Transistors

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

- **Field effect transistors**
  - Principle of operation
  - Characteristics
Introduction

- 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”
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

\[ I_{\text{OUT}} = A \cdot I_{\text{IN}} \]

- Current source controlled by a current
  \( A \) = current “gain”

\[ I_{\text{OUT}} = G \cdot V_{\text{IN}} \]

- Current source controlled by a voltage
  \( G \) = transconductance.

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Transistors

Transistor PNP

Transistor NPN

diode « EB »
diode « BC »

Coupling between diodes

diode « EB »
diode « BC »

two coupled PN junctions (or diodes) ⇔ « transistor effect »

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

(a) Electrons moved into the p-type semiconductor
(b) 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

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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 one 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 Based.
- No current flow $\Rightarrow$ base-collector diode junction is reversed biased.
Now relatively small voltage is across the emitter-based junction such to forward-biased the junction.

- Electron from emitter flow toward the based ➔ 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.

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Kirchoff’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

\[ \beta_F = \frac{\alpha_T}{1 - \alpha_T} \iff \alpha_T = \frac{\beta_F}{\beta_F + 1} \]

\( \alpha_T \) is the common base forward short circuit current gain
\( \beta_F \) is the forward common emitter current gain (20 to 50)
An ideal junction would have \( \alpha_T \approx 1 \), 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:
\[ V_{BE} \approx 0.7V \quad \sim 0.3V < V_{CE} < V_{CC} \quad I_c \approx \beta_I I_B \]

Cut off mode:
\[ I_B \approx 0 \quad V_{CE} \approx V_{CC} \quad I_C \approx 0 \]

Saturated mode:
\[ V_{BE} \approx 0.8V \quad V_{CE} \approx 0.2V \quad I_c \neq \beta_I I_B \]

\[ V_{CC} = \text{voltage source for } C \text{ and } E. \quad V_{CE} n< V_{cc}! \]
# Operating mode for a PNP transistor

<table>
<thead>
<tr>
<th>Mode</th>
<th>Condition</th>
<th>Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Active mode</strong></td>
<td>$V_{BE} \approx -0.7V$</td>
<td>$-0.3V &lt; V_{CE} &lt; V_{CC}$ $(&lt; 0)$</td>
</tr>
<tr>
<td></td>
<td>$I_c \approx \beta_I I_B$</td>
<td></td>
</tr>
<tr>
<td><strong>Cut off mode</strong></td>
<td>$I_B \approx 0$</td>
<td>$V_{CE} \approx V_{CC}$</td>
</tr>
<tr>
<td></td>
<td>$I_C \approx 0$</td>
<td></td>
</tr>
<tr>
<td><strong>Sat, mode</strong></td>
<td>$V_{BE} \approx -0.8V$</td>
<td>$V_{CE} \approx -0.2V$</td>
</tr>
<tr>
<td></td>
<td>$I_c \neq \beta_I I_B$</td>
<td></td>
</tr>
</tbody>
</table>

![Diagrams](https://via.placeholder.com/150)

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

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Characteristics of a bipolar junction

Parameters choices

The various operating currents and voltages \((I_E, I_B, V_{BE}, V_{CE}, \ldots)\) 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

\[ I_E(V_{BE}, V_{CB}) : \]

\[ V_{CB} = 0, -15 \]

\[ \sim \] characteristics for a PN junction

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

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

\[ I_C(V_{CB}, I_E) : \]

\[ I_C \approx I_E \]
Field Effect transistor (FET)

- Three terminals: S, D, and G, (sometimes 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 ($V_{GS}$) “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

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Field Effect transistor (FET)

**N-type channel**

**P-type channel**
Typical characteristics

\[ L_T(V_{DS}) \mid V_{GS} \]

\( (V_G - V_T) = 10 \text{ volts} \)

- **Linear region**
- **Saturation region**

**JFET operating characteristics (notional)**

- **Pinch-off**
- **ohmic**
- **breakdown**

\[ V_A = 100 \]

\[ V_{GS} = 0, -1, -2, -3, -4, -5 \]

\[ V_D \text{ (V)} \]

\[ I_D \text{ (2μA/μ)} \]

\[ V_D \text{ (V)} \]

\[ I_D \text{ (Drain Current)} \]

\[ V_A \text{ (Drain to Source Voltage)} \]

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Typical characteristics

Pinch-off regime for $V_{DS} > V_{DS_{sat}}$:

$$I_D \approx I_{DSS} \left(1 - \frac{V_{GS}}{V_{GS_{off}}}\right)^2 = k\left(V_{GS} - V_{GS_{off}}\right)^2$$

Linear (Ohmic) regime for $V_{DS} < V_{DS_{sat}}$:

$$I_D \approx 2k \left[\left(V_{GS} - V_{GS_{off}}\right) - \frac{V_{DS}}{2}\right] \cdot V_{DS}$$

$k = \frac{I_{DSS}}{V_{GS_{off}}^2}$
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)
  - $V_{DS_{sat}} > V_{CE_{sat}}$: 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 $\beta_F$)
  - From manufacturing higher dispersion in $g_m$ value compared to $\beta_F$

- **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
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

\[ V_{th} = R_{th} I_B + V_{BE} \rightarrow I_B = \frac{V_{th} - V_{BE}}{R_{th}} \]

\[ V_{CC} = R_C I_C + V_{CE} \rightarrow I_C = \frac{V_{CC} - V_{CE}}{R_C} \]
$V_{BEQ} \approx 0.6-0.7V$, 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.