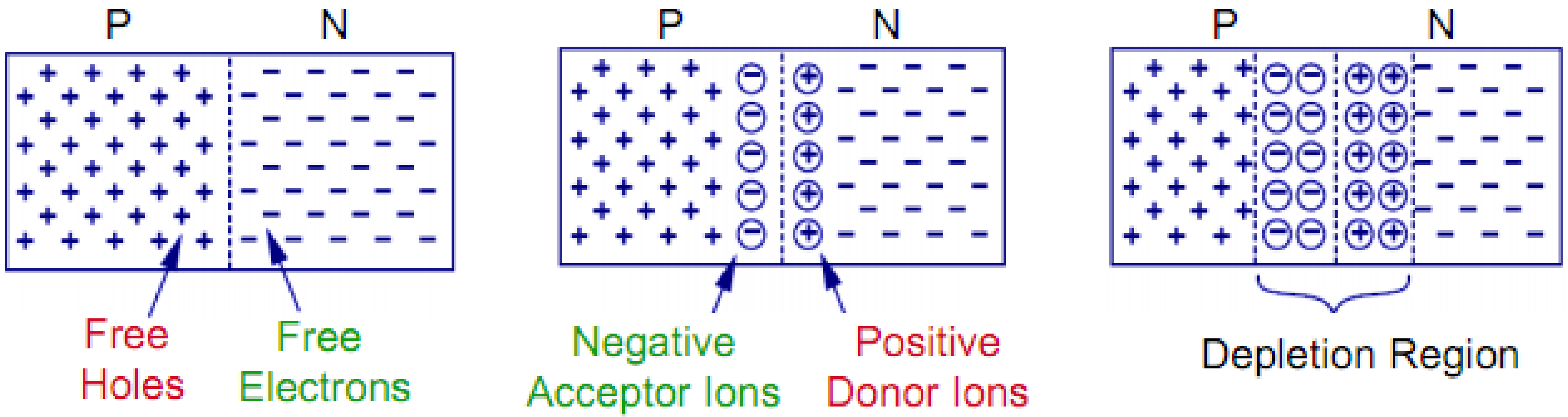
# ELEC2104 – Week 6

# Bipolar junction transistors

THE UNIVERSITY OF SYDNEY

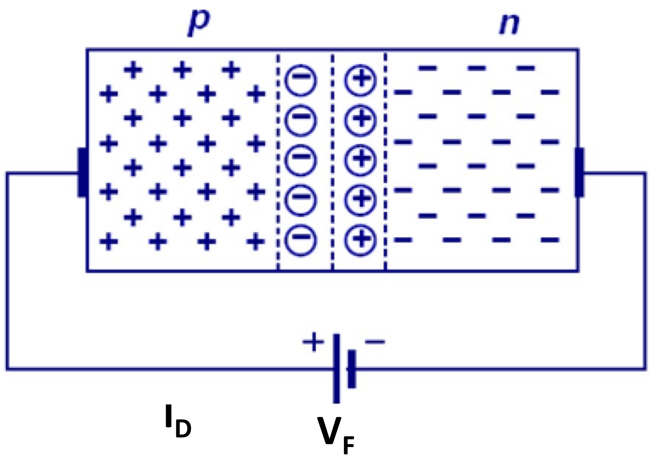
# PN Junction Review

- As free electrons and holes diffuse across the junction, a region of fixed ions is left behind. This region is known as the “depletion region.”
- The fixed ions in depletion region create an electric field, hence potential difference from p to n.
- Fermi level is flat if the device is not under external bias.
- With no external field applied, the drift current flowing in one direction cancels out the diffusion current flowing in the opposite direction



# PN Junction Review

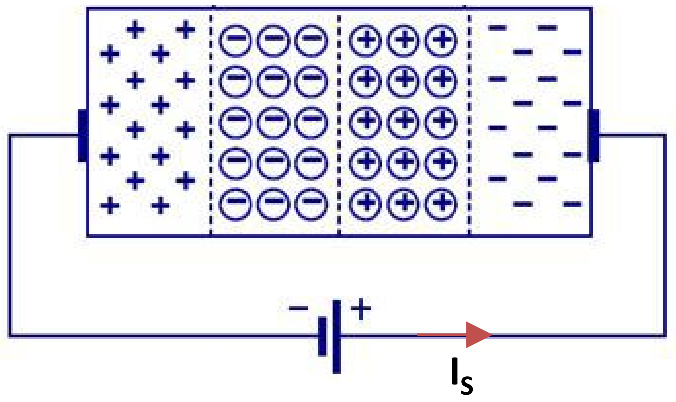
- Forward bias




$$I_D = I_S\left[\exp\left(\frac{V_F}{V_T}\right) - 1\right]$$

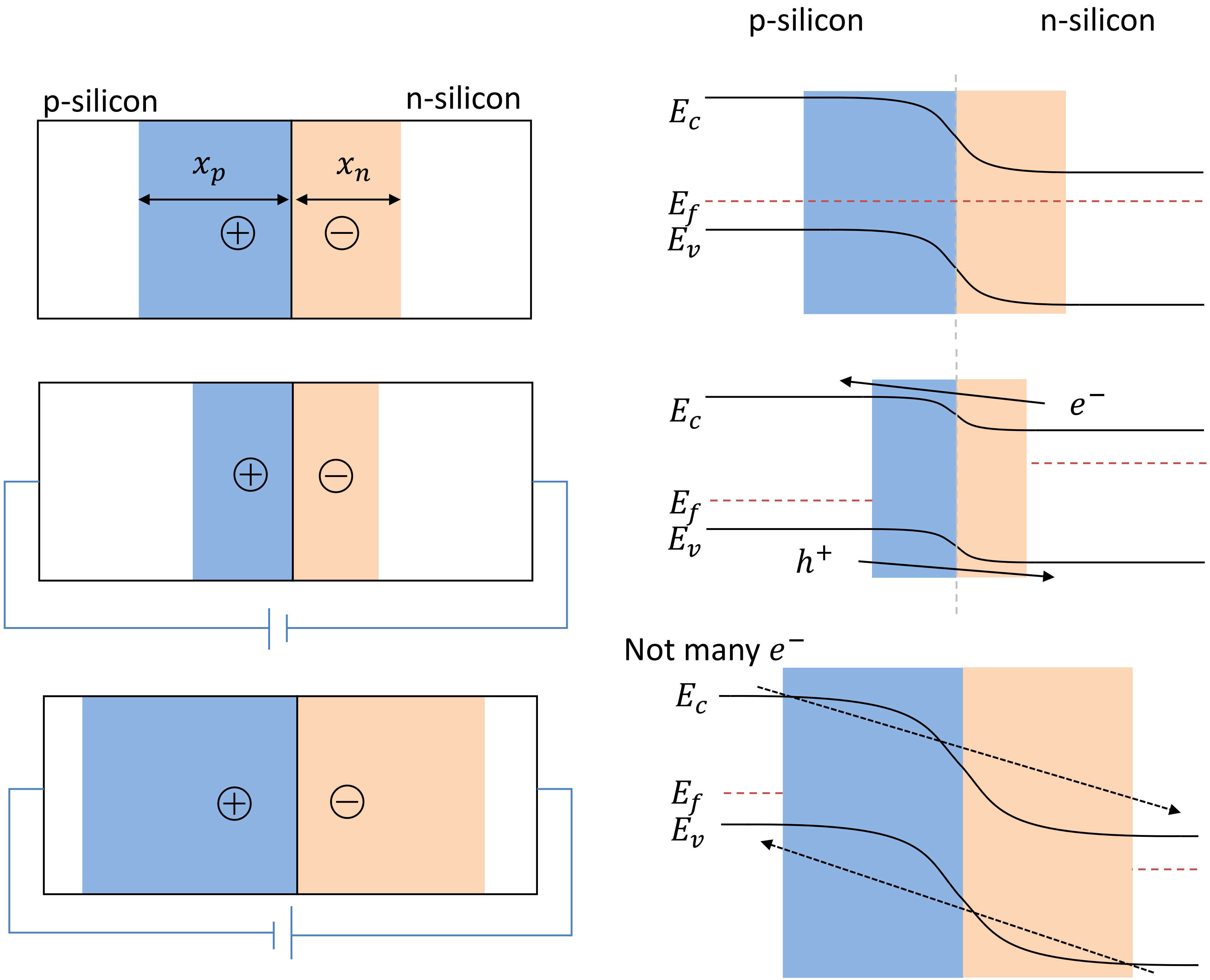
$$V_T = 26\text{meV}$$

- Reverse bias



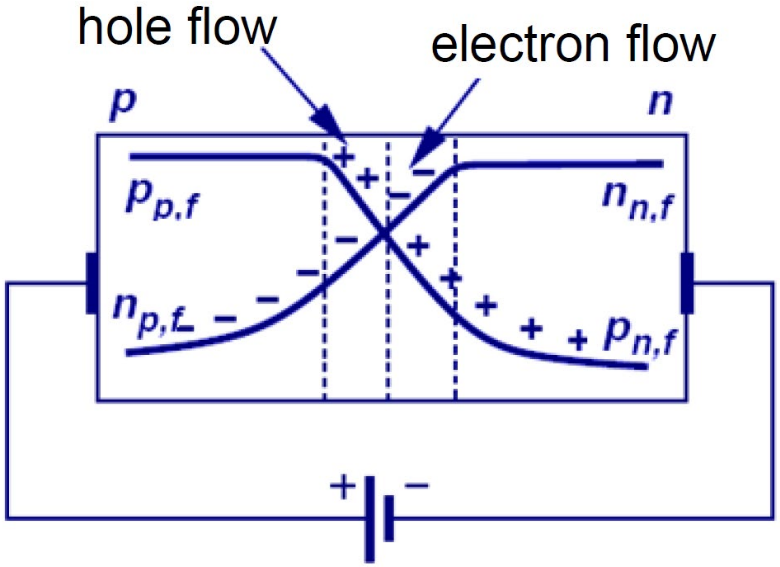

$$I_D = -I_S$$

Small current due to flow of minority carriers


p-silicon
n-silicon
$x_p$
$x_n$
$E_c$
$E_f$
$E_v$
$e^-$
$h^+$
Not many $e^-$

# I/V Characteristics in Forward Bias

- Recombination of the minority carriers with the majority carriers accounts for the dropping of minority carriers as they go deep into the P or N region




**Minority carrier concentrations must vary**

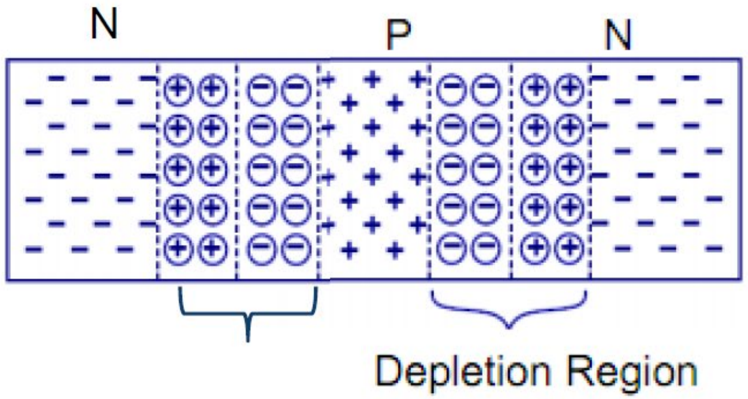
# BJT

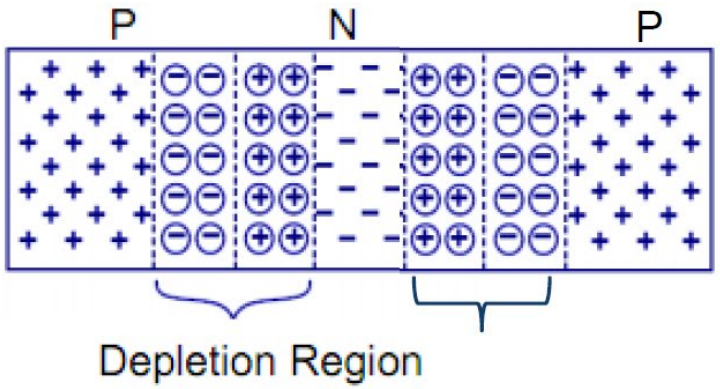
# Bipolar junction transistors (BJT)

- Invented (1940s) before Field-effect transistors (FET)
- Three terminal device (you can control the circuit now)
- Most digital circuits use FETs
- BJTs are used when high speed, high precision, or high current scenarios
- Current driven (FET is voltage driven)
- npn has higher performance than pnp
- insulated-gate bipolar transistor (IGBT): important in electric cars.

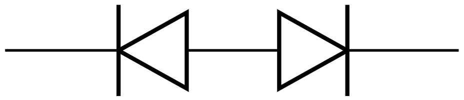
# Bipolar Junctions

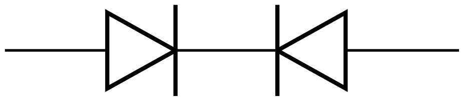
- We are going to append another doped semiconductor to the PN junction.
- This is called a bipolar junction
- Can be NPN or PNP



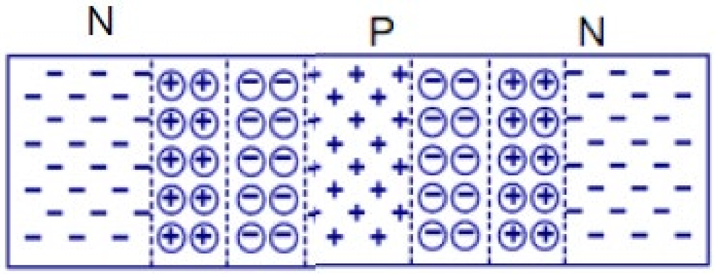

Are they just two PN diodes in series?





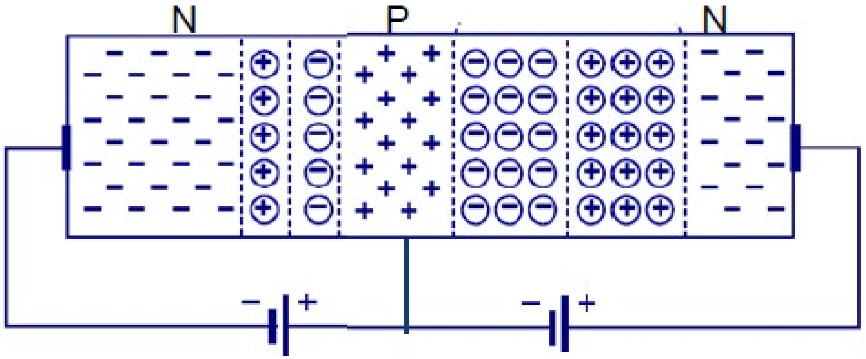
# Biasing a bipolar junction

- Equilibrium: No voltages applied, diffusion currents cancel out drift current induced by built-in voltage at junctions.




- What happens if we bias this device?
  - Apply a positive voltage across both junctions

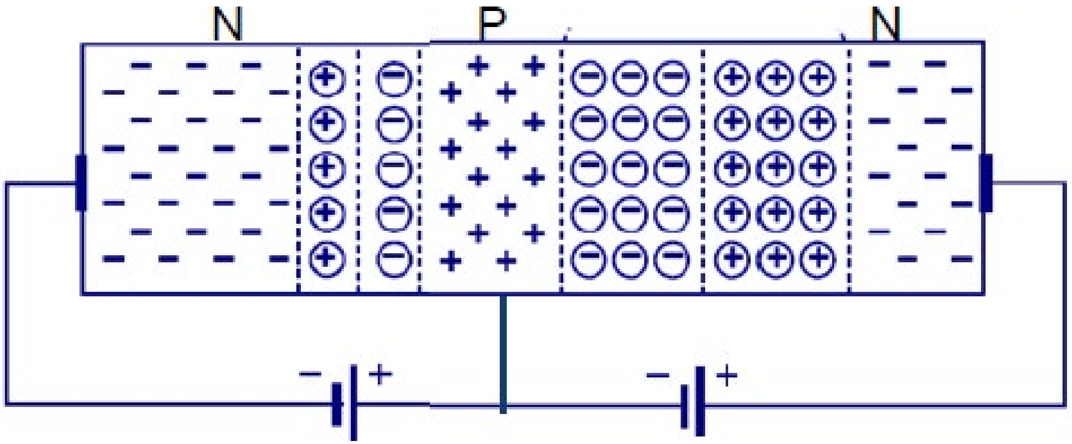
**Forward bias**




**Reverse bias**

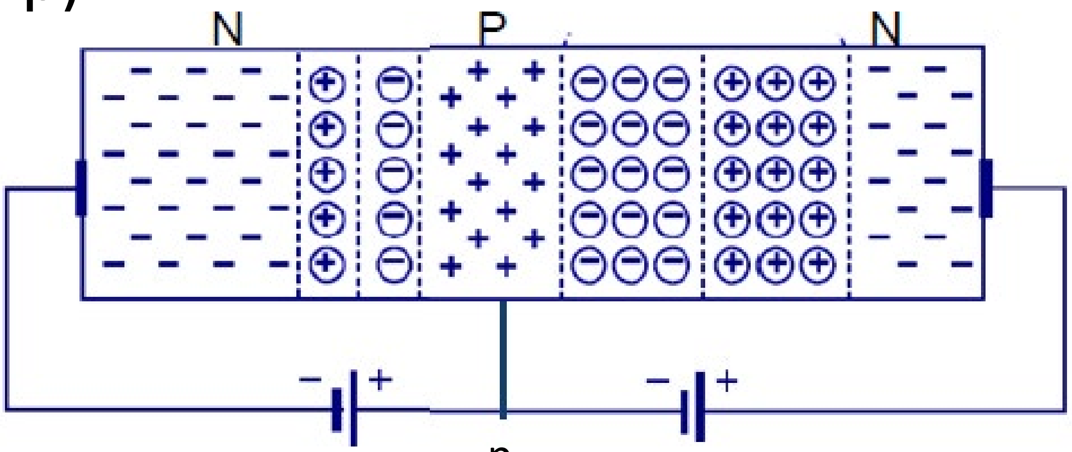
# Biasing a bipolar junction

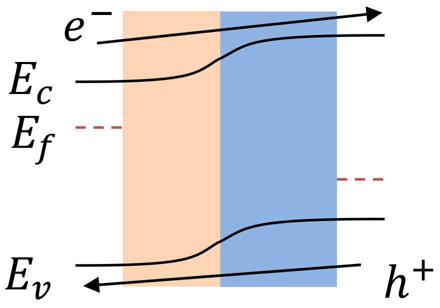
- One junction is forward-biased while the other is reverse-biased
- Examine what happens to a carrier from left to right:
  - The forward-biased junction is a diode that is on. Electrons move across the junction in the form of diffusion current
  - In the middle region, some electrons can combine with holes in the p-doped region

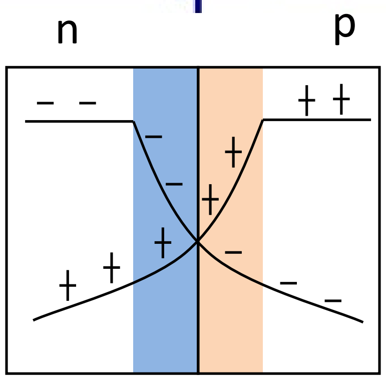


# At the emitter-base junction

- Left side: some electron from n make it to p region (becoming minority carrier in p)



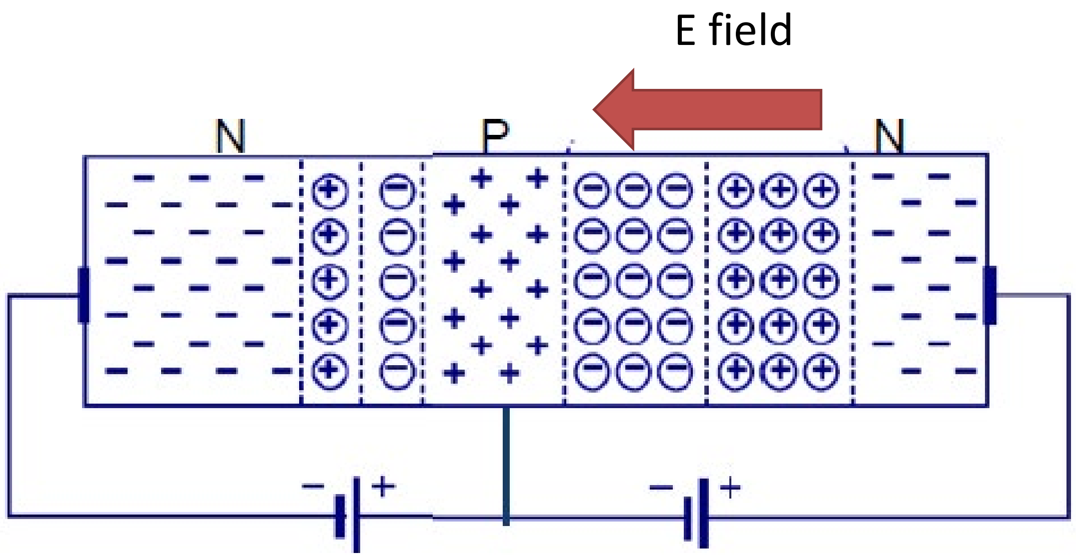



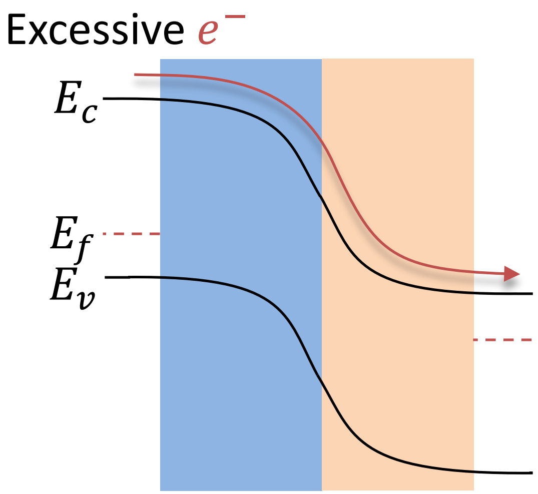




What happens to the free electrons that do not recombine with holes?

# At the base-collector junction

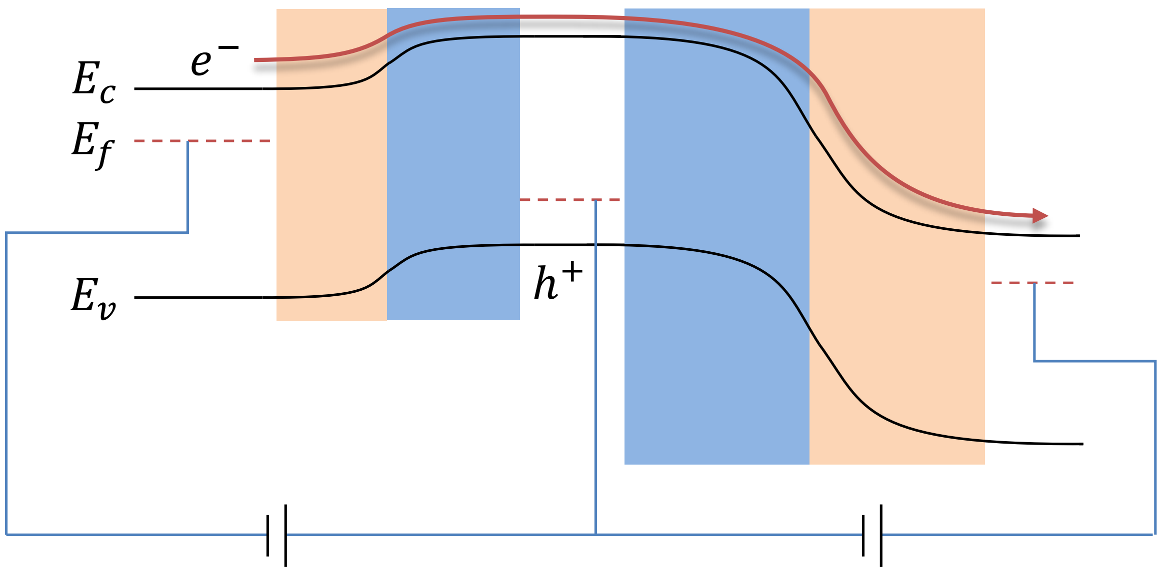
- Electrons made it to the pn junction on the right:
  - The built-in electric field in the pn junction on the right quickly collect the electrons to the n side.

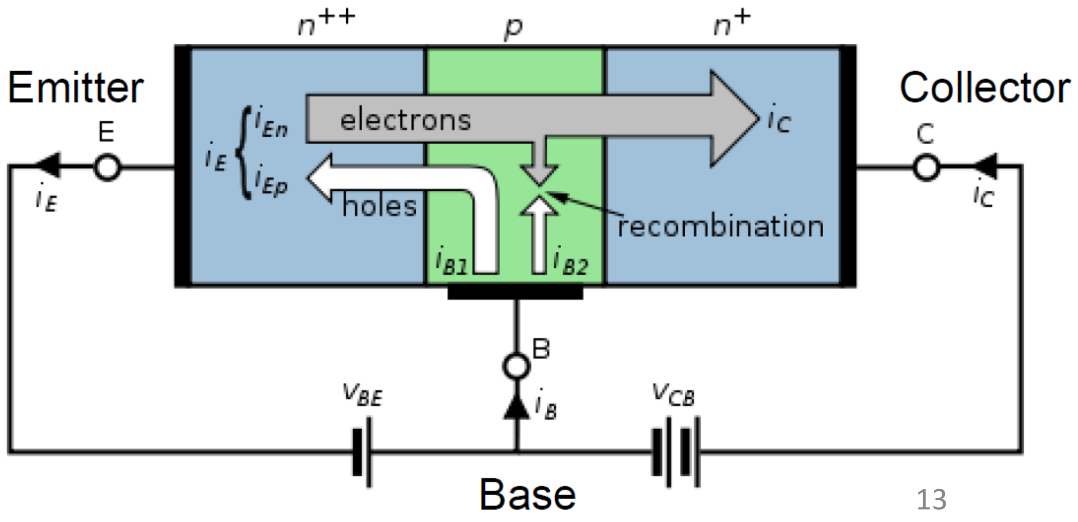


# Biasing a bipolar junction

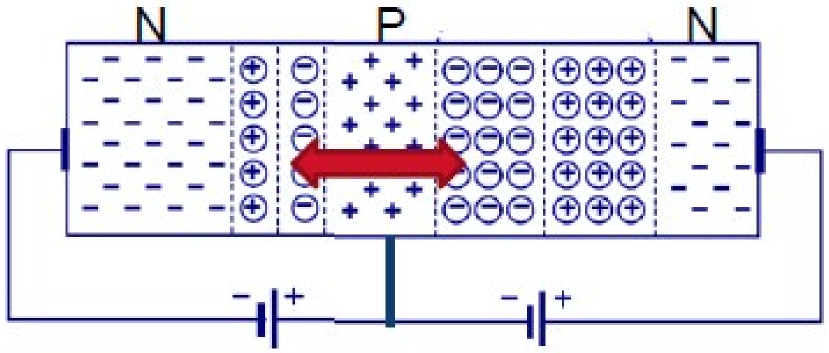
- Remember, wires contacts "talk" to Fermi levels. Roughly speaking, they directly control the majority carriers. The base contact doesn't talk to electrons here (minority carriers) directly.
- The p region is filled with holes, and its Fermi level is controlled by the base contact. The p concentration here is near constant. Even under bias, the energy levels and the Fermi level here appear to be almost flat.
- "Under the water", the minority electrons secretly move across
- Of all the electrons made through the p region from the emitter, a small portion will recombine with holes, or they will go directly to the base contact
- The holes from base does diffuse to emitter, which causes another portion of the base current

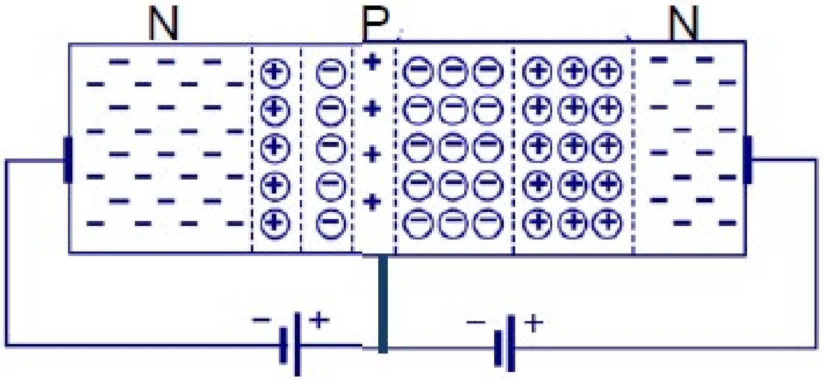


# Better BJT

- We want this device to operate such that electrons (emitted) from the left side will enter the depletion region and be swept to (collected at) the right side of the n region before they have a chance to recombine with holes
- How to minimize the probability of an electron recombining with a hole?

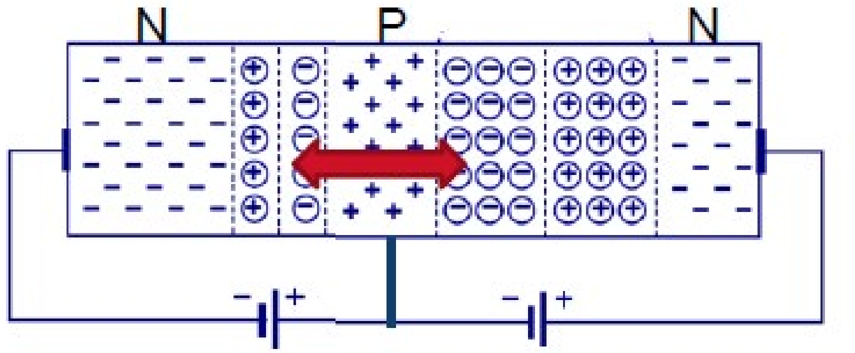


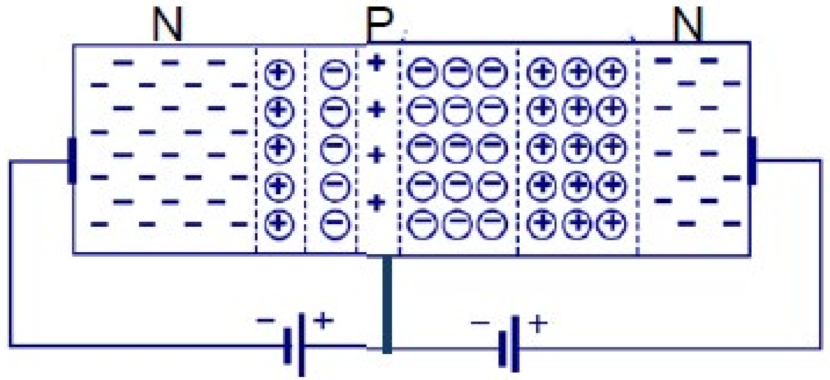

**Increase the probability of emitted electrons which travel toward the "collecting side"**

# $n^+$ emitter, thin base

- We want this device to operate such that electrons (emitted) from the left side will enter the depletion region and be swept to (collected at) the right side of the n region before they have a chance to recombine with holes
- How to minimize the probability of an electron recombining with a hole?



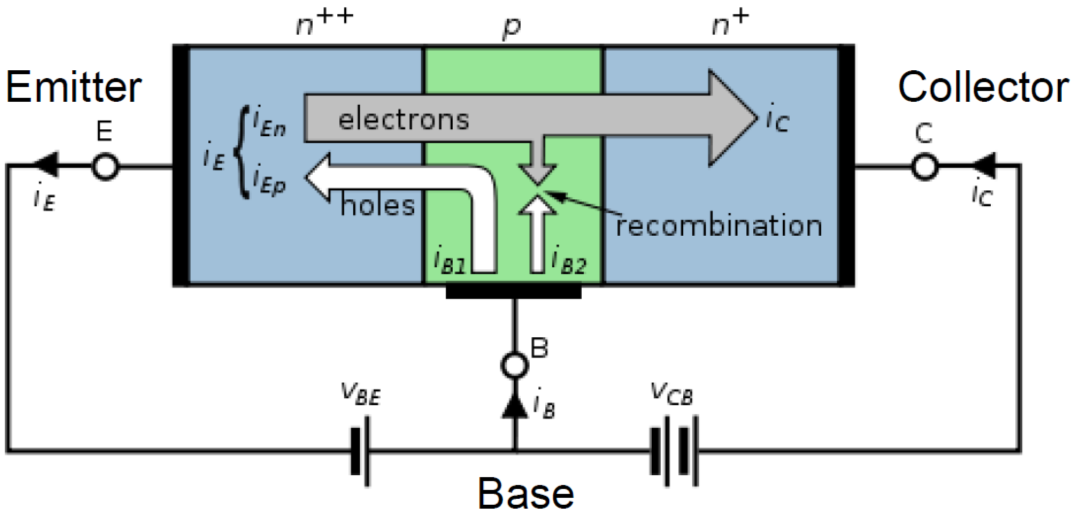

Left side n-type is made very heavily doped ($n^+$)



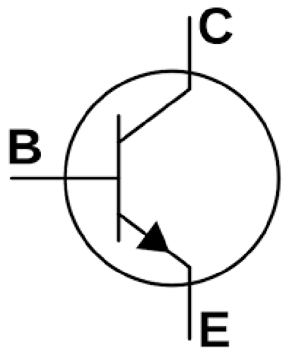

The middle region is made very narrow ($0.1\mu m \sim 100\ \mu m$)

# Bipolar Junction Transistor

- This device is called a bipolar junction transistor (BJT)
- Regions: **Emitter, Base, Collector**
- In typical operation, the base-emitter diode is forward biased and the base-collector diode is reverse biased
- The emitter is usually much more heavily doped than the other regions



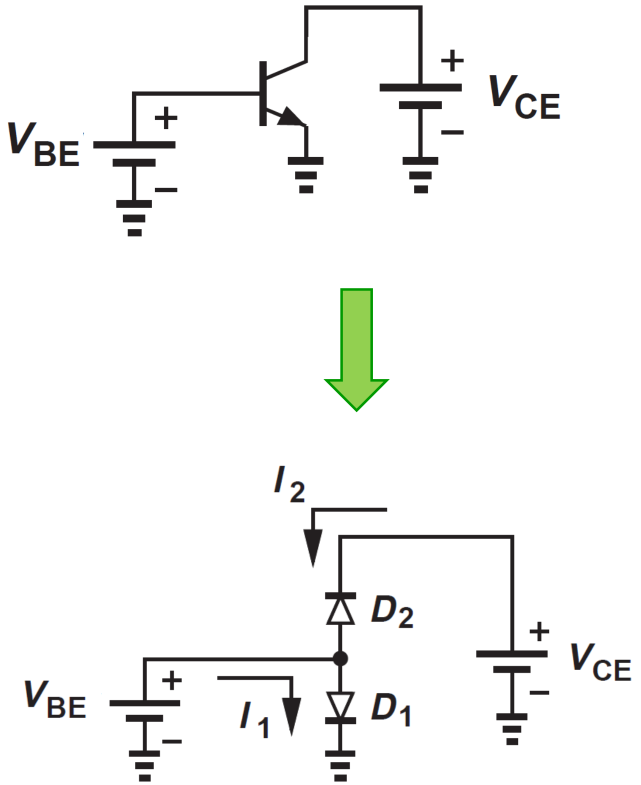

A small amount of current from the base can induce a much larger current from the emitter




Symbol of a NPN BJT

# Bipolar Junction Transistor

- Is BJT the same as two back-to-back diodes?

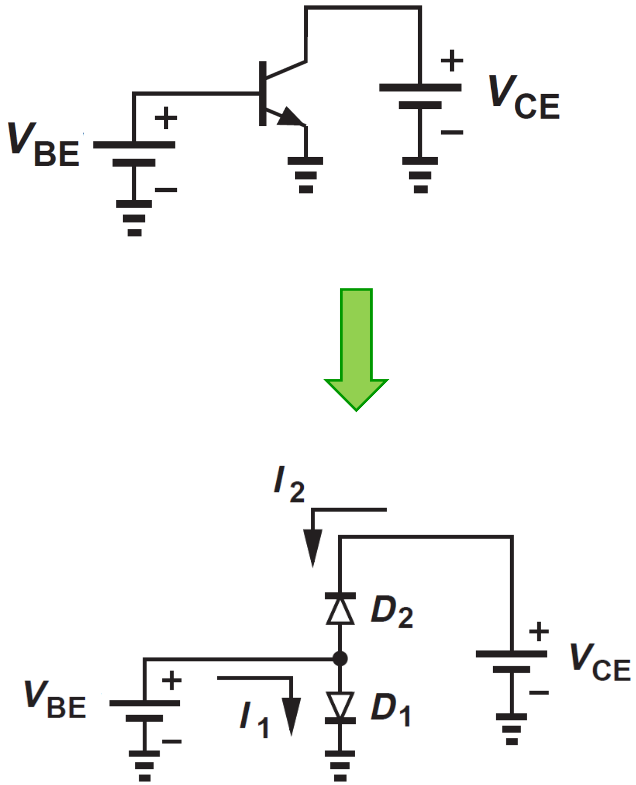


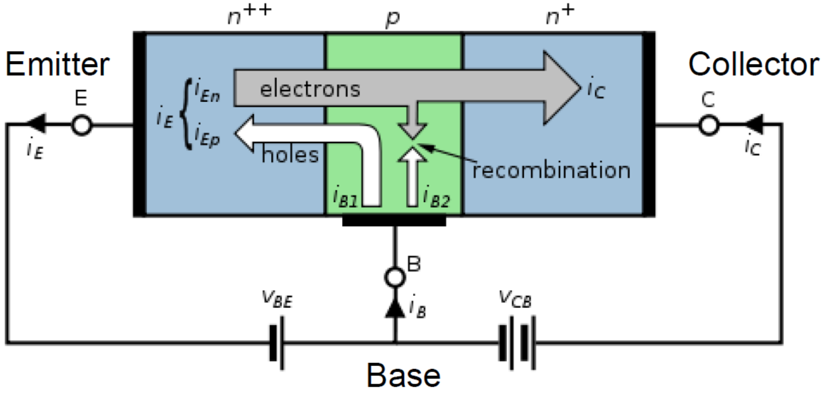

Does D1 carry a current?

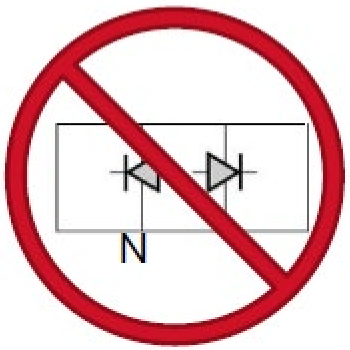
Does D2 carry a current?

# Bipolar Junction Transistor

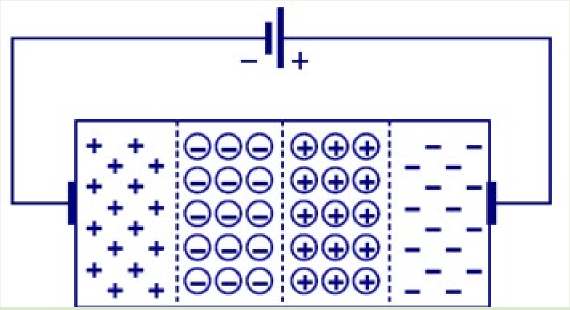
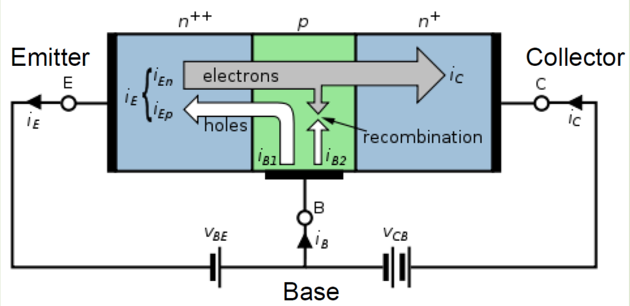
- Is BJT the same as two back-to-back diodes?



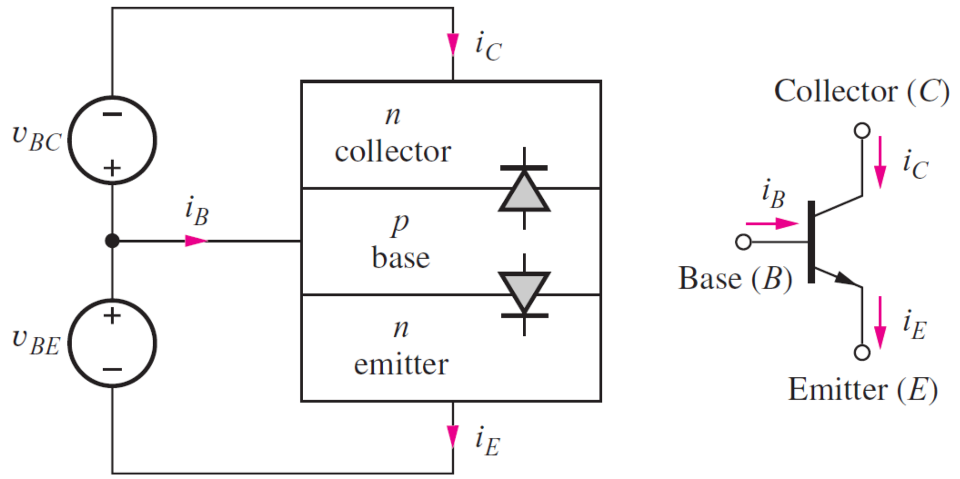



# Bipolar Junction Transistor

| Reverse biased PN junction | Reverse biased PN junction in a BJT configuration |
|---|---|
| ▪ Majority carriers that diffuse into the depletion region are pushed back to where they came from<br>▪ A reverse-biased diode by itself should only have a small reverse-saturation current $I_S$ (assuming it is not in reverse breakdown).<br>▪ $I_S$ is a result of minority carrier drift.<br> | ▪ The heavily doped emitter (N-type) provides a large amount of electrons<br>▪ These electrons diffuses into the lightly doped base (P-type) which forms a number of minority carriers<br>▪ The base is so narrow that these electrons get through before they can recombine with the holes<br> |

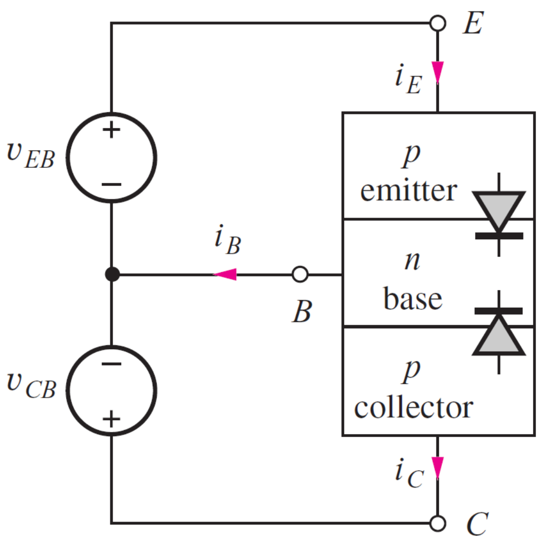
# NPN and PNP

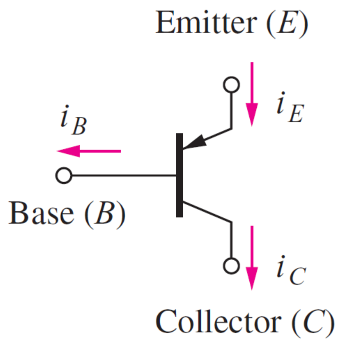
- NPN and PNP transistors have the same functionality, different majority carriers.
- In typical circuits, NPN transistors have emitters connected to a lower voltage than the collector
  - Emitter is a source of electrons
- Emitter has an arrow because it is forward-biased



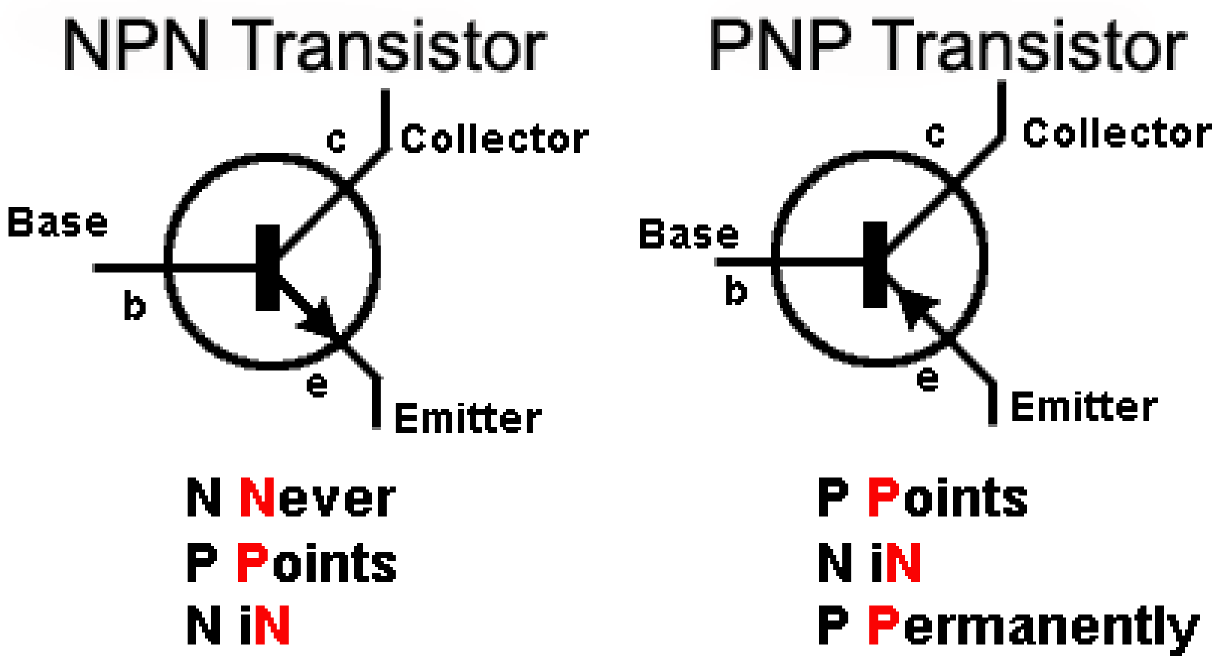
# NPN and PNP

- PNP transistors are fabricated by reversing the layers of the NPN transistor
- Collectors connected to a lower voltage than the emitter
  - Emitter is a source of holes



# NPN and PNP

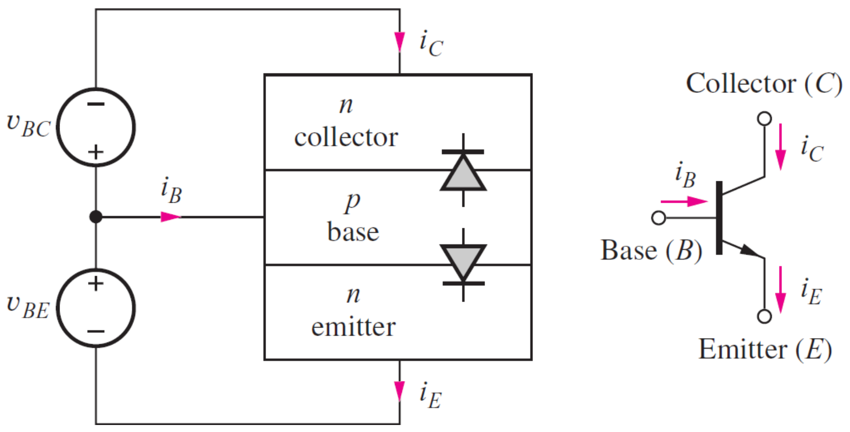


NPN Transistor
c
Collector
Base
b
e
Emitter
N Never
P Points
N iN
PNP Transistor
c
Collector
Base
b
e
Emitter
P Points
N iN
P Permanently

# Transport in BJT

# NPN BJT Transport Model

- Emitter injects electrons into base region, almost all of them travel across narrow base and are removed by collector
- Base-emitter voltage $v_{BE}$ and base-collector voltage $v_{BC}$ determine currents in transistor
  - Positive when they forward-bias their respective *PN* junctions.
- Terminal currents: collector ($i_C$), base ($i_B$), emitter ($i_E$).

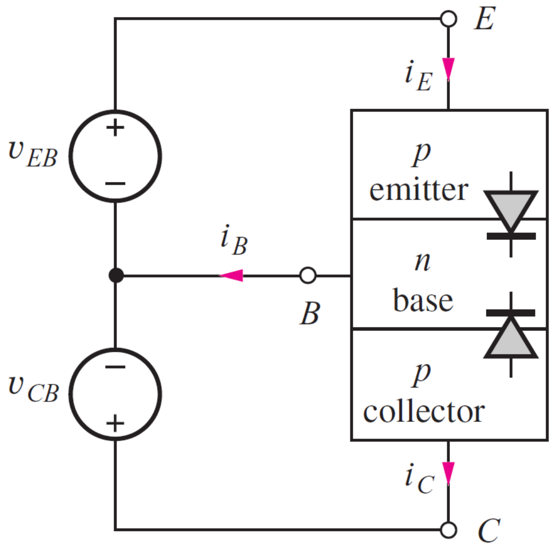


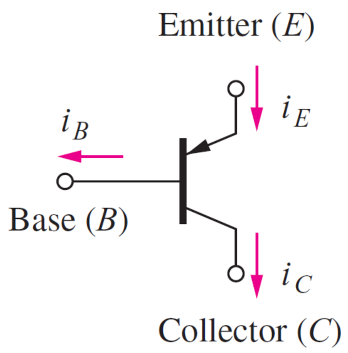

Note: Voltage subscripts denote positive-negative terminals

# PNP BJT Transport Model

- Voltages $v_{EB}$ and $v_{CB}$ are positive when they forward bias their respective *pn* junctions.
- Collector current and base current exit transistor terminals and emitter current enters the device.

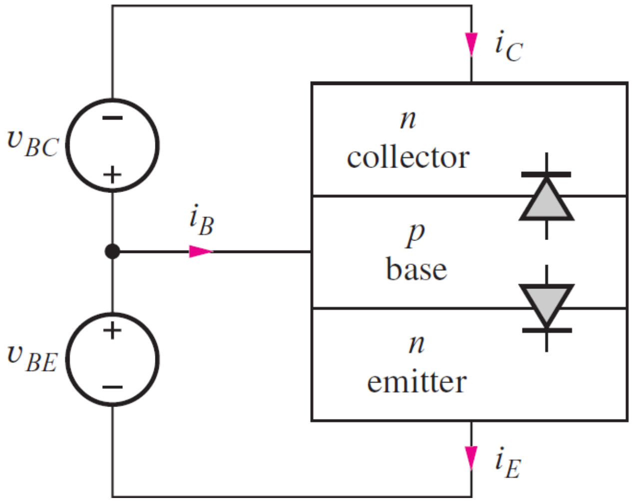
Attention to the sign

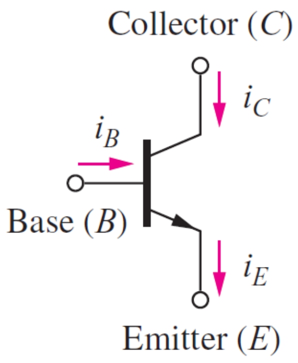


# NPN Forward Active Region

- NPN forward active region: $V_{BE} > 0$, $V_{BC} < 0$.
  - Base-emitter is forward-biased, base-collector is reverse-biased
- This is the most frequently used mode
- The base-emitter voltage establishes the emitter current $i_E$



# NPN Forward Active Collector Current

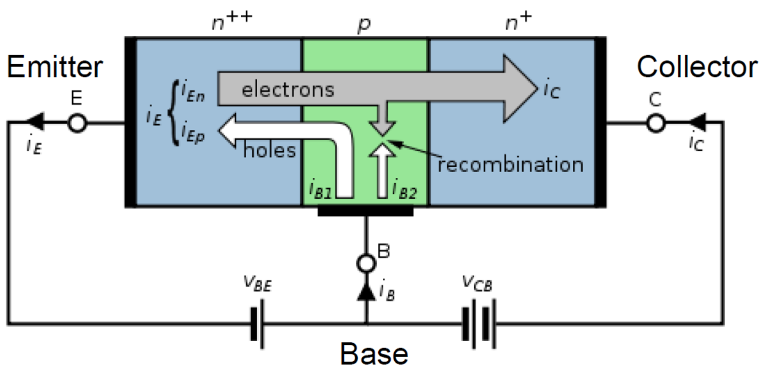
- **Forward transport current:** Current flow from collector is the same equation as the forward diode current for the base-emitter diode
- Simple way to remember what's going on:
  - In a pn-junction this current flows from n to p; here the $V_{BE}$ is forward biasing the B-E pn junction, only that the electron current from emitter doesn't go to p contact (base), instead, it mostly go to the collector.
- The BJT can be understood as a voltage-controlled current source.

$$i_C = i_F = I_S\left[\exp\left(\frac{V_{BE}}{V_T}\right) - 1\right]$$

$$I_S = \frac{AqD_n{n_i}^2}{N_A W_B}$$

$$10^{-18}A \le I_s \le 10^{-9}A$$

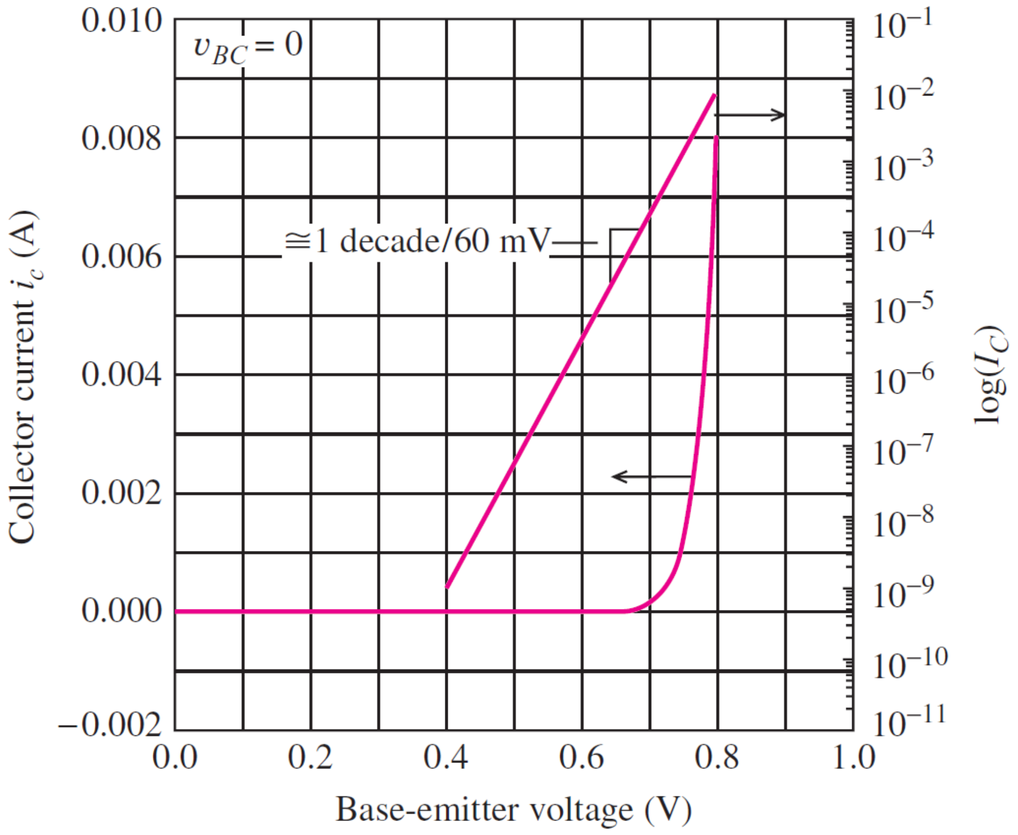
| | |
|---|---|
| $W_B$ | width of base |
| $A$ | area |
| $q$ | elementary charge |
| $N_A, N_D$ | acceptor and donor density |
| $D_n, D_p$ | diffusion constants |
| $V_T = k_B T$ | Thermal voltage |
| $k_B$ | Boltzmann constant |
| $n_i$ | intrinsic carrier density |




$I_S$ is transistor saturation current which is analogous to the diode's reverse saturation current → $I_S = Aqn_i^2\left(\frac{D_n}{N_A L_n} + \frac{D_p}{N_D L_p}\right)$

# NPN Forward Active I-V Characteristics

- Relation between collector current and base-emitter voltage of transistor
- Almost identical to transfer characteristic of *pn* junction diode



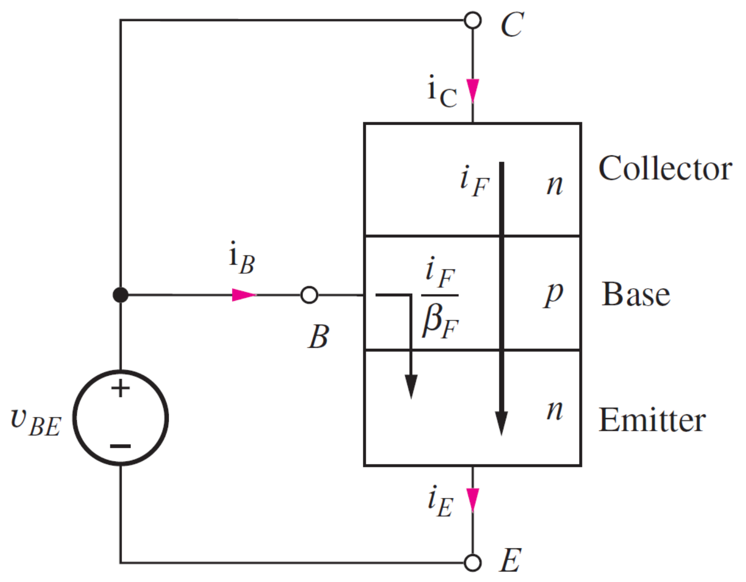
# NPN Forward Active Base Current

- **Base current**: Smaller current, which is proportional to collector current:

$$i_B = \frac{i_C}{\beta_F} = \frac{I_S}{\beta_F}\left[\exp\left(\frac{V_{BE}}{V_T}\right) - 1\right]$$

- $\beta_F$ is the forward **common-emitter current gain** and depends on the base width and emitter doping

$$10 \le \beta_F \le 500$$

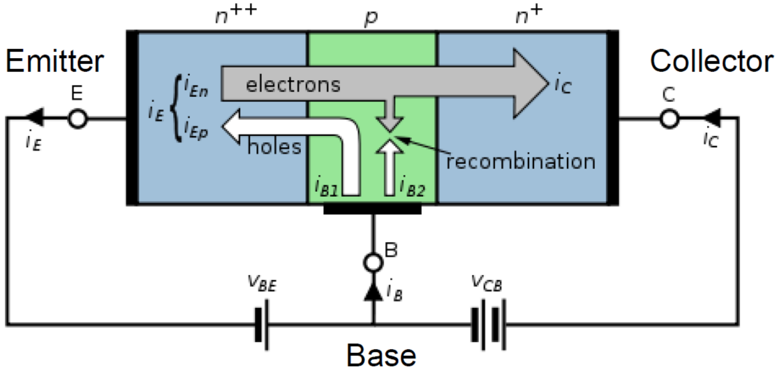


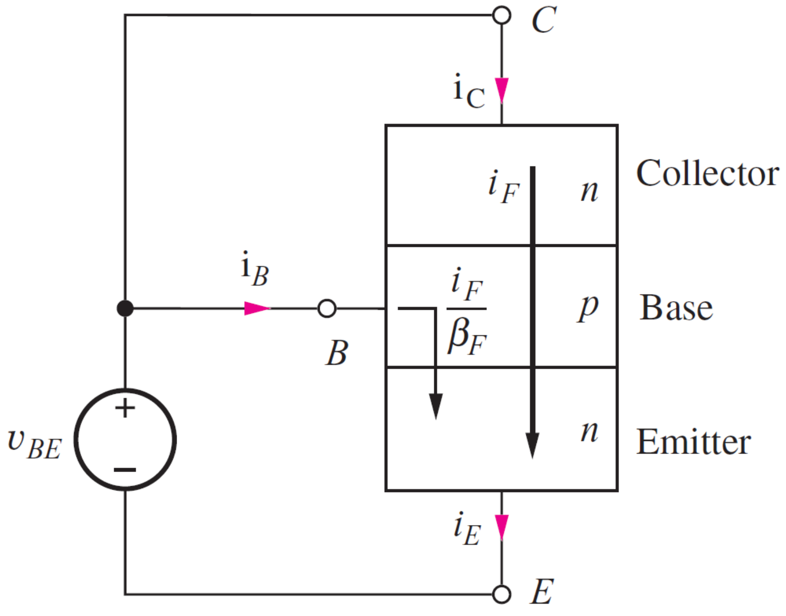

$I_C$ is equal to $I_F$ which is the forward transport current

# NPN Forward Emitter Current

- By Kirchoff's current law, emitter current is the sum of base and collector currents

$$
\begin{aligned}
i_E &= i_C + i_B \\
&= I_S\left(1 + \frac{1}{\beta_F}\right)\left[\exp\left(\frac{V_{BE}}{V_T}\right) - 1\right] \\
&= \frac{I_S}{\alpha_F}\left[\exp\left(\frac{V_{BE}}{V_T}\right) - 1\right]
\end{aligned}
$$




- $\alpha_F$ is the forward **common-base current gain**:

$$0.95 \leq \alpha_F = \frac{\beta_F}{\beta_F + 1} \leq 1.0$$

$$\beta_F = \frac{\alpha_F}{1 - \alpha_F}$$

# Forward active current summary

- Transistor "amplifies" its base current by a factor of $\beta_F$ $(\gg 1)$
  - Injection of a small current into the base produces a much larger current in both collector and emitter terminals

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

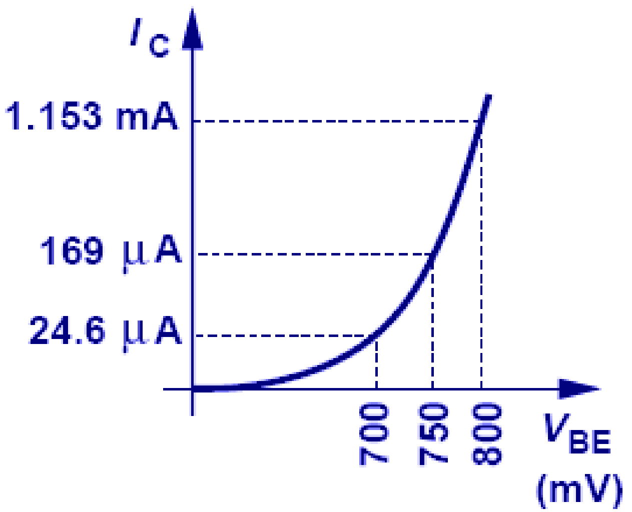
$$i_E = (\beta_F + 1)i_B$$

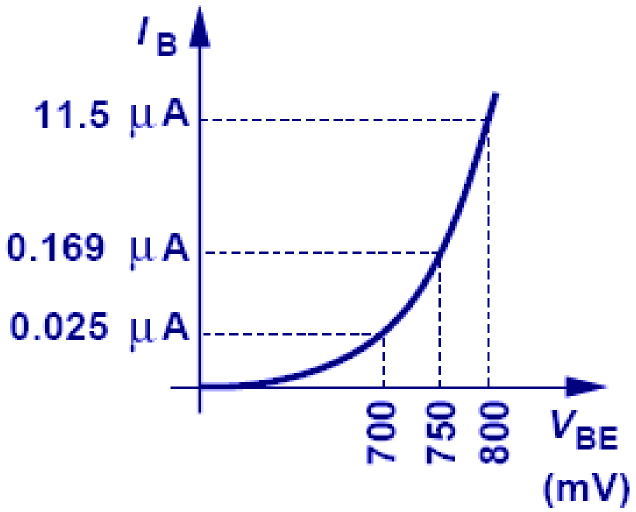
- Collector and emitter currents are almost equal ($\alpha_F \approx 1$)

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

# BJT Current Amplifier

- A forward-active BJT is frequently used as an amplifier because a small amount of current in the base results in a much larger current in the collector
- Example I-V characteristics: $\beta_F$ = 1000, $I_S$ = 5 X $10^{-17}$A, $V_T$ = 26 mV.



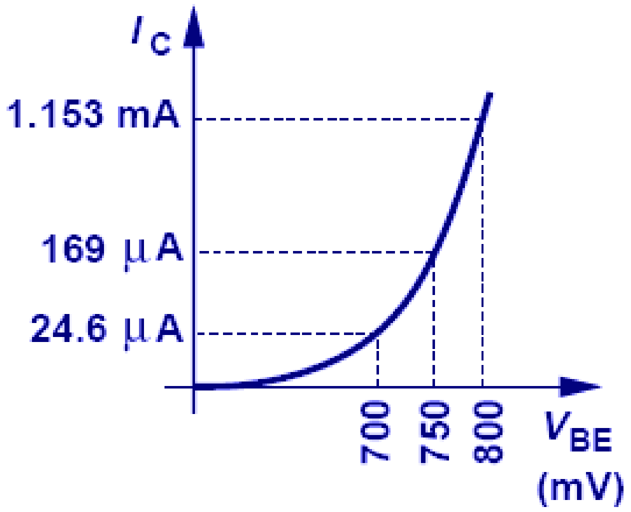



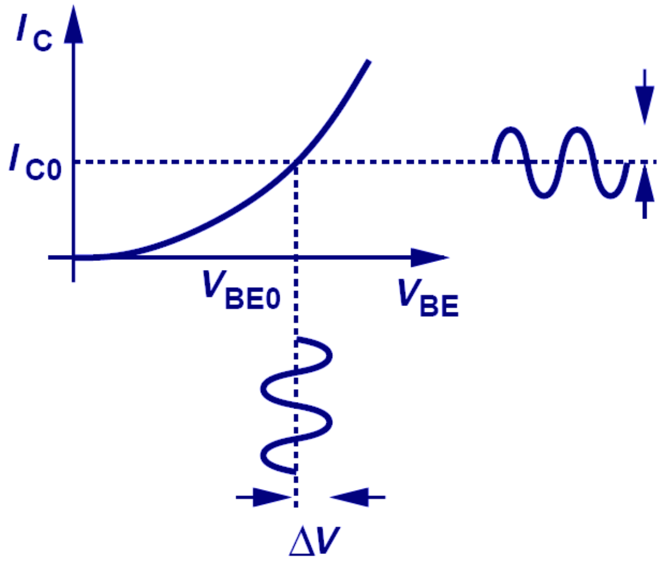

$$i_C = I_S\left[\exp\left(\frac{V_{BE}}{V_T}\right) - 1\right] \approx I_S \exp\left(\frac{V_{BE}}{V_T}\right)$$

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

# BJT Current Amplifier

- Then, a small **change** in current in the base results in a proportional change in current in the collector



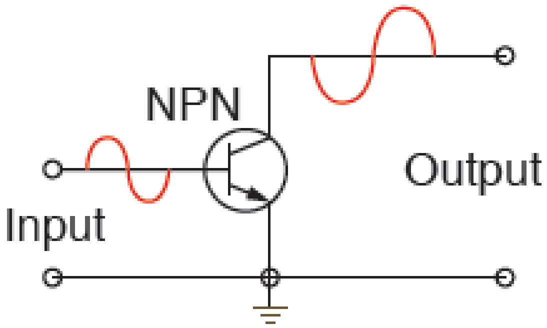
# BJT Configurations

- Different ways to configure a BJT when operating as an amplifier (forward active operation)

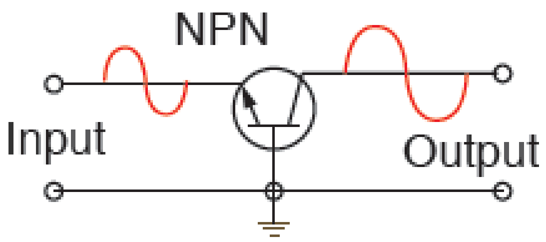
- **Common Emitter**
  Emitter terminal is common between input and output side

- **Common Base**
  Base terminal is common between input and output side

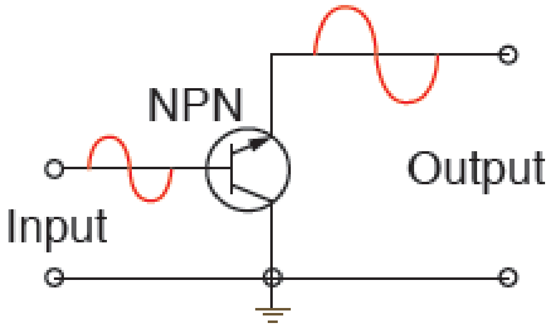
- **Common Collector**
  Collector terminal is common between input and output side




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



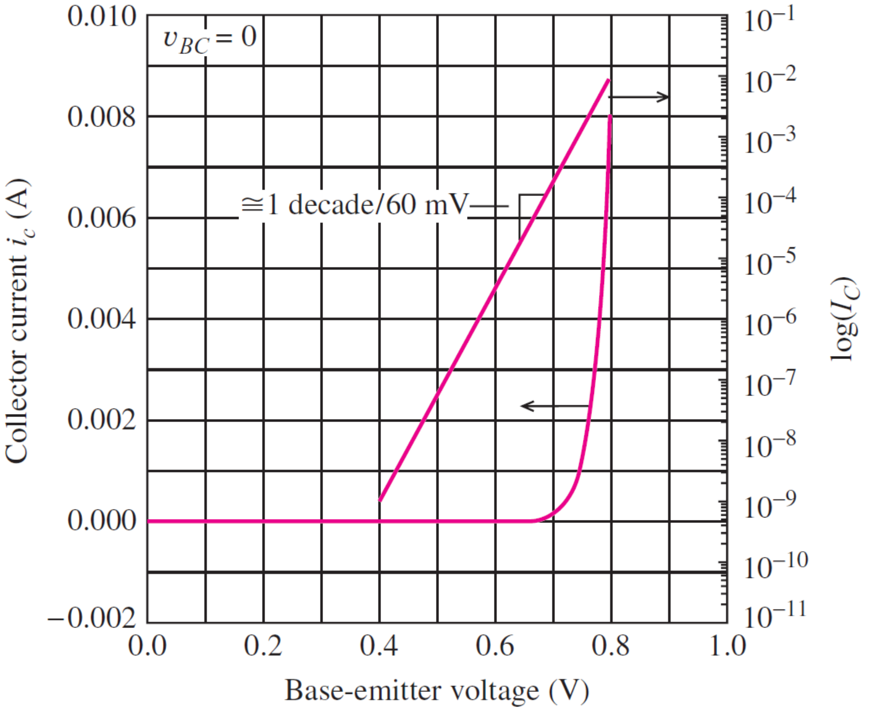

$$\frac{i_C}{i_E} = \alpha_F$$



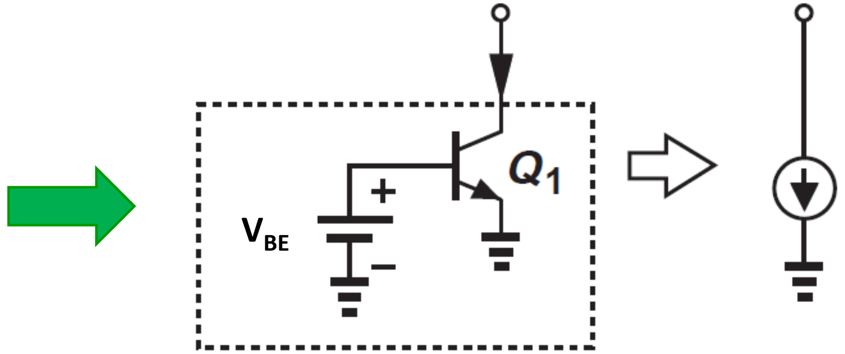

$$\frac{i_E}{i_B} = \beta_F + 1$$

# NPN Forward Active I-V Characteristics

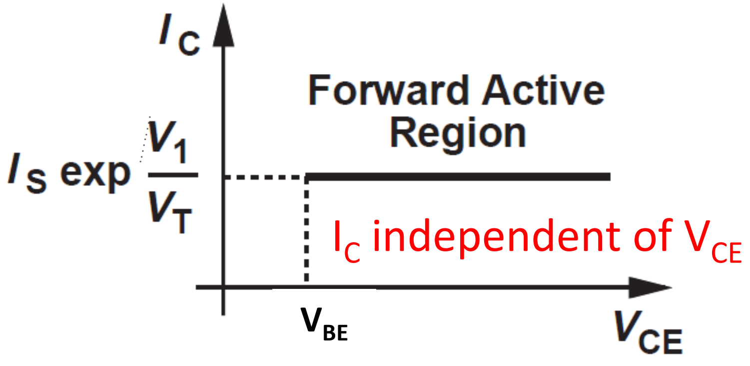
- Relation between collector current and base-emitter voltage of transistor.
- Almost identical to transfer characteristic of *pn* junction diode




$$i_C \approx I_S \exp\left(\frac{V_{BE}}{V_T}\right)$$

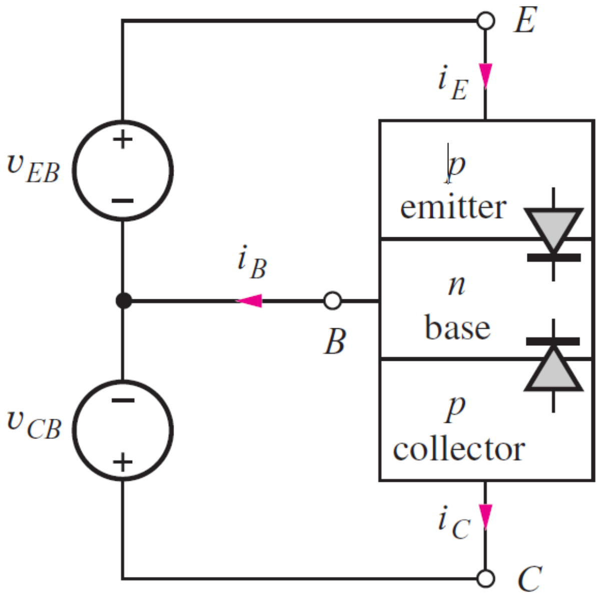


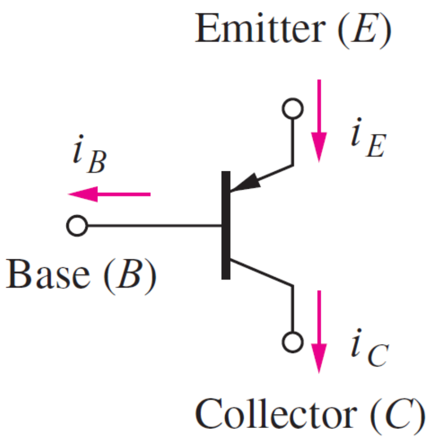

For a fixed $V_{BE}$, device acts like a constant current source, assuming B-C junction is not in breakdown. $I_C$ independent of $V_{CE}$



# PNP Forward Active Region

- PNP forward active region: $V_{EB} > 0$, $V_{CB} < 0$
  - Same concept as NPN, but bias voltages are opposite because the diodes are pointing in the opposite direction
  - Remember, for NPN in forward-active region: $V_{BE} > 0$, $V_{BC} < 0$.
- Base-emitter is still forward-biased, base-collector is still reverse-biased



# PNP Forward Active Region

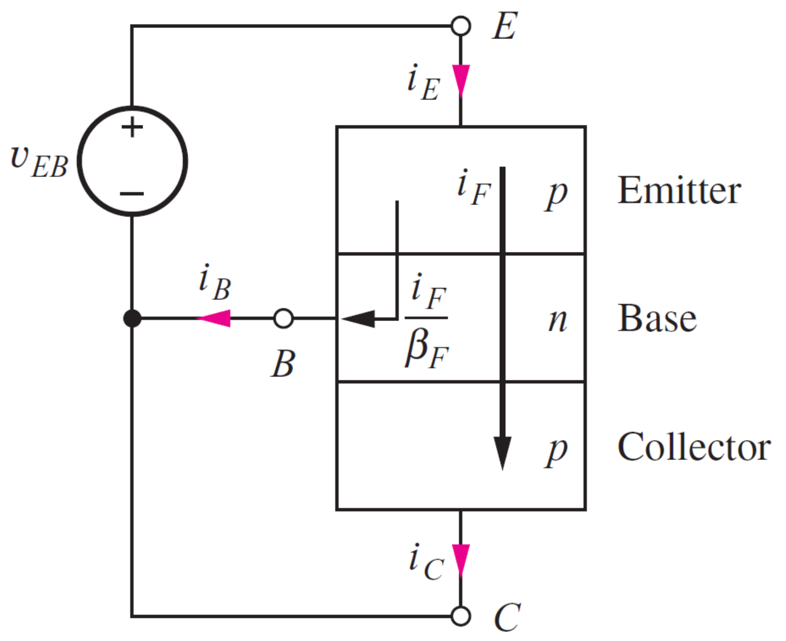
- These are all exactly the same as those for NPN transistors
- The only difference is that the voltages and currents are referenced in the opposite direction

$$i_C = i_F = I_S\left[\exp\left(\frac{V_{EB}}{V_T}\right) - 1\right]$$

$$i_B = \frac{I_S}{\beta_F}\left[\exp\left(\frac{V_{EB}}{V_T}\right) - 1\right]$$

$$i_E = i_C + i_B$$

$$\frac{i_C}{i_B} = \beta_F \qquad \frac{i_C}{i_E} = \alpha_F$$

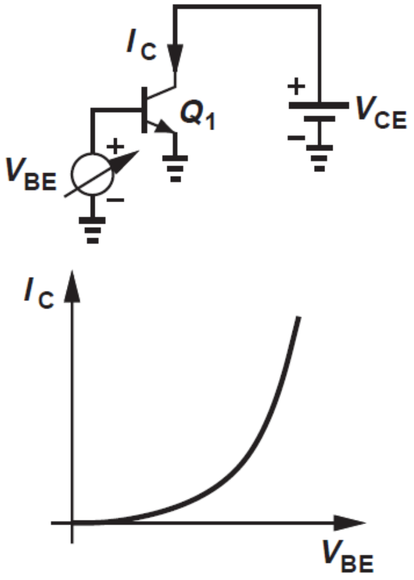


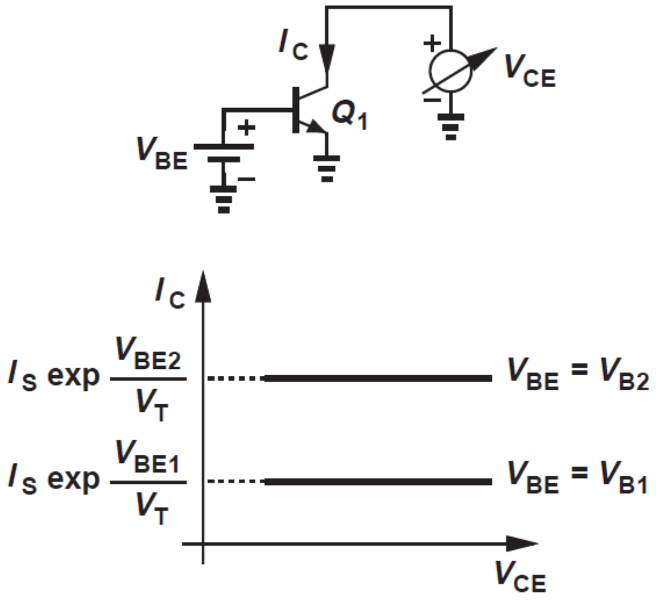
# Summary of I/V characteristics in BJT

- Principal characteristics of interest
- For collector current:

$$I_C \approx I_S \exp\left(\frac{V_{BE}}{V_T}\right)$$

Voltage-dependent
current source




$V_{CE}$ doesn't matter
(as long as BC
junction is reverse
biased and not in
breakdown)

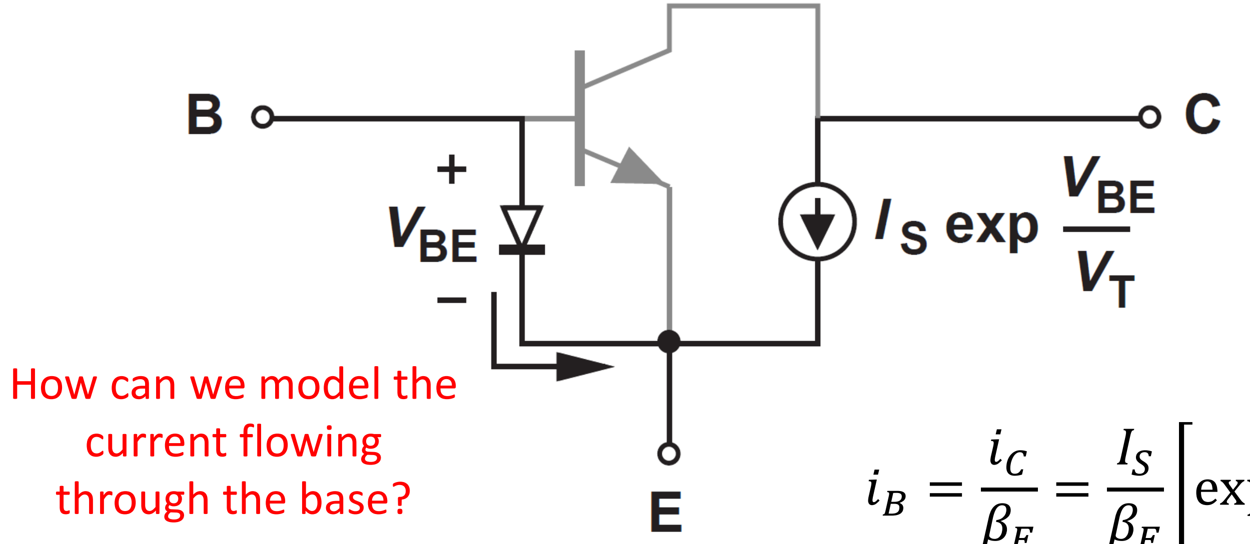
- Base and emitter current follows the same behaviour:

$$I_B = \frac{I_C}{\beta} \qquad I_E = \frac{\beta + 1}{\beta} I_C$$

# BJT Large signal model

# BJT Large Signal Model

- Large-signal circuit analysis deals with inputs which have such a large range that devices cannot be turned into linear models
- Time to construct a model that will be useful for analysis and circuit designs:

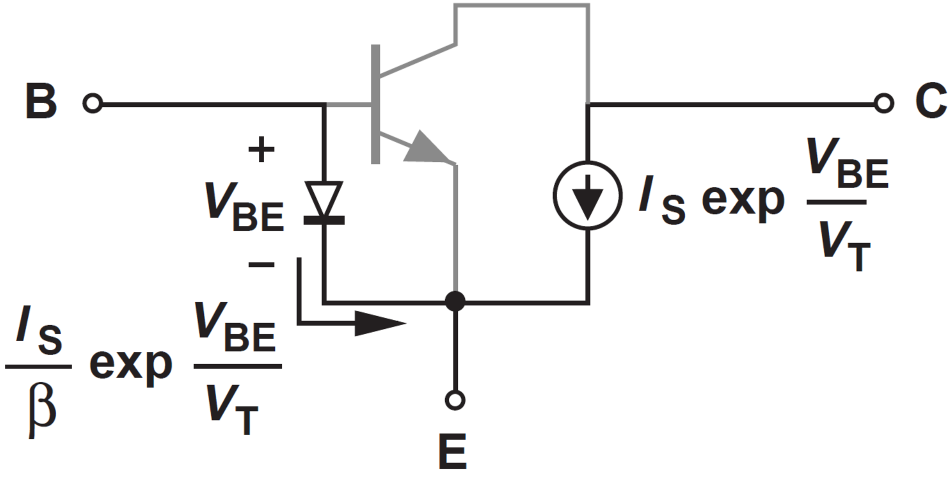



$$i_B = \frac{i_C}{\beta_F} = \frac{I_S}{\beta_F}\left[\exp\left(\frac{V_{BE}}{V_T}\right) - 1\right]$$

- A virtual diode placed between base and emitter terminals
- A virtual voltage controlled current source is placed between the collector and emitter

# BJT Large Signal Model

- Base-emitter junction is modelled by a diode whose cross section is 1/β times that of the actual emitter area



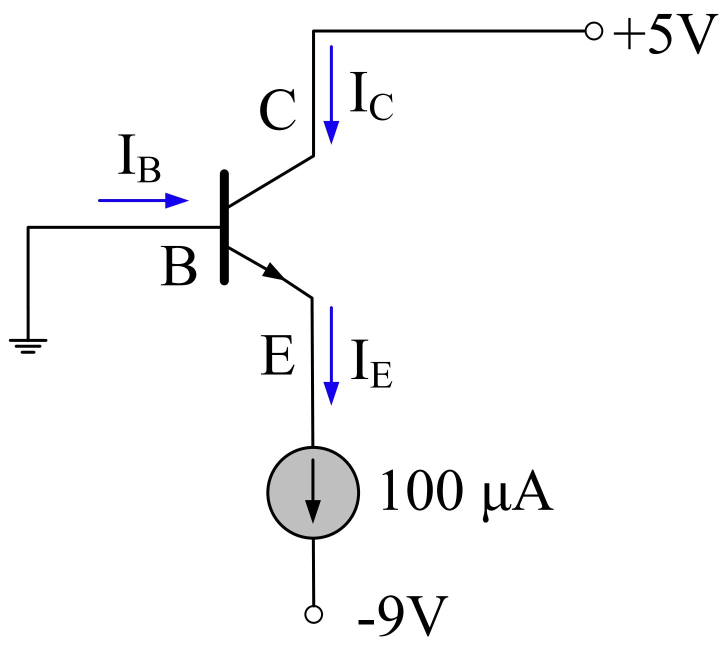

- The chain of dependencies of currents and voltages in a bipolar transistor:

$$\boxed{V_{BE} \rightarrow I_C \rightarrow I_B \rightarrow I_E}$$

# Large Signal Circuit Analysis

**Example 1:** Estimate terminal currents and base-emitter voltage for the following circuit.

Let $I_S = 10^{-16} A, \alpha_F = 0.95, V_{BC} = V_B - V_C = -5\,V, I_E = 100\mu A, V_T = 25\,mV$



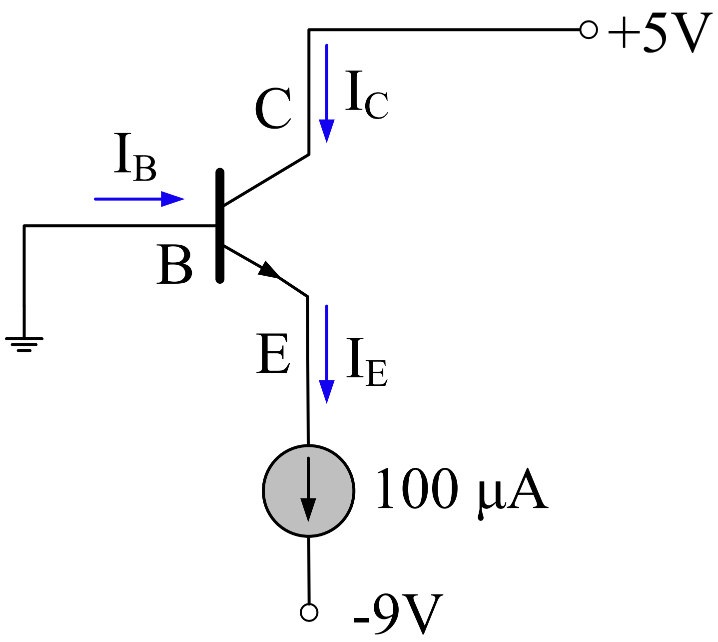

**Observations:**

1. There is a current source at the emitter terminal
2. The base-emitter diode must be forward-biased, and $V_{BE} > 0$
3. $V_{BC} < 0$, base-collector is reverse-biased.
4. The transistor is in forward-active operation region.

# Large Signal Circuit Analysis

Parameters given:

$$I_S = 10^{-16}A, \alpha_F = 0.95, V_{BC} = V_B - V_C = -5\ V, I_E = 100\mu A, V_T = 25\ mV$$




$$I_C = \alpha_F I_E = 0.95 \times 100\mu A = 95\mu A$$

$$\beta_F = \frac{\alpha_F}{1-\alpha_F} = \frac{0.95}{1-0.95} = 19$$

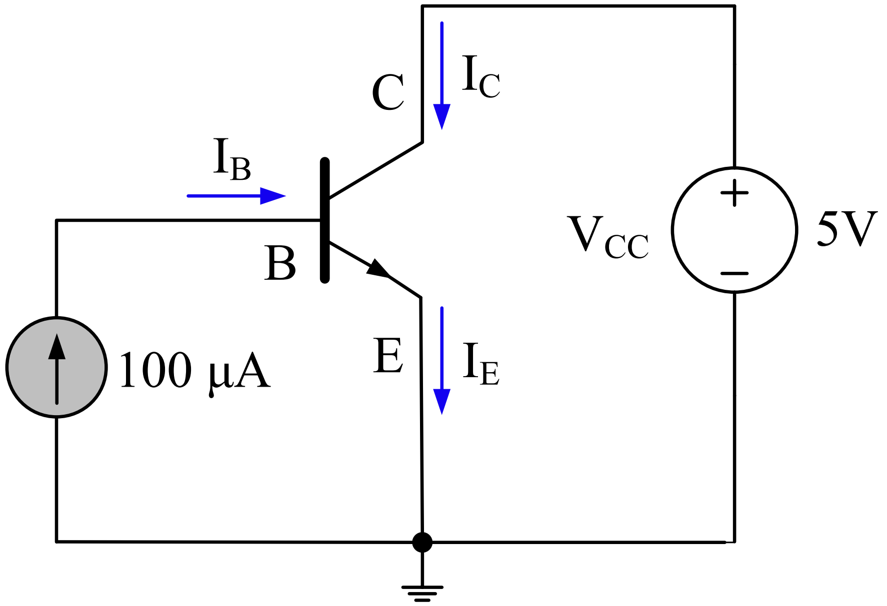
$$I_B = \frac{I_E}{\beta_F + 1} = \frac{100\mu A}{19+1} = 5\mu A$$

$$V_{BE} = V_T \ln\left(\frac{\alpha_F I_E}{I_S}\right) = 0.69V$$

# Large Signal Circuit Analysis

**Example 2:** Estimate terminal currents, base-emitter, and base-collector voltage for the following circuit.

Let $I_S = 10^{-16} A, \alpha_F = 0.95, V_C = +5\,V, I_B = 100\mu A, V_T = 25\,mV$



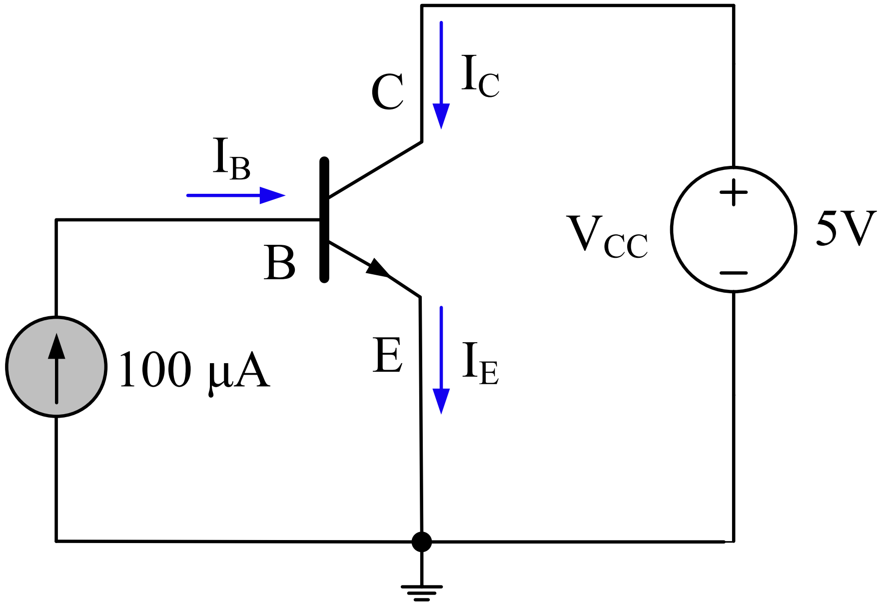

**Observations:**

1. There is a current source going into the base
2. The base-emitter diode must be forward-biased, and $V_{BE} > 0$
3. Base-collector is reverse-biased.
4. The transistor is in forward-active operation region.

# Large Signal Circuit Analysis

Parameters given:

$$I_S = 10^{-16}A, \alpha_F = 0.95, V_C = +5\,V, I_B = 100\mu A, V_T = 25\,mV$$




$$I_C = \beta_F I_B = 19 \times 100\mu A = 1.9mA$$

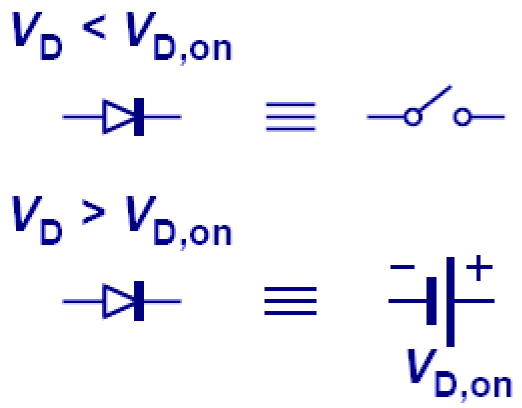
$$\begin{aligned} I_E &= (\beta_F + 1) I_B \\ &= 20 \times 100\mu A = 2mA \end{aligned}$$

$$V_{BE} = V_T \ln\left(\frac{I_C}{I_S}\right) = 0.764V$$

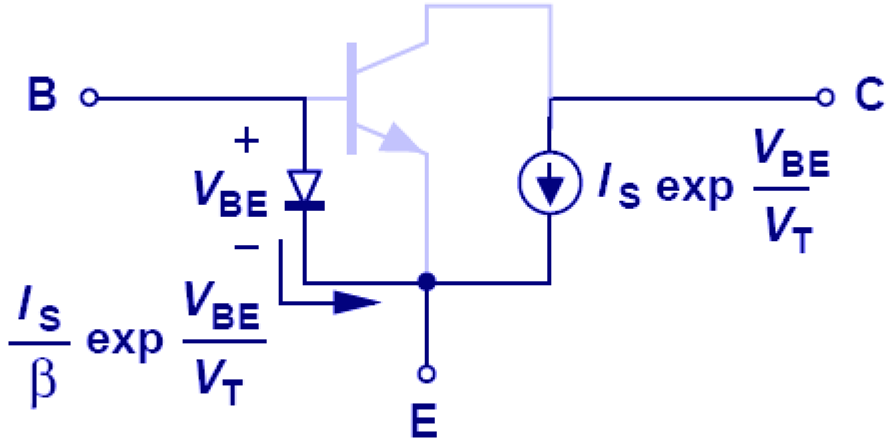
$$\begin{aligned} V_{BC} &= V_B - V_C = V_{BE} - V_C \\ &= 0.764V - 5 = -4.24V \end{aligned}$$

# BJT Model

- To further simplify the model,
  - Replace diode with a **constant-voltage diode** model
- When analyzing circuits, you must determine that the base-emitter junction is forward-biased before applying this model




CVD diode model

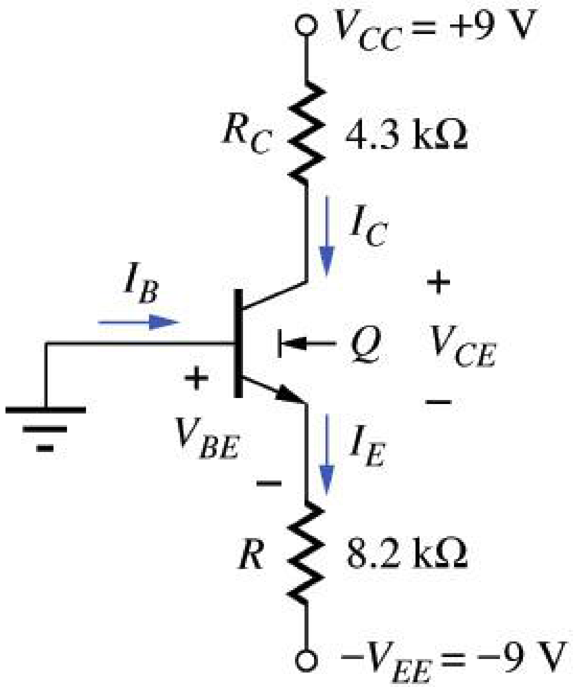


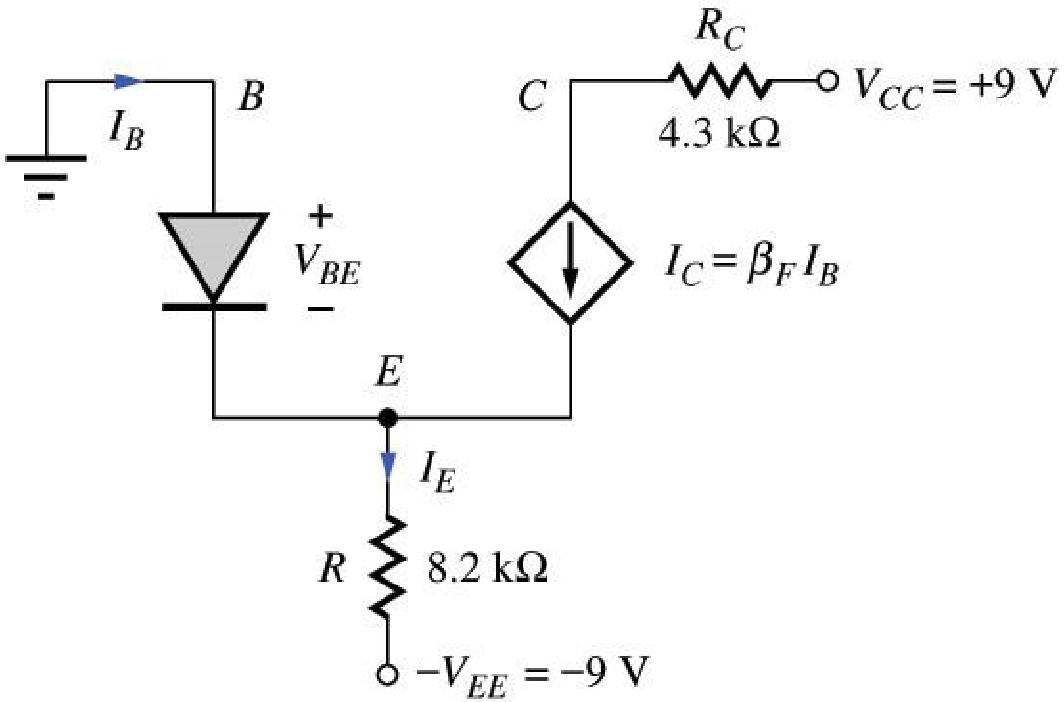

BJT model

# BJT Analysis

**Example:** Find Q-point for the following circuit. Let $\beta_F = 50, V_{BC} = -9\ V, V_{D,on} = 0.7V$

Assume transistor is in the forward-active operation. Then we can replace the BJT with a diode and a current source for large signal analysis.

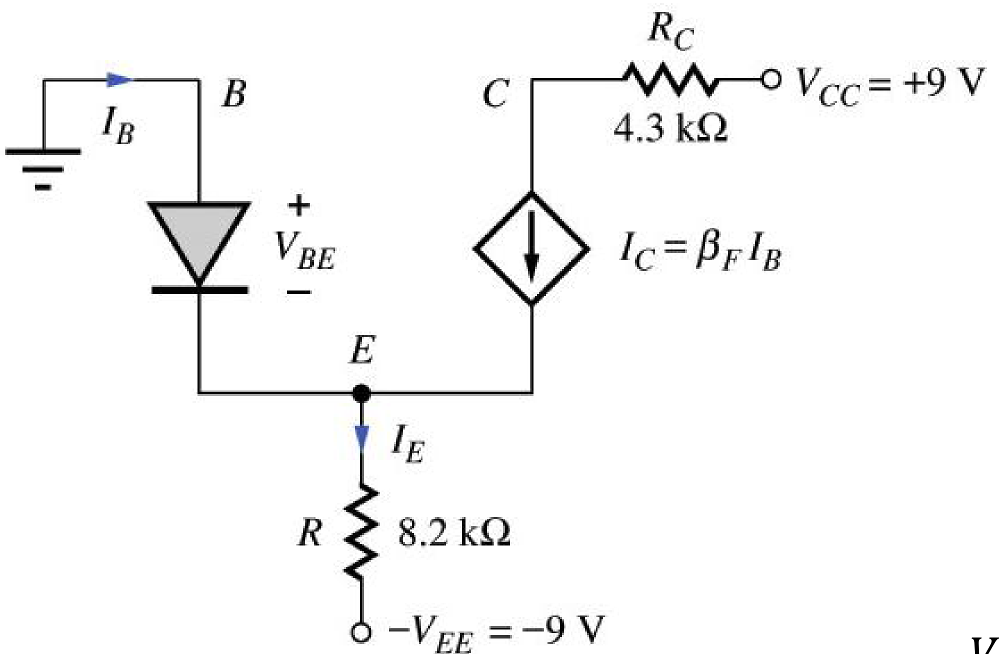


# BJT Analysis

Parameters given: $\beta_F = 50, V_{BC} = -9\ V, V_{D,on} = 0.7V$

Assume transistor is in the forward-active operation.




$$V_{BE} + 8200I_E - V_{EE} = 0$$

Assume CVD for BE junction, $V_{BE} = V_{D,on} = 0.7V$

$$I_E = \frac{V_{EE} - V_{BE}}{8200} = \frac{8.3}{8200} = 1.01\ mA$$

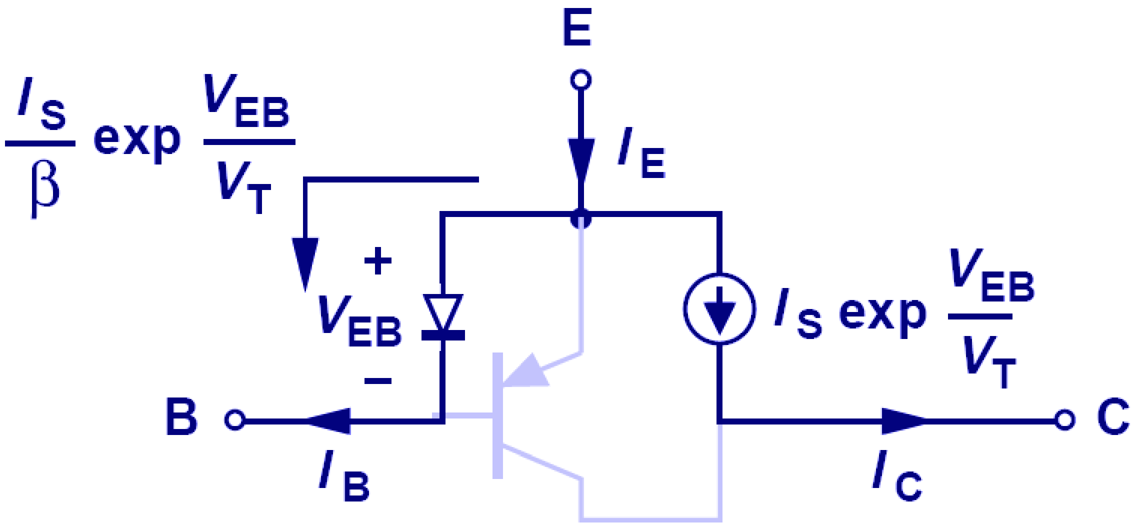
$$I_B = \frac{I_E}{\beta_F + 1} = 19.8\ \mu A$$

$$I_C = \beta_F I_B = 0.990\ mA$$

$$V_{CE} = V_{CC} - I_C R_C - (-V_{BE}) = 5.44V$$

# PNP Large Signal Model

- Exact same model as NPN, but currents and voltages are flipped




$$I_C = I_S \exp \frac{V_{EB}}{V_T}$$

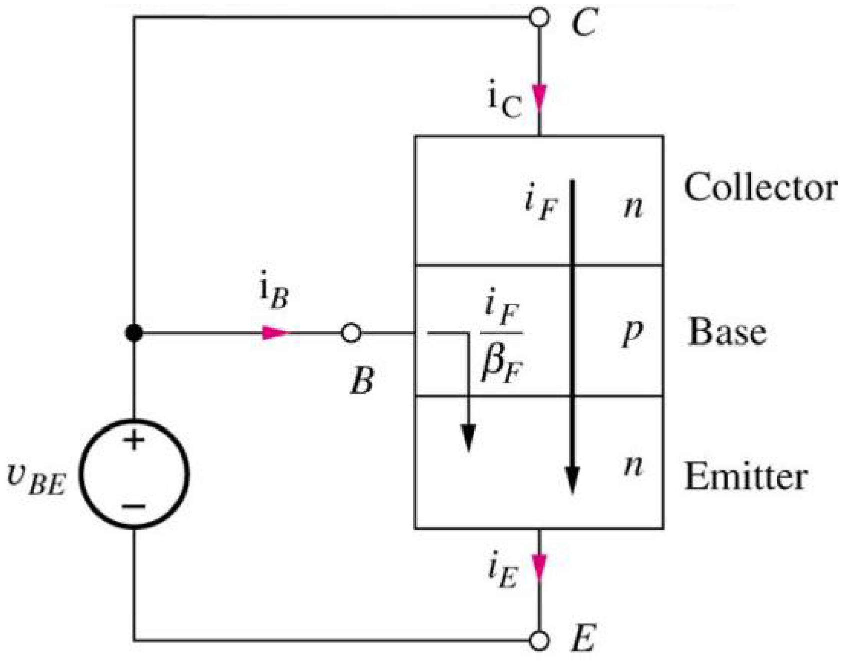
$$I_B = \frac{I_S}{\beta} \exp \frac{V_{EB}}{V_T}$$

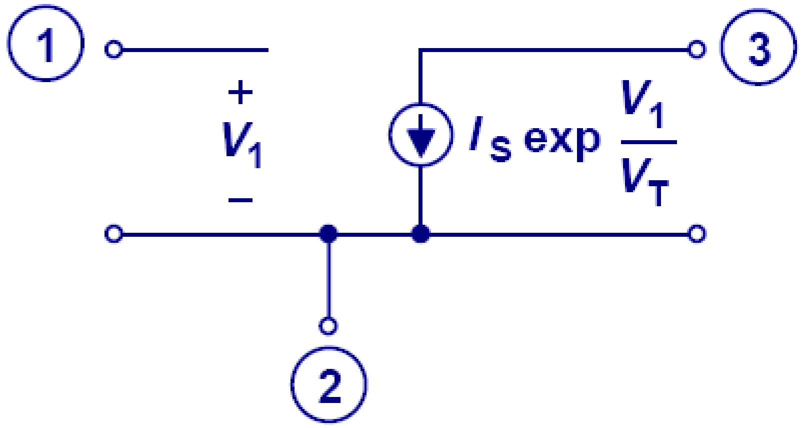
$$I_E = \frac{\beta + 1}{\beta} I_S \exp \frac{V_{EB}}{V_T}$$

# BJT small signal analysis

# BJT as Voltage-Controlled Current Source

- BJT can be modeled as a 3-terminal voltage-controlled current source
- Exponentials are a hassle
- If we keep the device operating around a given point with only small changes in the signal, we can create a linear model.

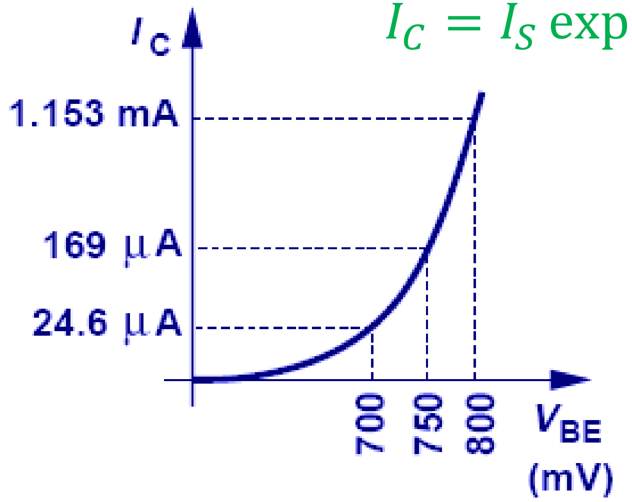


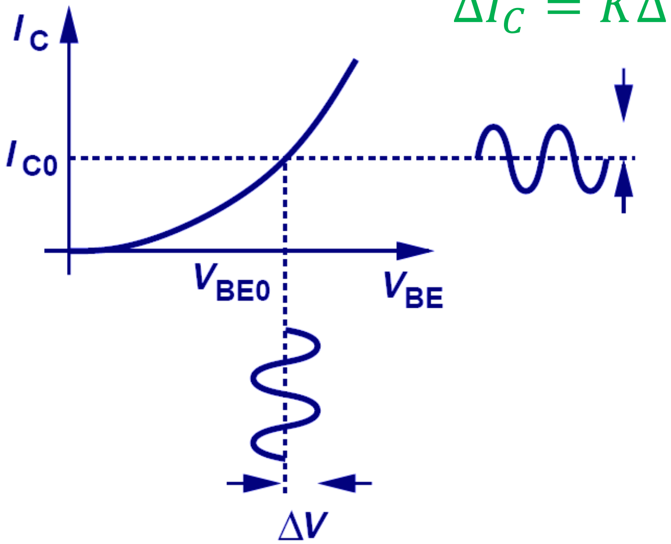
# BJT as Voltage-Controlled Current Source

- The relationship between $V_{BE}$ and $I_C$ is approximately linear when looking at small signals

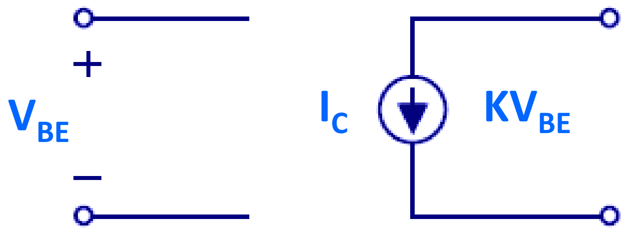
$$I_C = I_S \exp\left(\frac{V_{BE}}{V_T}\right)$$




$$\Delta I_C = K\Delta V_{BE}$$

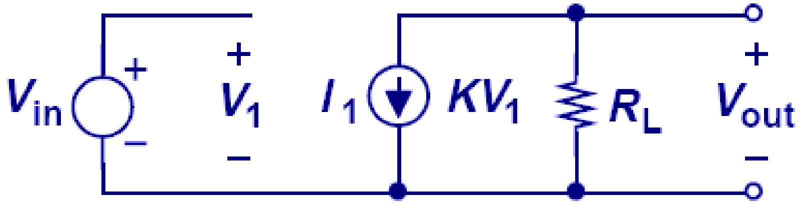



K represents some constant relation between $\Delta V_{BE}$ and $\Delta I_C$



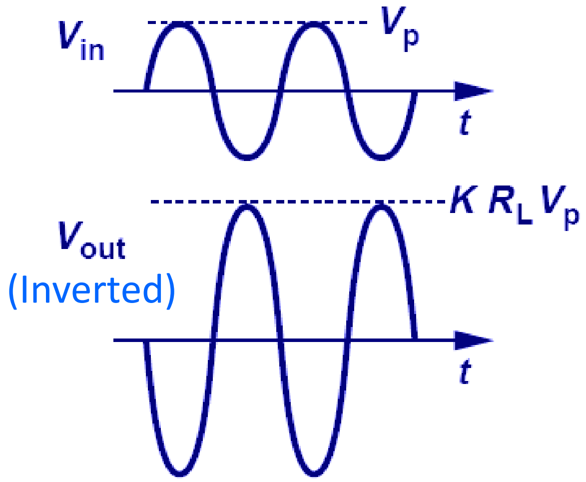
# BJT as Voltage-Controlled Current Source

- Output voltage can be measured across an output load




$$v_{out} = -K v_{in} R_L$$

- If $KR_L$ is greater than 1, then the signal is amplified

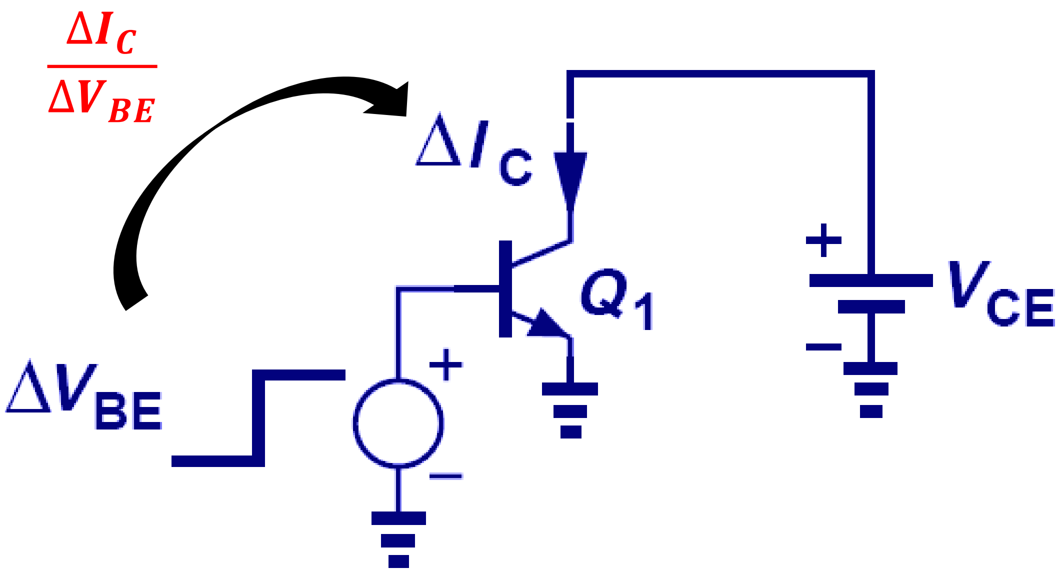



$$A_V = \frac{v_{out}}{v_{in}} = -KR_L$$

- How to quantify the device performance?
- How well can the voltage control the current source?
- What is K?

# BJT Transconductance

- Transconductance, $g_m$ is a small-signal measure of how well the transistor converts voltage to current.
- **$g_m$ is one of the most important parameters** in circuit design.
- Remember, for large-signal analysis, conductance G = 1/R




For small changes:

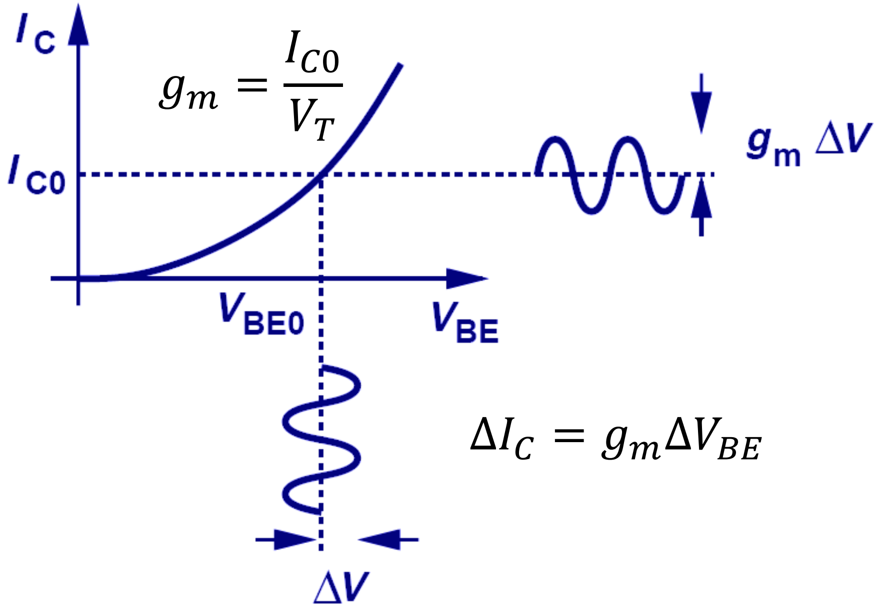
$$g_m = \frac{dI_C}{dV_{BE}} = \frac{d}{dV_{BE}}\left(I_S \exp\frac{V_{BE}}{V_T}\right)$$

$$g_m = \frac{1}{V_T}\left(I_S \exp\frac{V_{BE}}{V_T}\right)$$

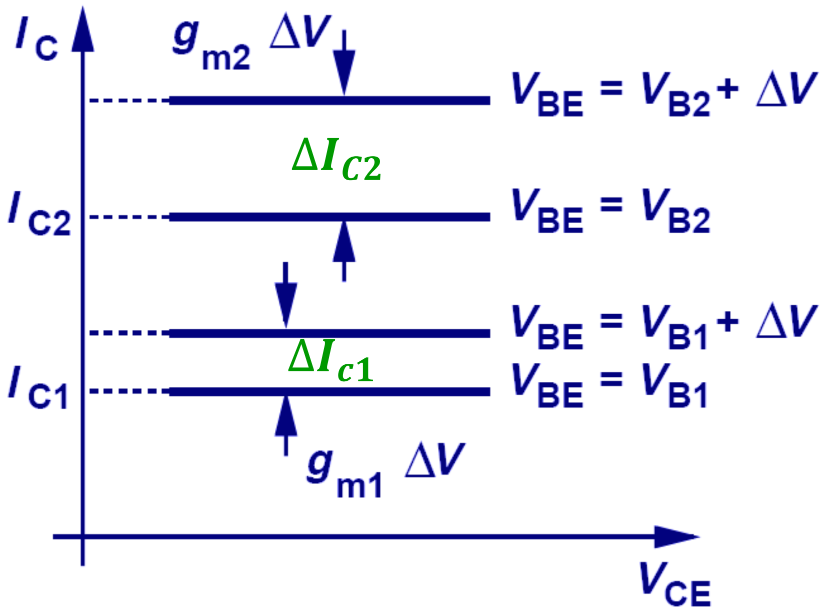
$$\boxed{g_m = \frac{I_C}{V_T}}$$

# BJT Transconductance

- $g_m$ can be visualized as the slope of $I_C$ versus $V_{BE}$ characteristics at a given collector current $I_{C0}$ and base-emitter voltage $V_{BE0}$
- A large $g_m$ will cause a large change in $I_C$ for the same change in $\Delta V_{BE}$




$I_{C2} > I_{C1}$

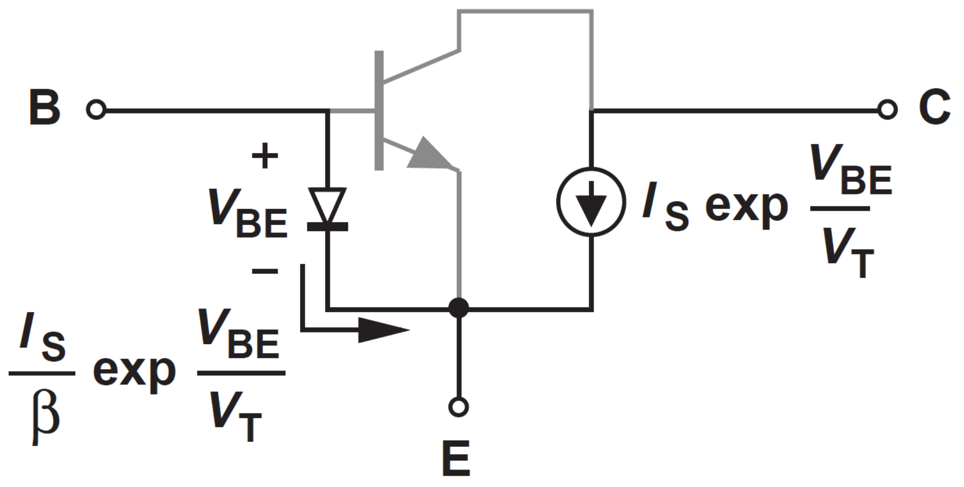



$g_{m2} > g_{m1} \rightarrow \Delta I_{C2} > \Delta I_{c1}$

# BJT Transconductance

**Question:**

- If $I_C$ remains constant, but β varies, does $g_m$ change?




$$g_m = \frac{I_C}{V_T}$$

So, no.

$\beta \nearrow, I_B \searrow$

- Collector bias (or quiescent) current plays an important role in the design of BJT amplifiers