

Transistors

- **Bipolar Junction transistors**
 - Principle of operation
 - Characteristics
- **Field effect transistors**
 - Principle of operation
 - Characteristics

Introduction

Radio based on vacuum tubes

- Fundamental building block of electronics in computers, cellular phone, and more...
- Semi-conductor device
- Use small voltage or current to control large voltage/current
- Fast response → transistor used in many elementary electronic functions including:
 - Amplification,
 - Switch,
 - Feedback system, regulation,
 - Signal modulation,
 - Oscillators.
- Integrated circuit contains thousands of transistor in very small areas.

1956 Nobel price was awarded to [William Bradford Shockley](#) , [John Bardeen](#) and [Walter Houser Brattain](#) for “their researches on semiconductors and their discovery of the transistor effect”

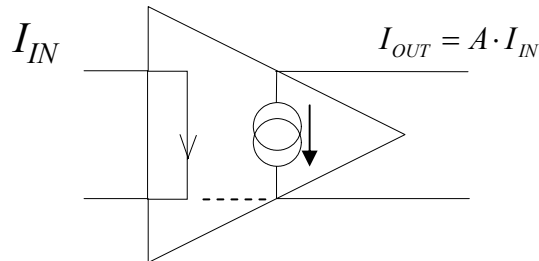


1st pocket radio based on transistors



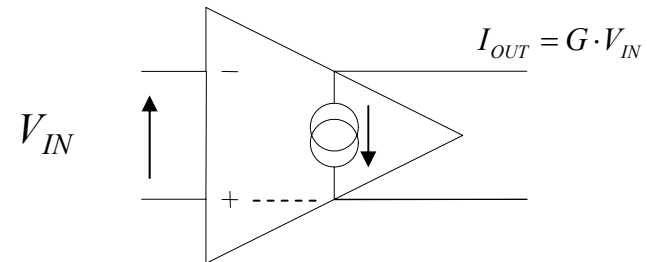
Transistor types

- Two types of transistor (based on two different physical mechanisms:
 - Field effect transistor
 - Bipolar Junction transistors.
- To 1st order they act as current source
 - FET ~ voltage-controlled current source
 - BJT ~ current-controlled current source



*Current source
controlled by a
current*

A = current “gain”



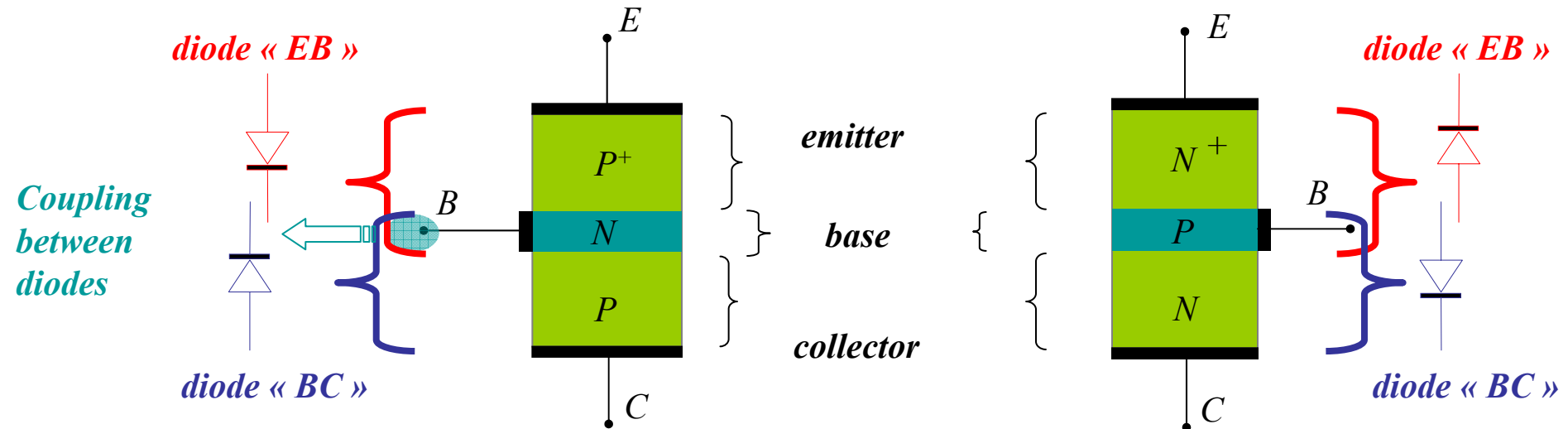
*Current source
controlled by a
voltage*

G = transconductance.

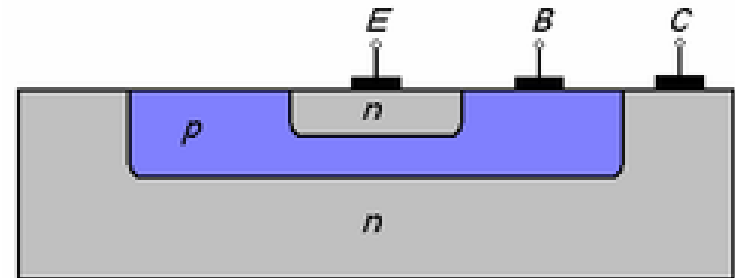
Transistors

Transistor PNP

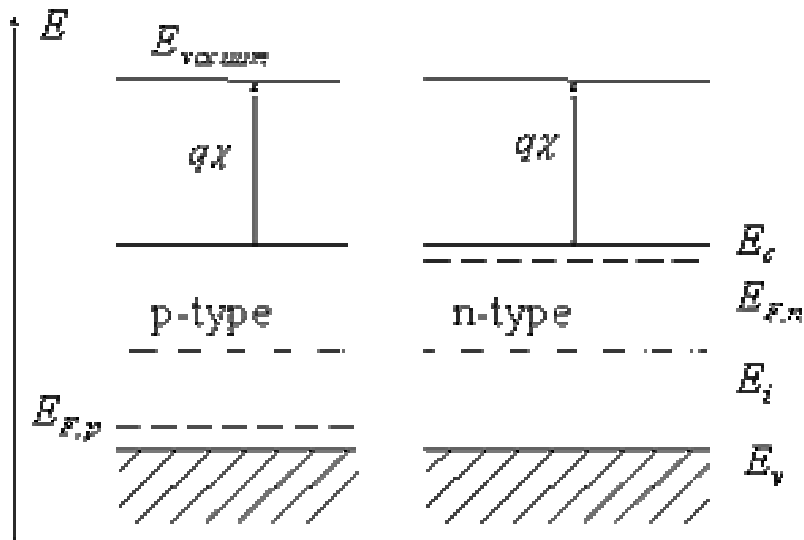
Transistor NPN



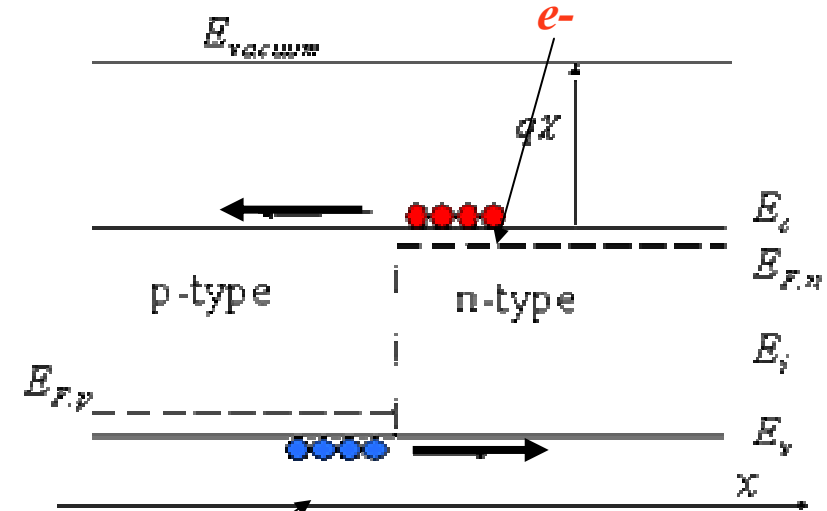
Two coupled PN junctions (or diodes) \Leftrightarrow « transistor effect »



Bipolar Junction Transistor (BJT) Going back to the p-n junction

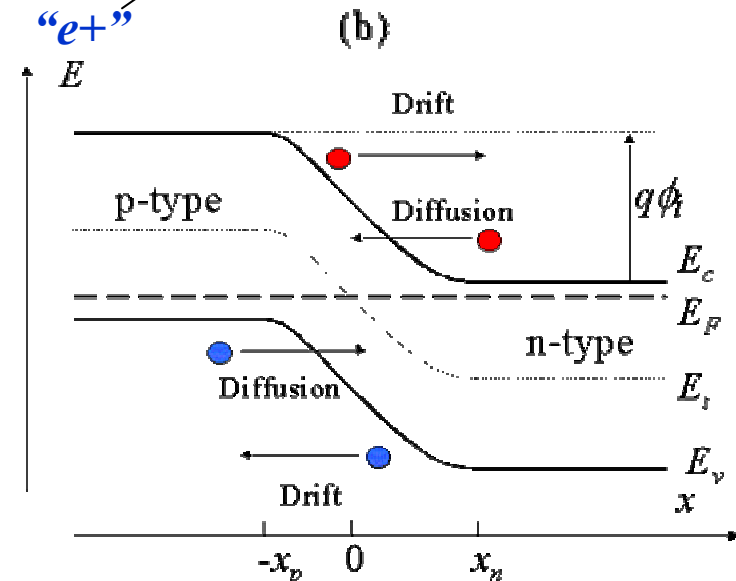


(a)

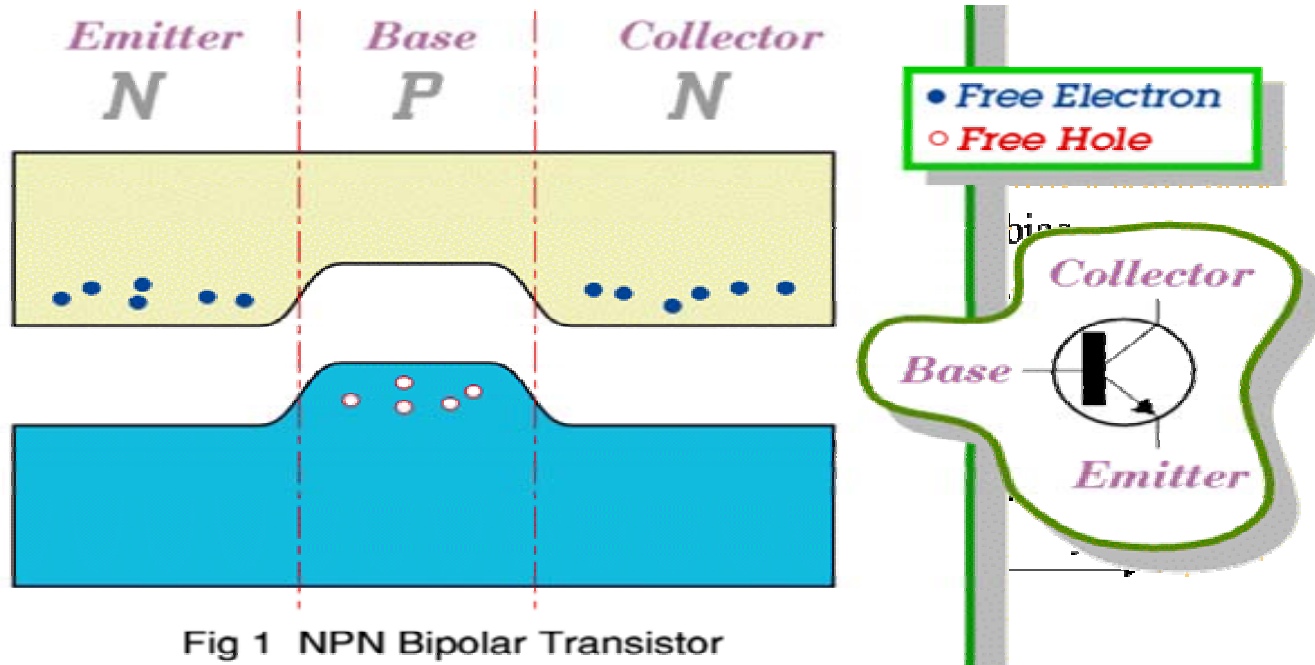


(b)

- Electrons moved into the p-type semiconductor
- Locally (at the junction interface) there is a recombination hole-electron
- This leaves positive ions in the n-type semiconductor and negative ions in the p-type semiconductor

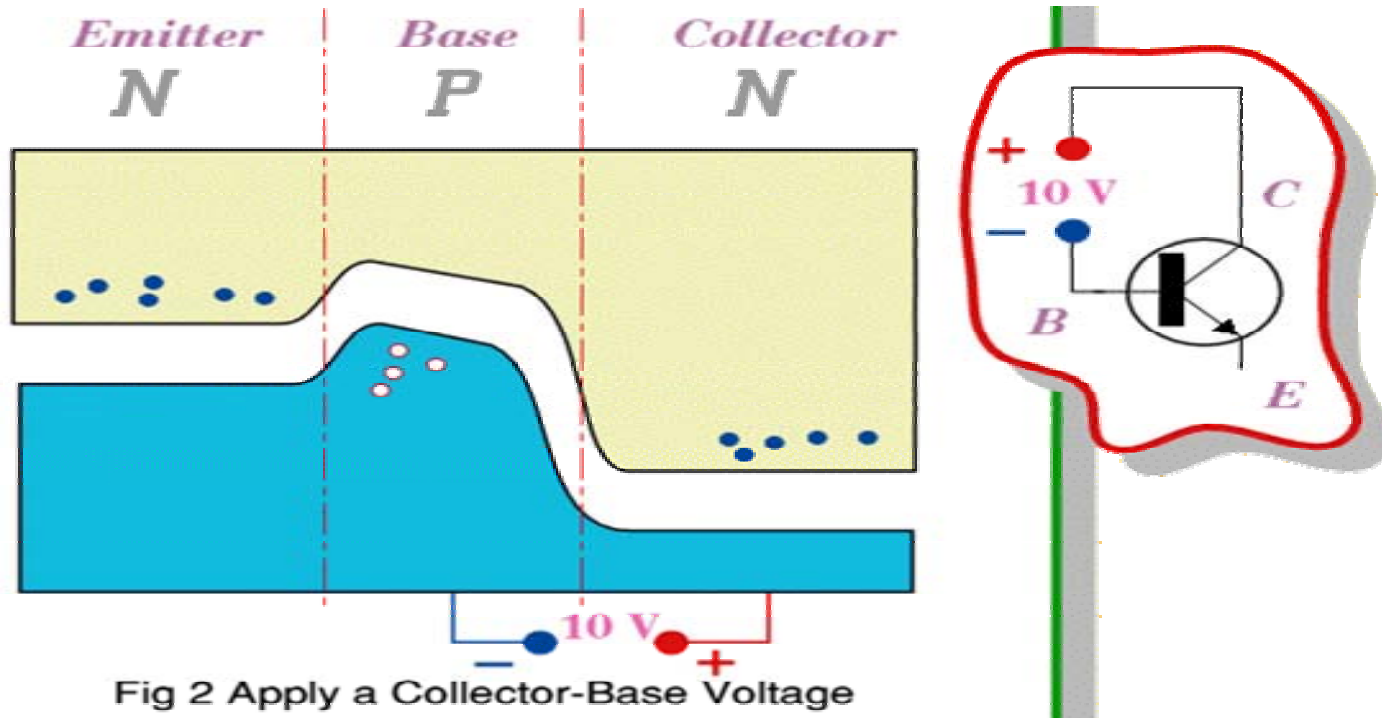


BJT: N-P-N transistor



- In each of the N-layers, conduction can take place (motion of free electrons in conduction band)
- In the P-type layer, conduction can take place (movement of free holes in valence band)
- In absence of externally applied E-field, depletion zones form at both P-N junction, so no charge move from on layer to the other.

BJT: N-P-N transistor



- Now voltage is applied between collector and base parts of the transistor, with polarity such to increase force pulling N type electron and P-type holes apart
- Effect is to widen the depletion zone between Collector and Base
- No current flow → base-collector diode junction is reversed biased.

BJT: N-P-N transistor

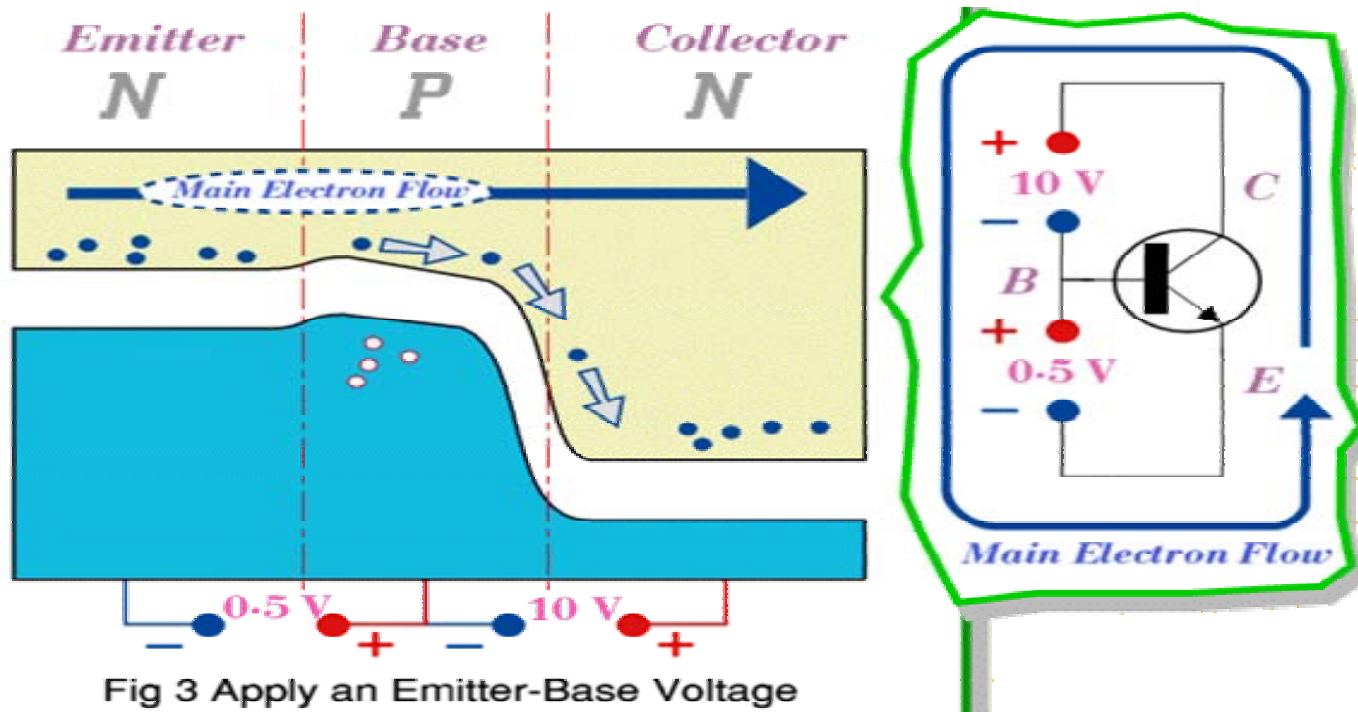


Fig 3 Apply an Emitter-Base Voltage

- Now relatively small voltage is across to the emitter-based junction such to forward-bias the junction
- Electron from emitter flow toward the base → current flow across emitter/base junction.
- Electron in the experience attractive force from positively biased collector
- Emitter/Collector current with magnitude depending on Emitter-base voltage

Current flow in a bipolar junction

■ Kirchhoff's current law imposes $I_E = I_B + I_C$

■ Let's define the parameter $\alpha_T = \frac{I_C}{I_E}$ and the current gain $\beta_F = \frac{I_C}{I_B}$

■ We have

$$\beta_F = \frac{\alpha_T}{1 - \alpha_T} \iff \alpha_T = \frac{\beta_F}{\beta_F + 1}$$

■ α_T is the common base forward short circuit current gain

■ β_F is the forward common emitter current gain (20 to 50)

■ An ideal junction would have $\alpha_T = 1$, real transistors have $0.95 < \alpha_T < 0.99$, a value close to unity for thin or weakly doped bases

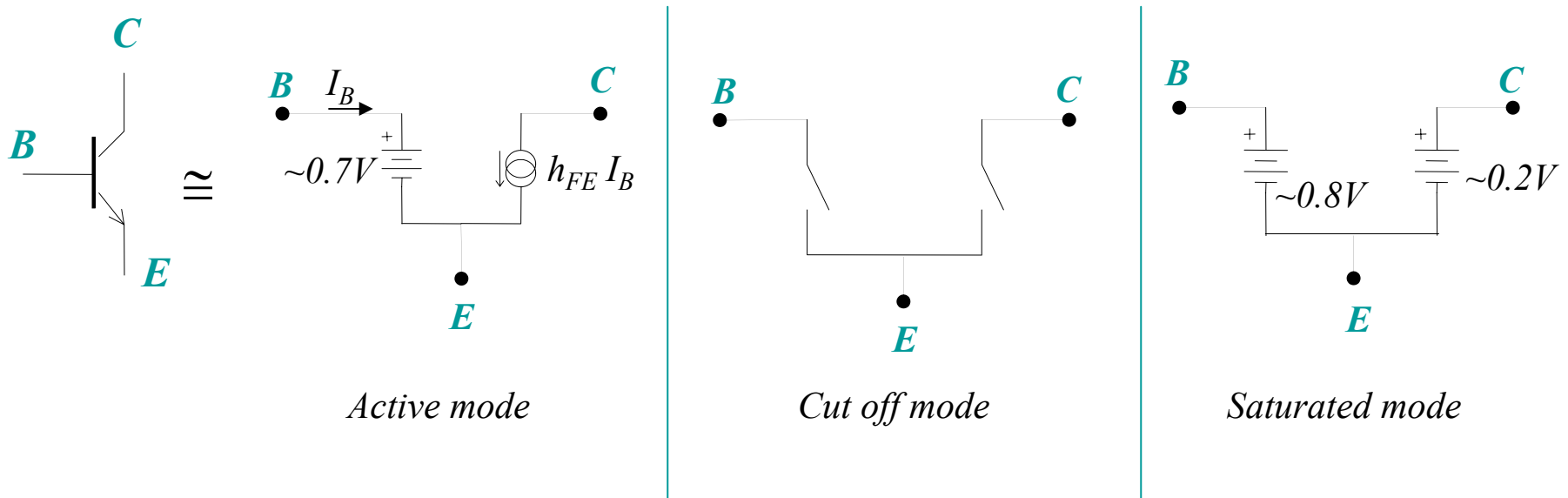
■ For a NPN BJT, $V_C > V_E$ while $V_C < V_E$ for a PNP

Operating mode for a NPN transistor

Active mode : $V_{BE} \approx 0.7V$ $\sim 0.3V < V_{CE} < V_{CC}$ $I_c \approx \beta_F I_B$

Cut off mode: $I_B \approx 0$ $V_{CE} \approx V_{CC}$ $I_C \approx 0$

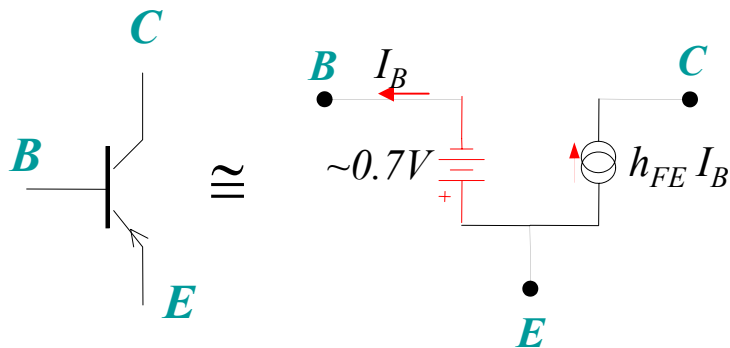
Saturated mode : $V_{BE} \approx 0.8V$ $V_{CE} \approx 0.2V$ $I_c \neq \beta_F I_B$



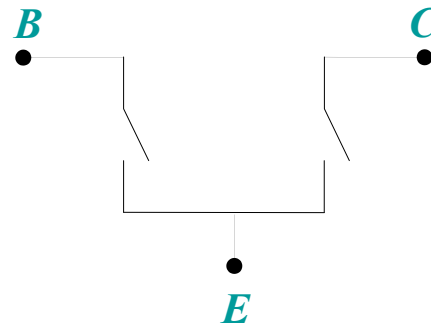
V_{CC} = voltage source for C and E. $V_{CE} < V_{CC}$!

Operating mode for a PNP transistor

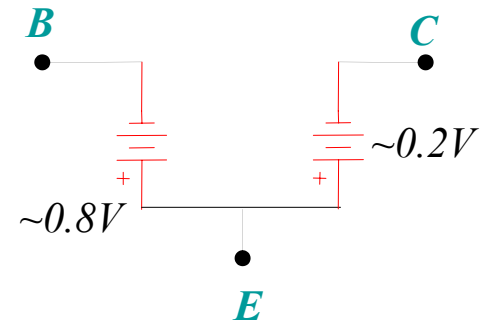
Active mode	$V_{BE} \approx -0.7V$	$\sim -0.3V < V_{CE} < V_{CC} \quad (< 0)$	$I_c \approx \beta_T I_B$
Cut off mode	$I_B \cong 0$	$V_{CE} \cong V_{CC}$	$I_C \approx 0$
Sat, mode	$V_{BE} \approx -0.8V$	$V_{CE} \approx -0.2V$	$I_c \neq \beta_T I_B$



Active mode



Cut off mode



Saturated mode

Characteristics of a bipolar junction

■ Parameters choices

The various operating currents and voltages (I_E , I_B , V_{BE} , V_{CE} , ...) of a transistor are related to each other

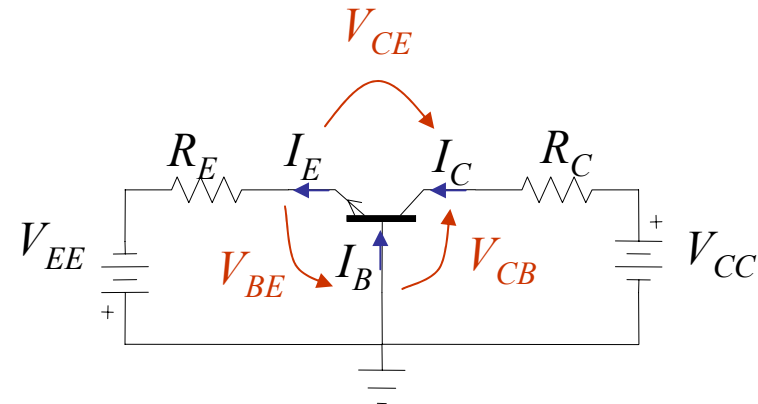
So different equivalent characteristics exist.

- For common base configuration,

characteristics : $I_E(V_{BE}, V_{BC})$, $I_C(V_{BC}, I_E)$

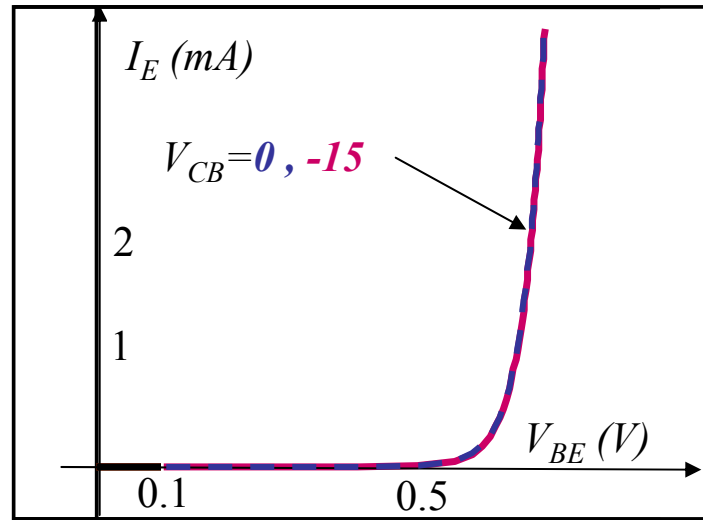
- For common emitter configuration,

characteristics : $I_B(V_{BE}, V_{CE})$, $I_C(V_{CE}, I_B)$



Characteristics

$I_E(V_{BE}, V_{CB}) :$

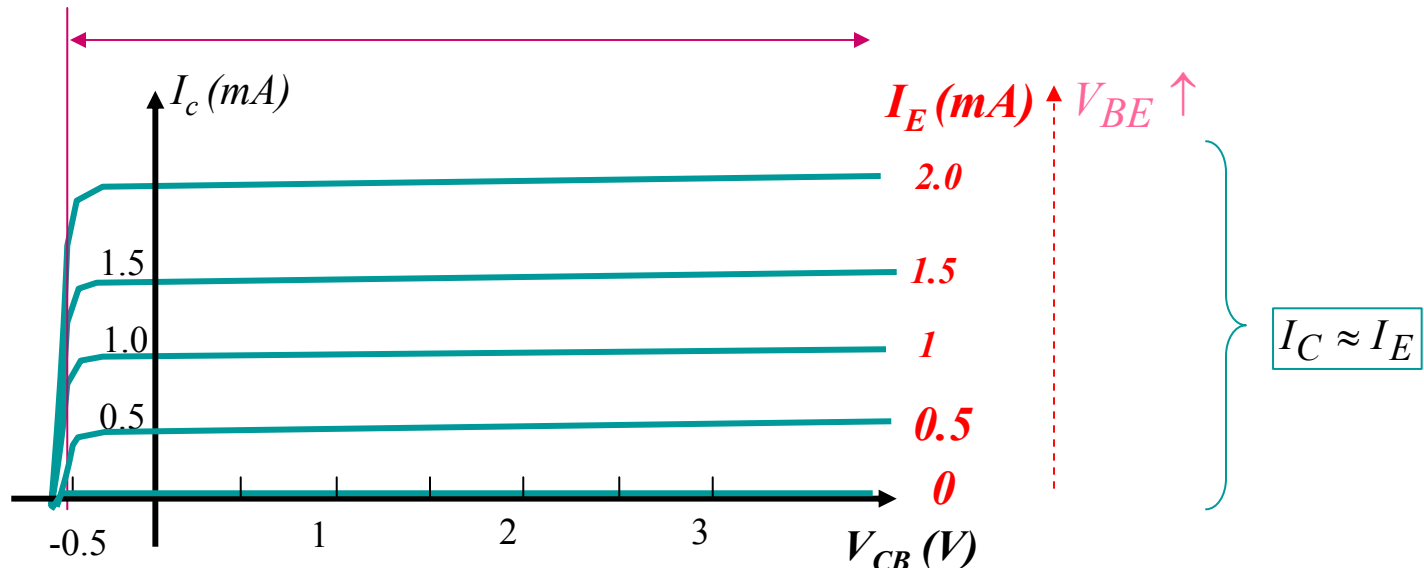


~ characteristics for a **PN junction**

$$I_E \cong I_s \left[\exp\left(\frac{V_{BE}}{V_T}\right) - 1 \right]$$

! Small influence of I_C (resp. V_{CB})

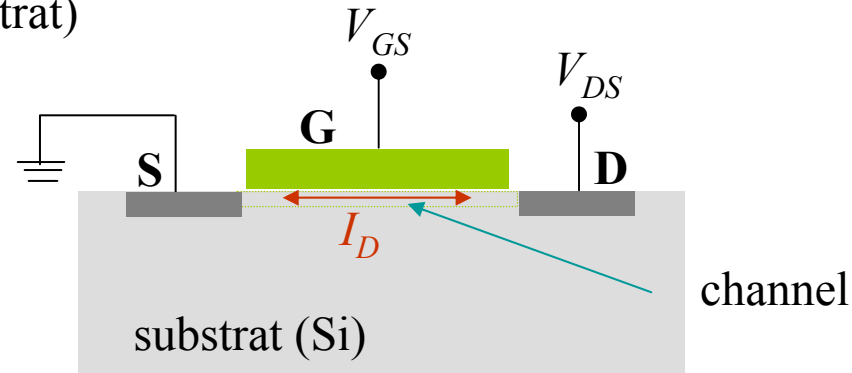
$I_C(V_{CB}, I_E) :$



Field Effect transistor (FET)

- Three terminals : S, D et G, (sometime four: substrat)

- A current (I_D) can flow from **source** S to **drain** D via a “**channel**” (area located close to the gate):



- The current flowing through the gate (I_G) is small.
 $\Rightarrow I_S = I_D$!

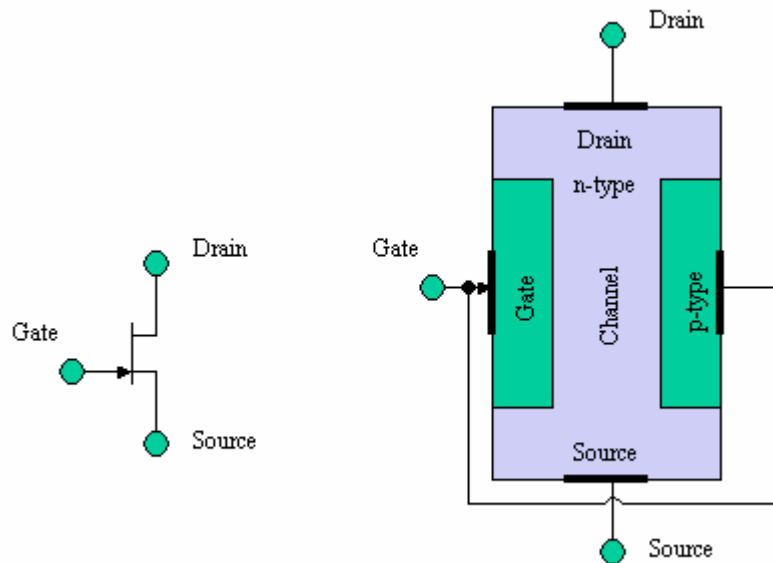
- I_D , at constant V_{DS} is controlled by the gate voltage – source (V_{GS}) \Leftrightarrow “electric field effect”

- *n-channel FET* : current induced by **electrons**, from S to D

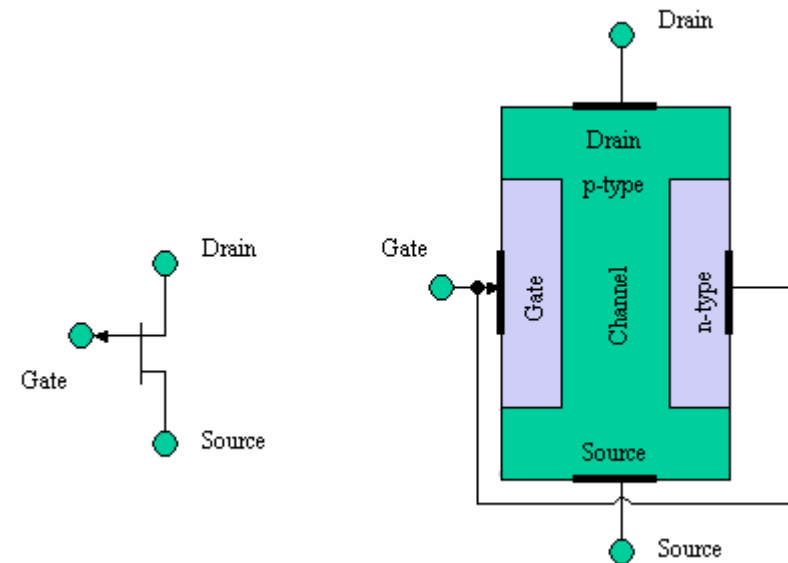
- *p-channel FET*: current carried by **holes**, from S to D

Field Effect transistor (FET)

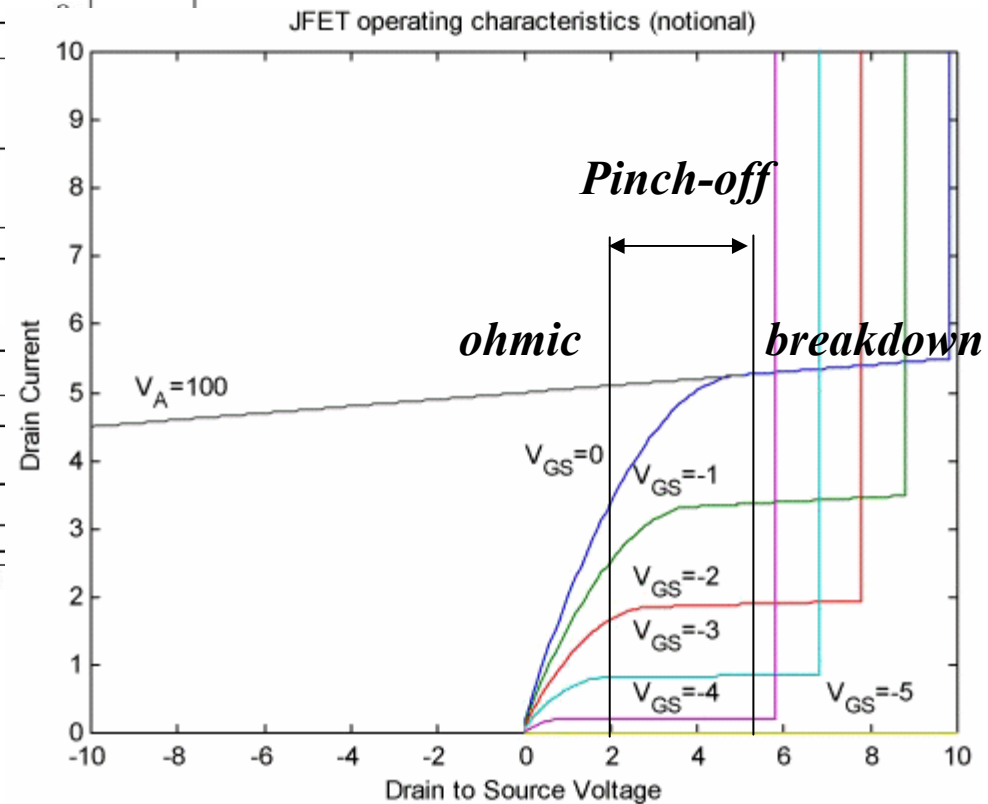
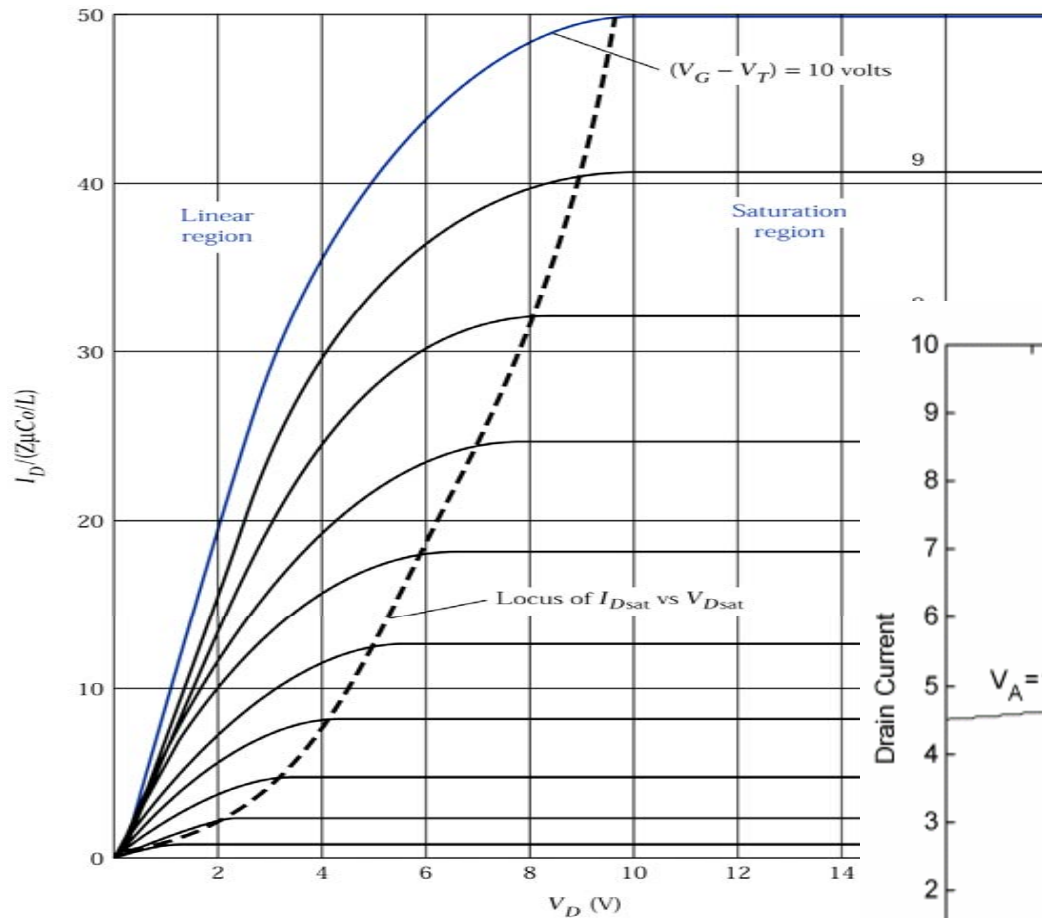
N-type channel



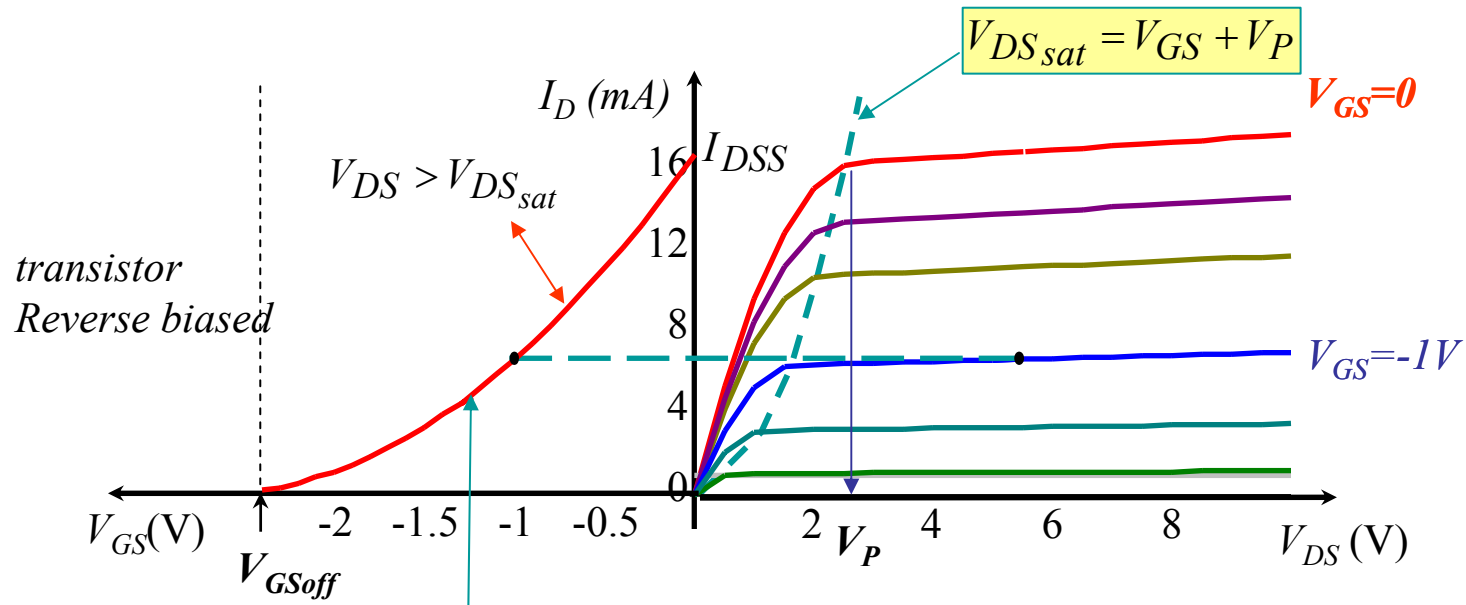
P-type channel



Typical $I_D(V_{DS}, V_{GS})$ characteristics



Typical characteristics



Pinch-off regime

for $V_{DS} > V_{DSsat}$

$$I_D \cong I_{DSS} \left(1 - \frac{V_{GS}}{V_{GSoff}} \right)^2 = k (V_{GS} - V_{GSoff})^2 \quad k = \frac{I_{DSS}}{V_{GSoff}^2}$$

Linear (Ohmic) regime

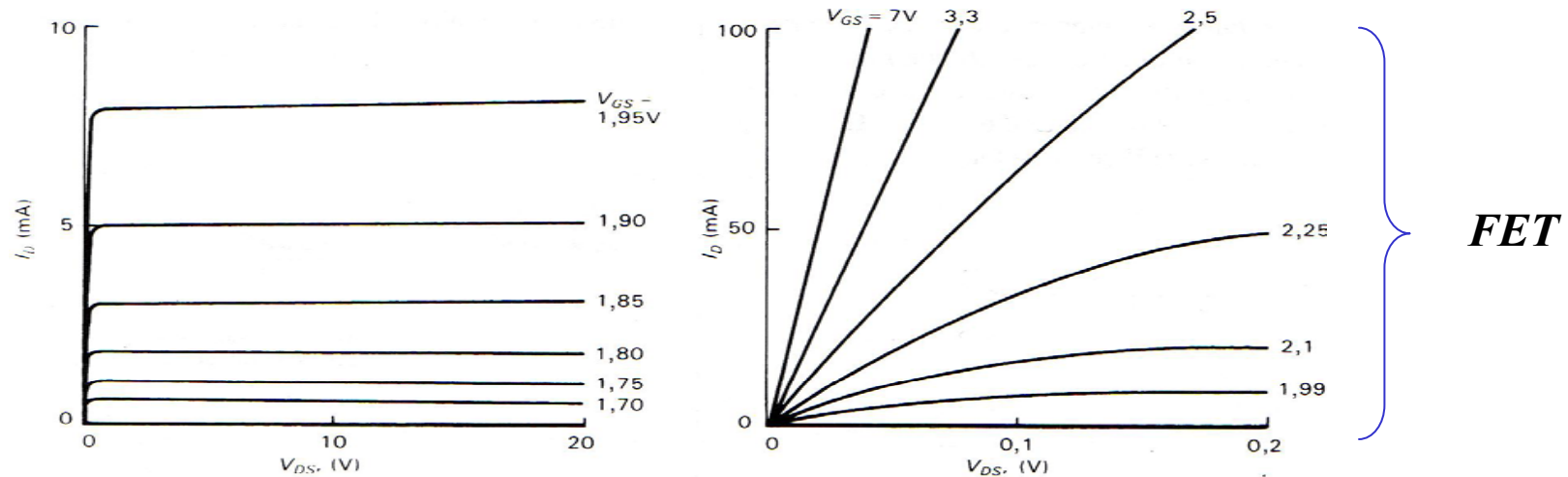
for $V_{DS} < V_{DSsat}$

$$I_D \cong 2k \left[(V_{GS} - V_{GSoff}) - \frac{V_{DS}}{2} \right] \cdot V_{DS}$$

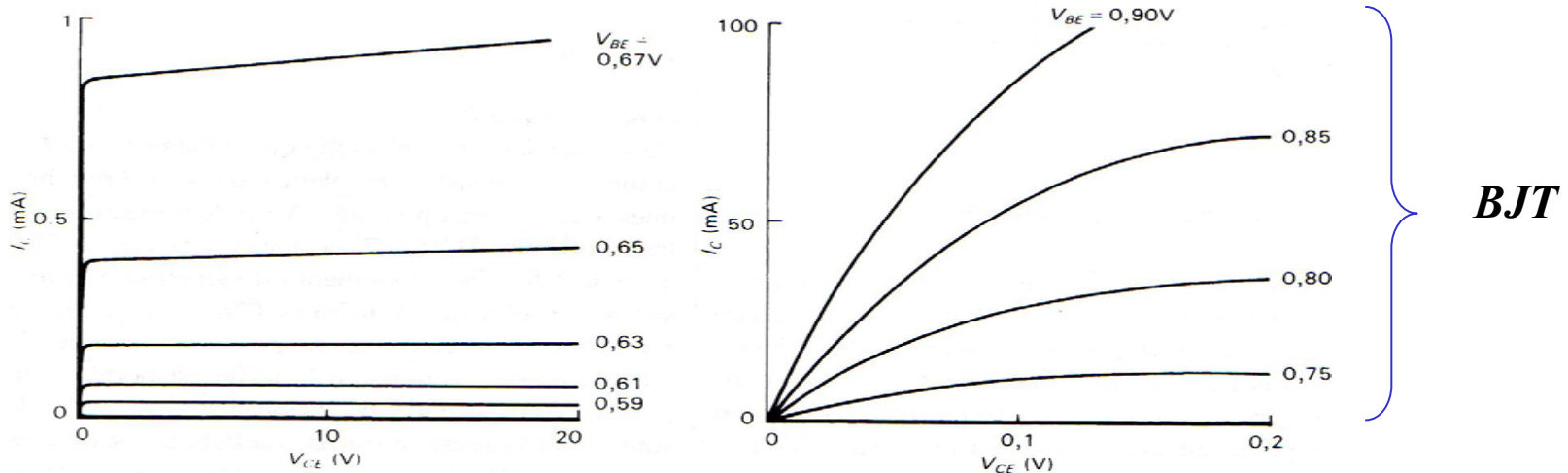
Differences between FET and BJT

- $I_G \ll I_B$
 - very high input impedance (sometime $> 10^{14}\Omega$)
 - Simpler circuits
- **linear regime**
 - slope = $f(V_{GS}) \Leftrightarrow$ variable resistance (nothing equivalent for BJT)
 - $V_{DSsat} > V_{CESat}$: higher residual voltage in saturated regime.
- **Saturation regime** (active mode)
 - I_D is controlled by a voltage
 - ↙ *transconductance* $g_m = \frac{dI_d}{dV_{gs}}$ (instead of β_F)
 - From manufacturing higher dispersion in g_m value compared to β_F
- **Different characteristics in active mode:**
 - BJT: with V_{CE} constant, $I_C = I_B$ or $I_C = \alpha I_E$
 - FET: with V_{DS} constant, $I_D = f(V_{GS}) = \text{nonlinear relationship}$
 - ↙ *depends on considered FET types....*

Differences between FET and BJT



A



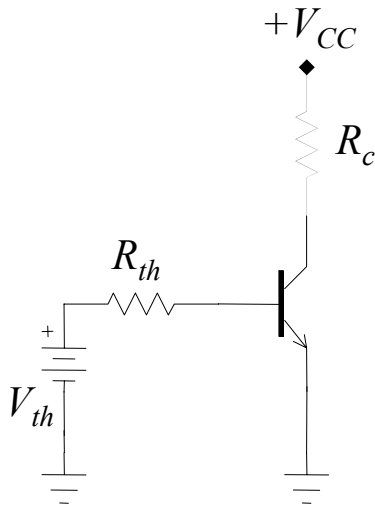
B

3-2

Load line to find operating point of a transistor

The operating point of a transistor is determined by **its characteristics** and by **Kirchhoff's law** applied to the considered circuit.

Example : ● How to find I_B , I_C , V_{BE} , V_{CE} ?

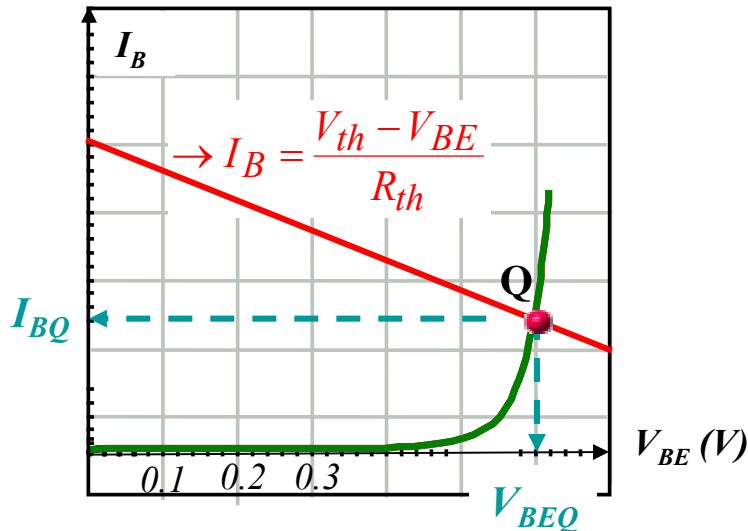


Load line

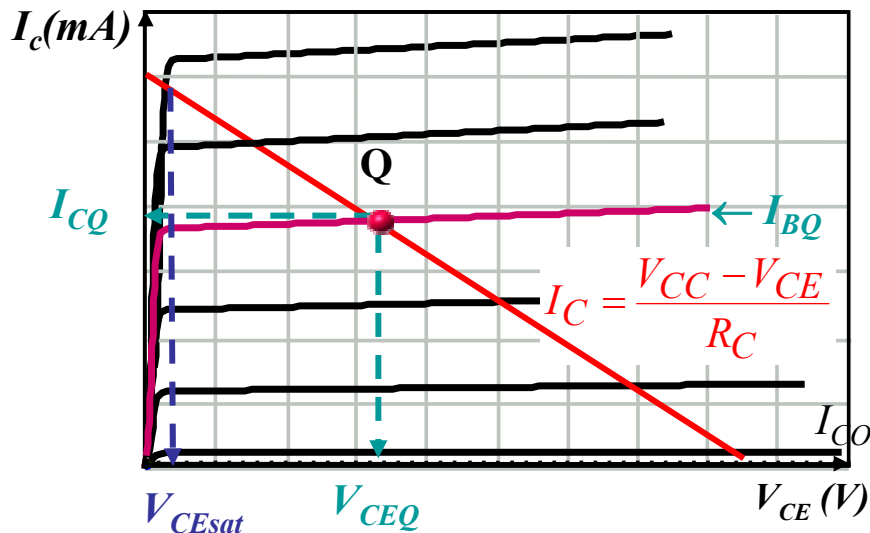
$$V_{th} = R_{th}I_B + V_{BE} \quad \rightarrow I_B = \frac{V_{th} - V_{BE}}{R_{th}}$$

$$V_{CC} = R_C I_C + V_{CE} \quad \rightarrow I_C = \frac{V_{CC} - V_{CE}}{R_C}$$

transistor



$V_{BEQ} \approx 0.6-0.7V$, dès que $V_{th} > 0.7V$
(transistor in active or saturated mode)



$$V_{CE_{sat}} \leq V_{CEQ} \leq V_{CC}$$

$$I_{CO} \leq I_c \leq \frac{V_{CC} - V_{CE_{sat}}}{R_C} \approx \frac{V_{CC}}{R_C}$$

Q is the operating point
of the transistor