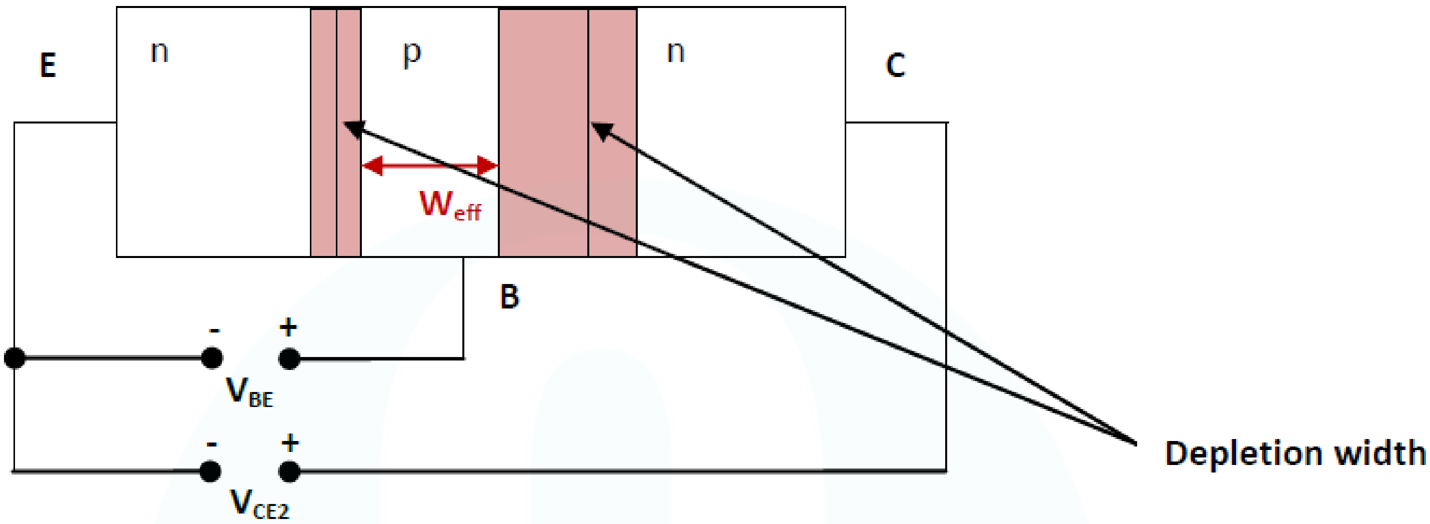
$$I_B = \frac{qAD_p}{L_p}\Delta p_E \tanh\frac{W_b}{2L_p}$$

Base width modulation (Early effect)

Variation in the width of the base in a bipolar transistor due to a variation in the applied base-to-collector voltage.

For example a greater reverse bias across the collector- base junction increases the collector-base depletion width.





$V_{BE} < V_{CE1} << V_{CE2}$

The emitter-base junction is unchanged because the voltage V_{BE} is the same.

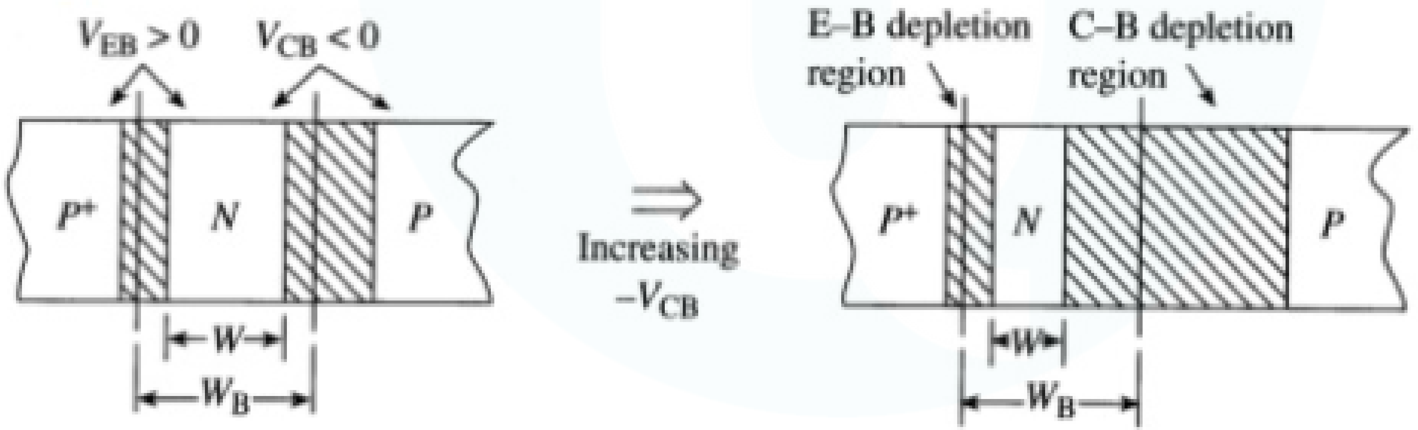
Base narrowing has two consequences that affect the current:

- There is a lesser chance for recombination within the “smaller” base region.
- The charge gradient is increased across the base, and consequently, the current of minority carriers injected across the emitter junction increases.

Base Width Modulation: "Early" Effect

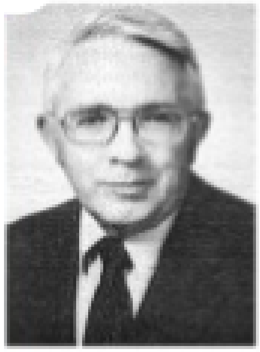
When bias voltages change, depletion widths change and the effective base width will be a function of the bias voltages

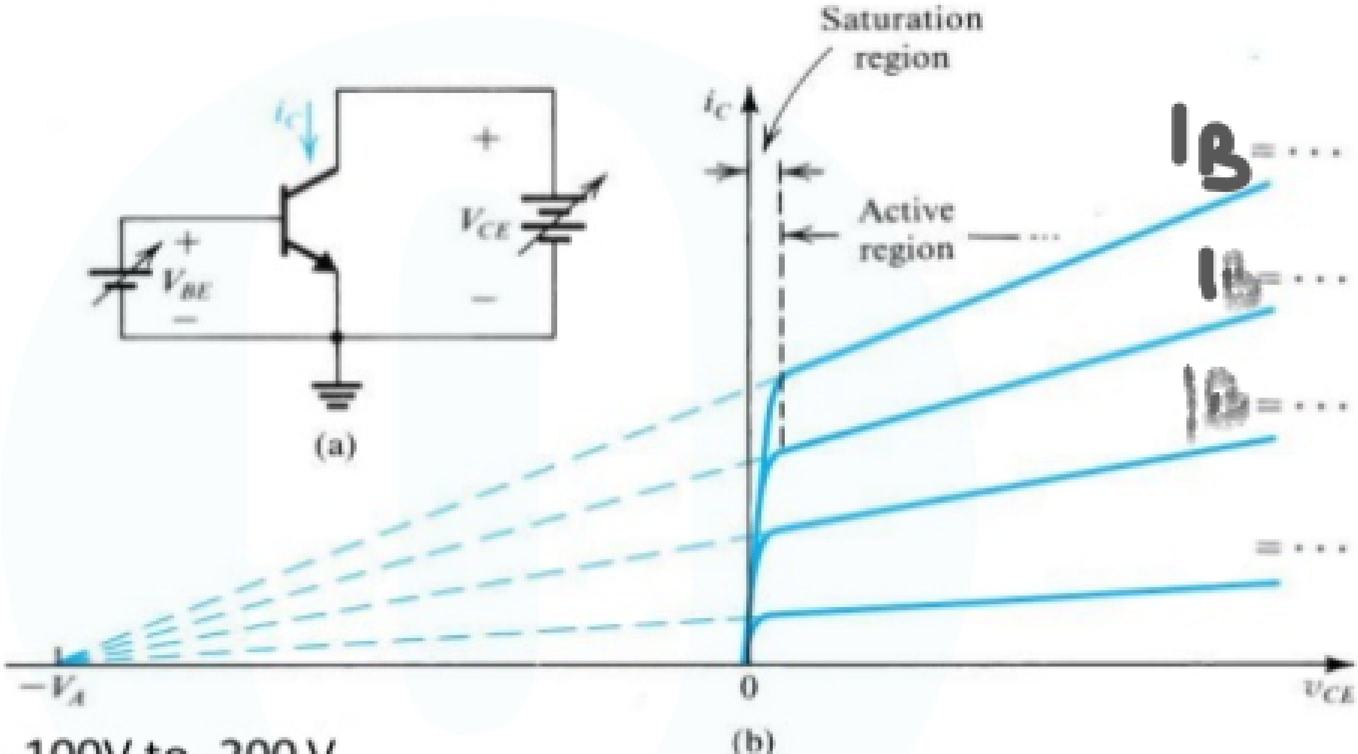
Most of the effect comes from the C-B junction since the bias on the collector is usually larger than that on the E-B junction



Base width gets smaller as applied voltages get larger

The Early Effect





Range is -100V to -200 V

Converge ~ at single point called "Early Voltage" (after James Early)

Large "Early Voltage" = Absence of "Base Width Modulation"