IIT Bombay

Makerspace (MS101)

2023 (Autumn)

EE-Lecture-10

Introduction to Transistors
Using Bipolar Junction Transistor (BJT) and
Metal Oxide Field Effect Transistor (MOSFET) as Switch

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Transistors: Introduction

A transistor is a semiconductor device with three terminals, used in analog & digital applications. It can be modelled as a ‘two-port network’, with ‘input-dependent output variable’.

Commonly used transistors

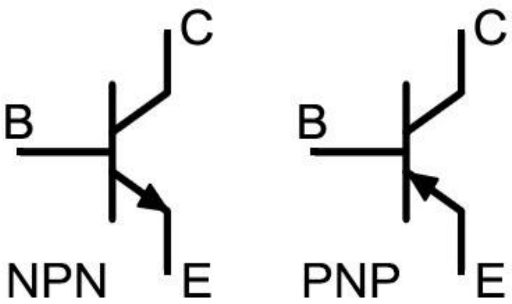
(a) Bipolar Junction Transistor (BJT)

(b) Metal Oxide Field Effect Transistor (MOSFET)

Circuit Symbol

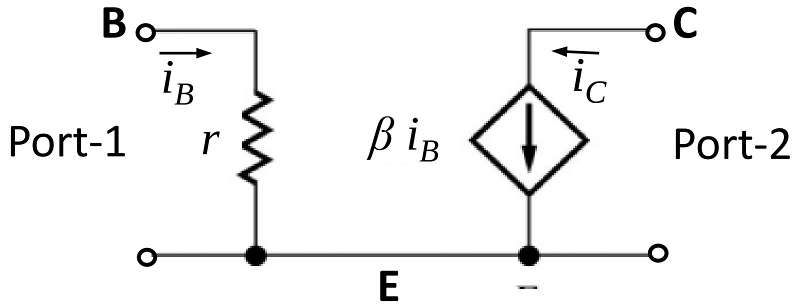
Simplified Small-Signal Model

Bipolar Junction Transistor

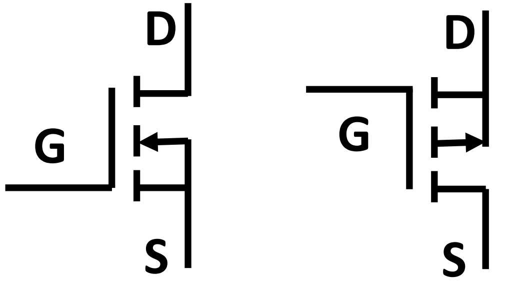


B: Base
C: Collector
E: Emitter

β: Current gain



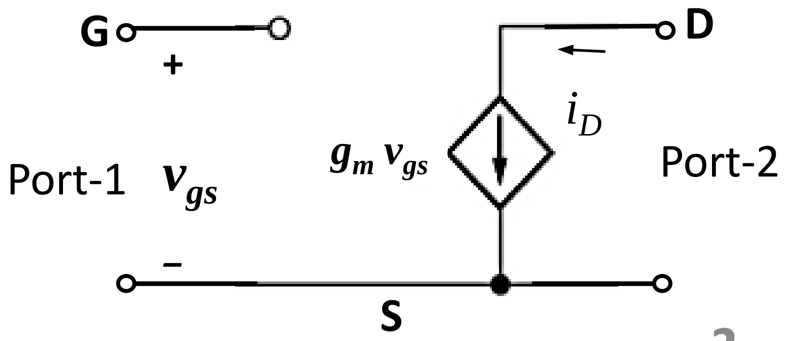
MOSFET (Enhancement mode)



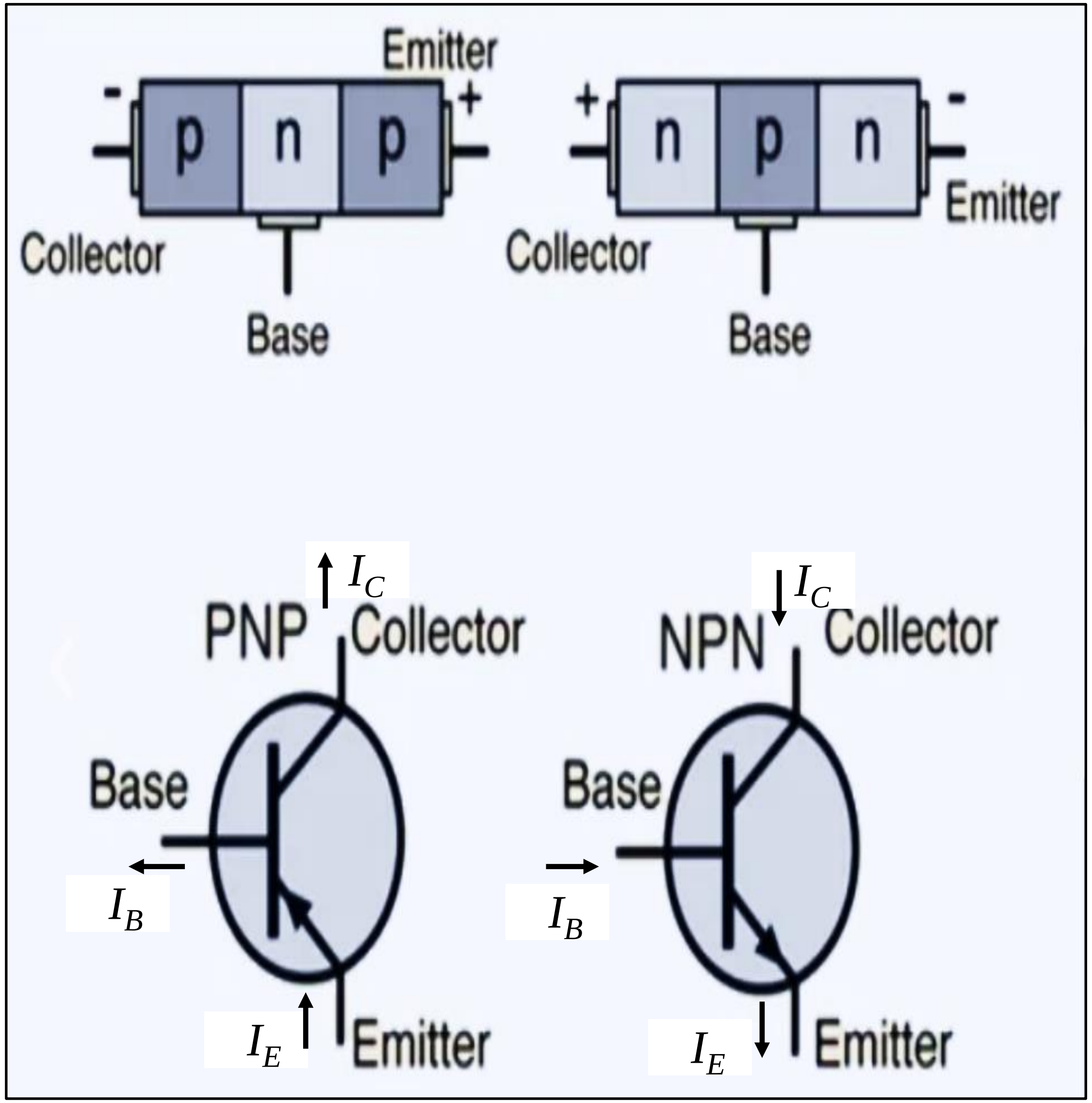
N-Channel **P-Channel**

G: Gate
D: Drain
S: Source

g_m: trans-conductance

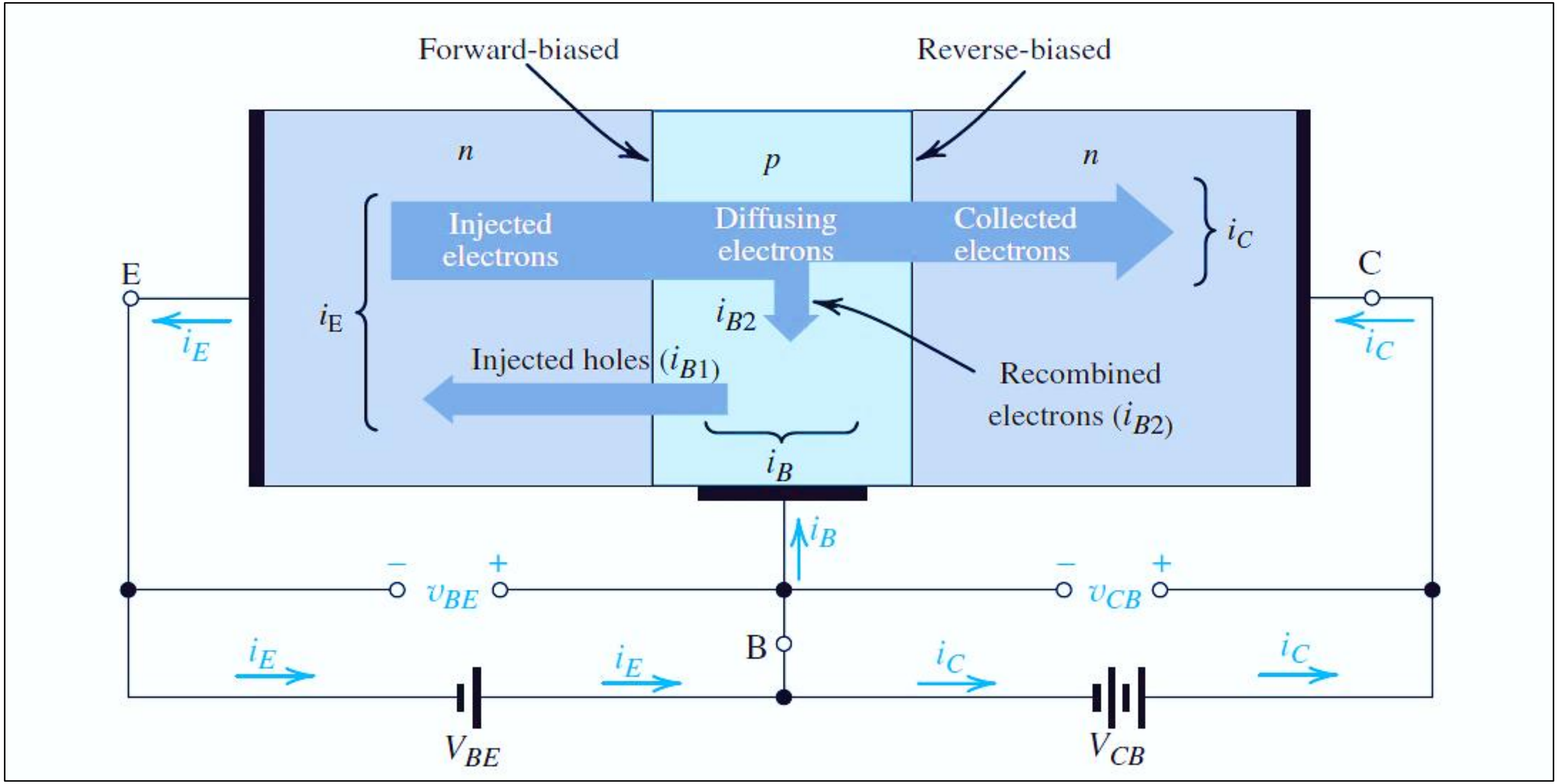


Bipolar Junction Transistor (BJT)



Types	NPN, PNP
Terminals	emitter (E), base (B), collector (C)
Controlling quantity	Current-controlled device: Base Current (I_B) controls Collector Current (I_C).
BJTs have lower input resistance (≈ 10 kΩ to 1 MΩ in common-emitter mode) and hence consume more power from the input signal source than MOSFETs.	

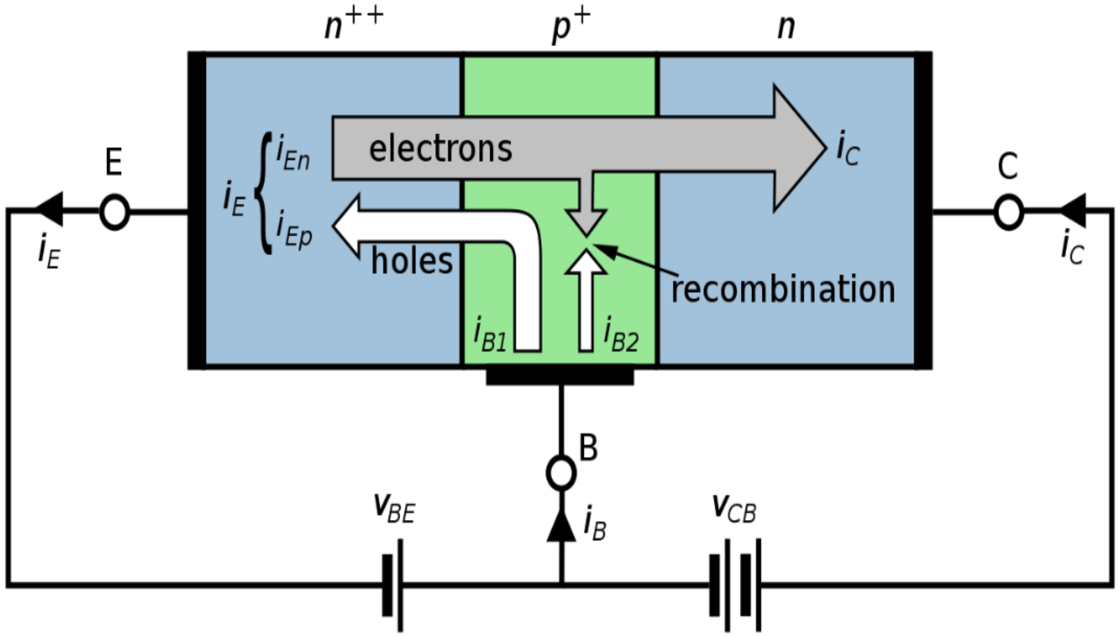
Bipolar Junction Transistor Operation



NPN transistor biased in active mode (BE junction: forward biased , BC junction: reversed biased)

Source: Fig 6.3:-Sedra A S, Smith K C, “Microelectronic Circuits”, Oxford University Press, 7Ed. **ISBN: 9780199339136**

BJT Operation



Cricket analogy

- The emitter is the bowler who shoots balls (electrons) toward the base.
- The base is the batsman, a tail-ender who swings away but connects with only 1-2% of the incoming balls (electrons).
- Most of the balls (electrons) are collected by the wicketkeeper.

Current relations

KCL: $I_E = I_B + I_C$

Transistor action

$\Delta I_C = \alpha\, \Delta I_E$ ($\alpha \approx 0.90 - 0.99$)

$\Delta I_C = \beta\, \Delta I_B$

$I_C = \beta\, I_B$ is used as an approximate relation.

Relation between α & β

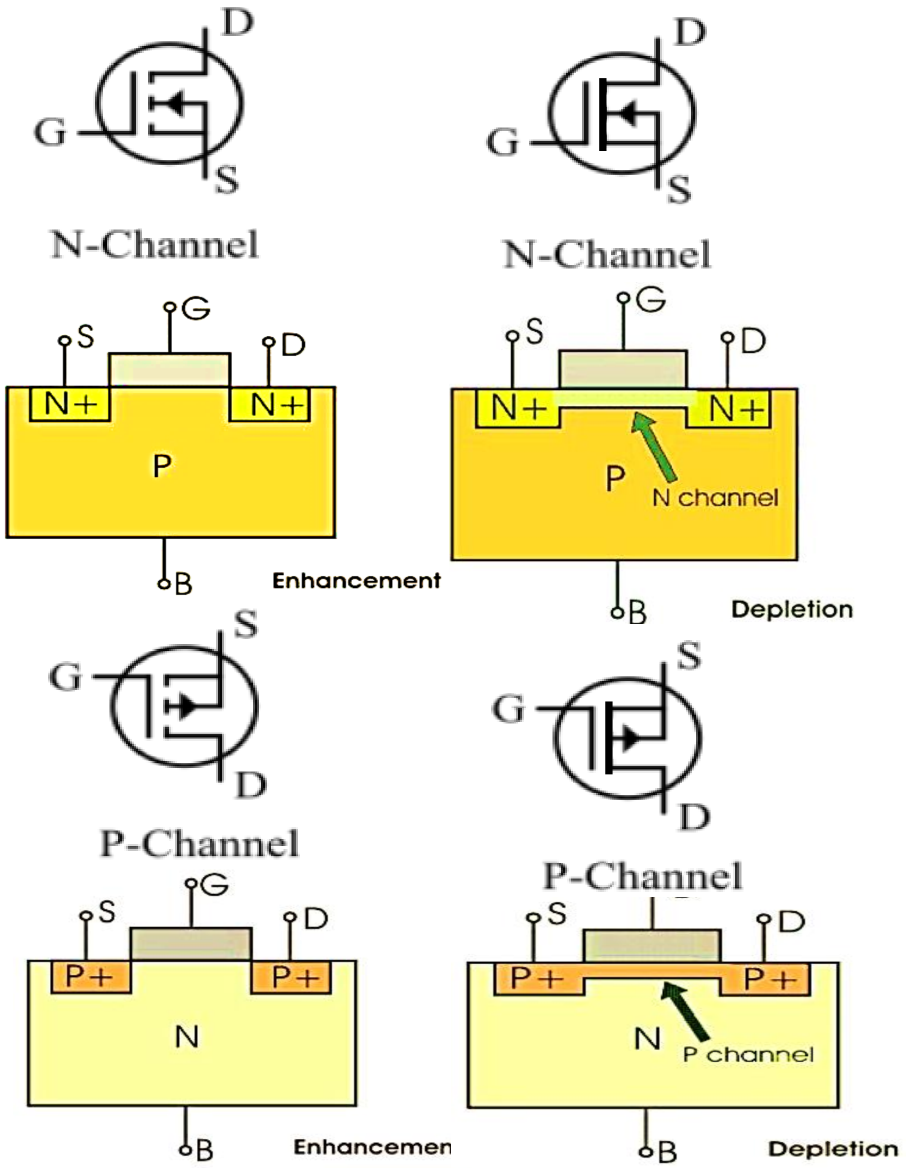
$\Delta I_E = \Delta I_B + \Delta I_C \;\Rightarrow\; \Delta I_B = \Delta I_E - \Delta I_C = (1/\alpha - 1)\, \Delta I_C$

$\Rightarrow\; \Delta I_C = \alpha/(1-\alpha)\, \Delta I_B = \beta\, \Delta I_B$

$\Rightarrow\; \beta = \alpha/(1-\alpha)$

Example: $\alpha = 0.98 \Rightarrow \beta = 0.98/0.02 = 49$

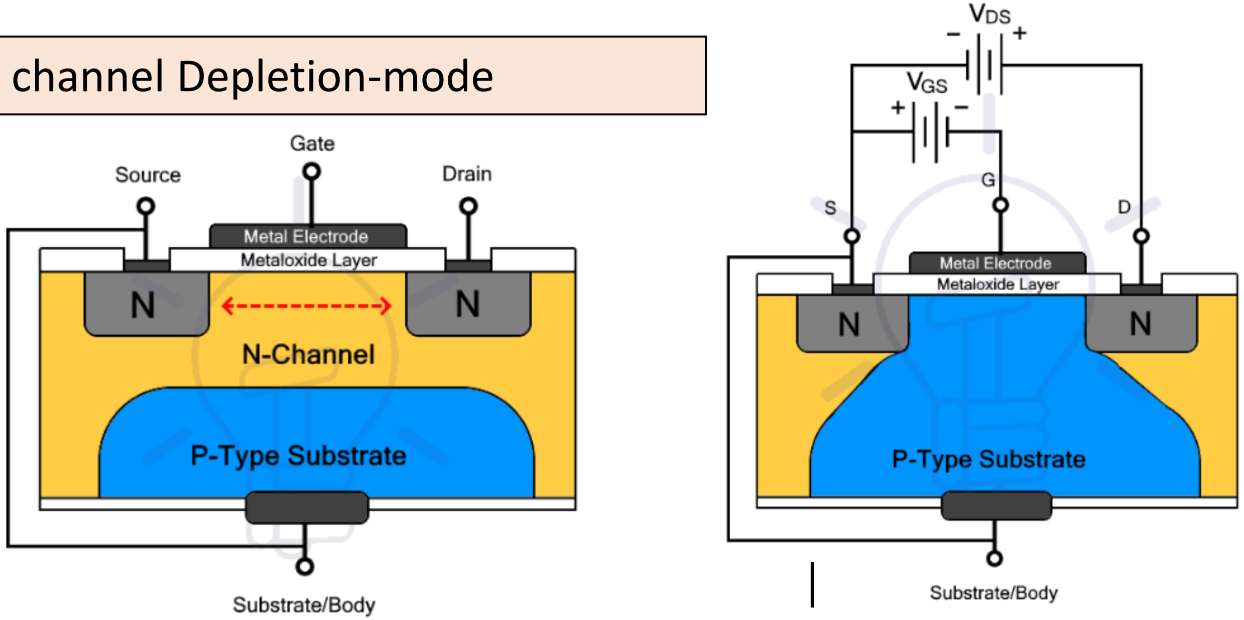
MOSFETs: Introduction



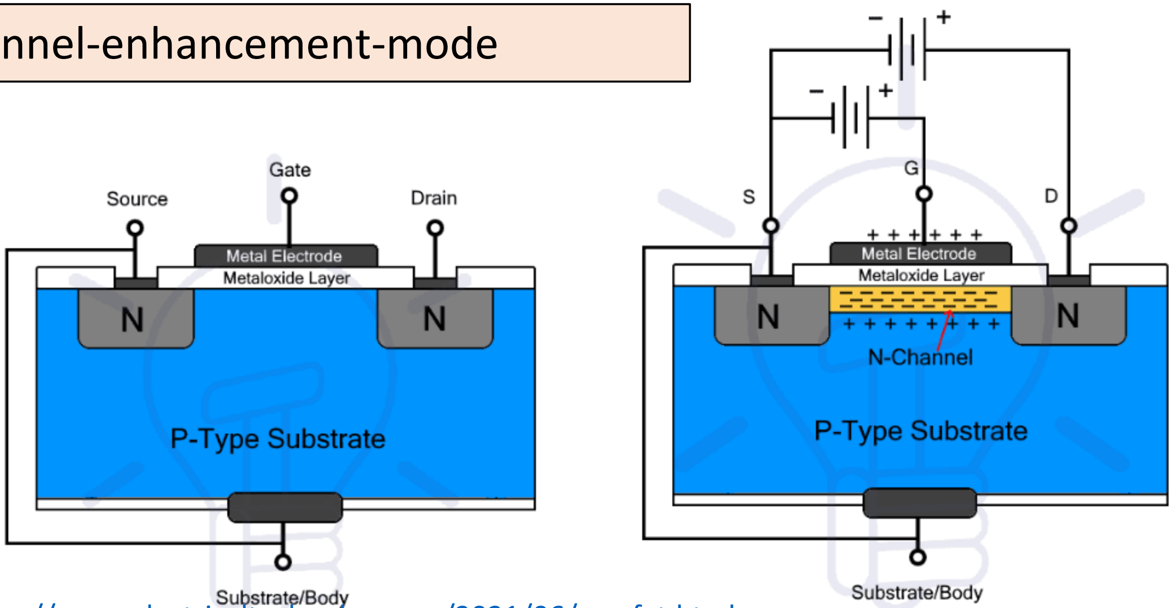
Types: N-channel & P-channel, fabricated in two modes (enhancement & depletion) as schematically shown in figures.	
Types	N-channel enhancement-mode P-channel enhancement-mode N-channel depletion-mode P-channel depletion-mode
Terminals	source (S), drain (D), gate (G), substrate or body or bulk (B, often connected to S.
Controlling quantity	Voltage-controlled device: Gate-Source voltage (V_{GS}) controls drain current (I_D)
MOSFETs have high input resistance (10 MΩ to 100 MΩ) and hence consume less power from the input signal source than BJTs.	

MOSFET Operation

N- channel Depletion-mode



N- Channel-enhancement-mode



Source: https://www.electricaltechnology.org/2021/06/mosfet.html

Device ON / OFF operation

ON: Low resistance for drain-source current flow.

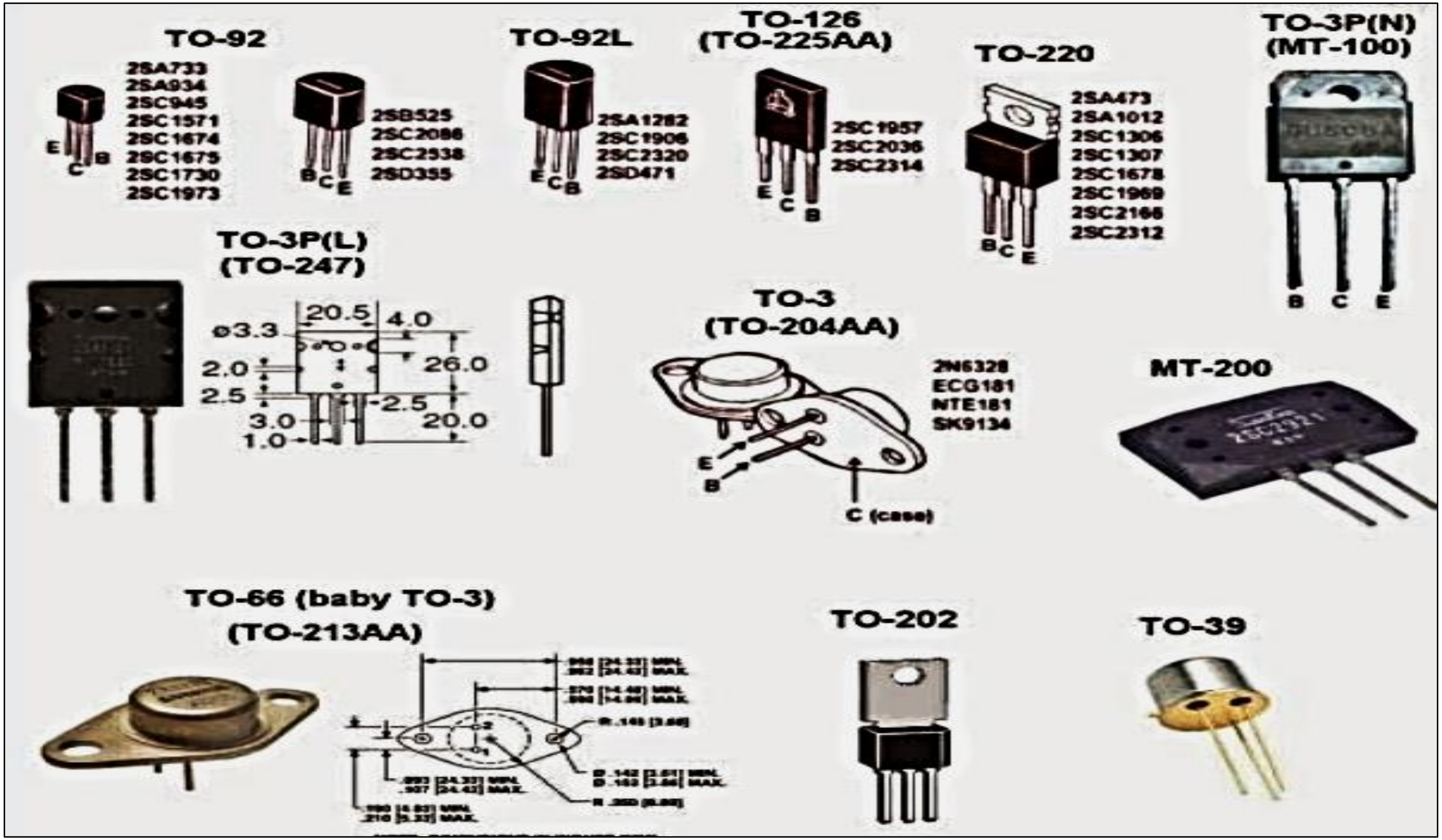
OFF: Very high resistance for drain-source current flow.

Depletion mode: Channel for drain-source current flow is available at V_{GS} = 0. It gets depleted for negative V_{GS}, and it is totally depleted for V_{GS} below the threshold voltage V_T (-ve for N-channel).

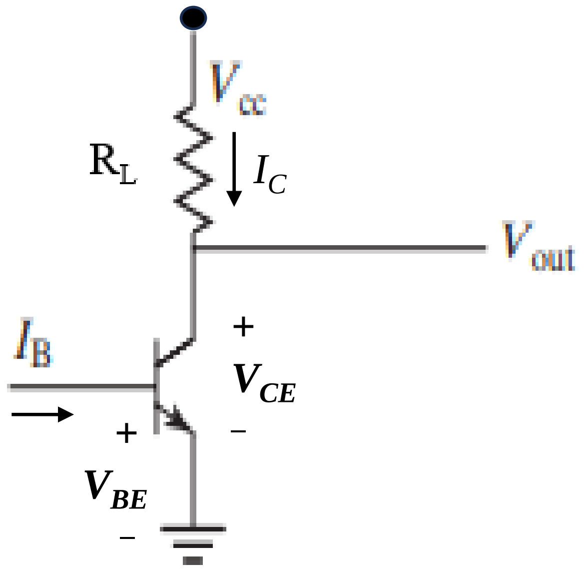
Enhancement mode: No channel is available at V_{GS} = 0. The channel is formed for V_{GS} above the threshold voltage V_T (+ve for N-channel).

MOSFET Type	Condition for Switching
N-channel Enhancement	OFF for $V_{GS} < V_T$ (0.6 to 1 V)
N-channel Depletion	OFF for $V_{GS} < V_T$ (—1.3 to 0.0 V)
P-channel Enhancement	OFF for $V_{GS} > V_T$ (—1.0 to 0.6 V)
P- channel Depletion	OFF for $V_{GS} > V_T$ (0.0 to 1.3 V)

Commercially Available Transistor Packages



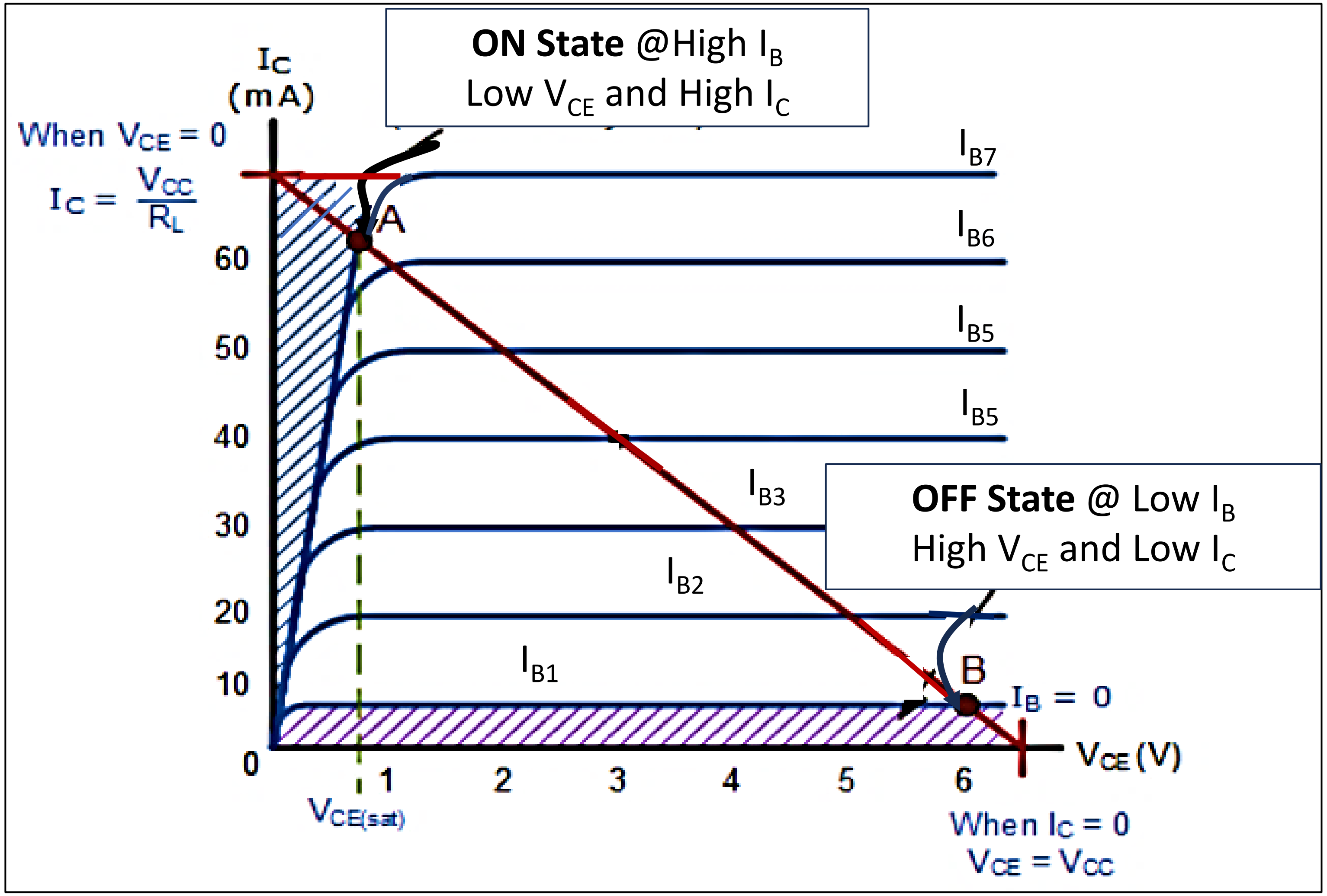
Switching Characteristics of BJT (on V_{CE}-I_C Plane)



BJT is switched ON / OFF by changing the base current I_B.

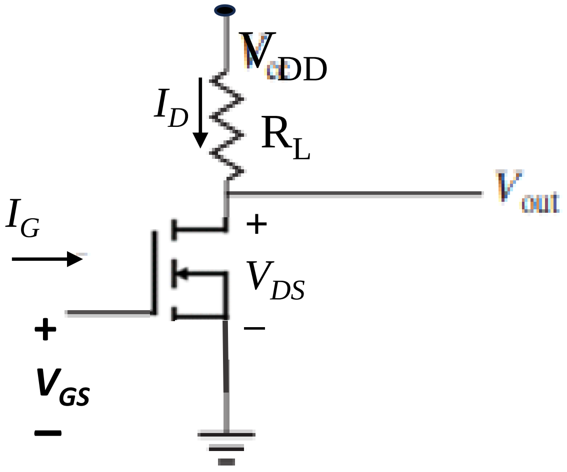
OFF: $V_{BE} < V_\gamma$. ($V_\gamma \approx 0.5$ V)
$I_B \approx 0$. $V_{CE} \approx V_{CC}$. $I_C \approx 0$.

ON: $I_B > I_C / \beta$.
$V_{BE} = V_{BES}$. $V_{CE} = V_{CES}$.
$I_C = (V_{CC} - V_{CES}) / R_L$
($V_{BES} \approx 0.8$ V. $V_{CES} \approx 0.2$ V)



Typical 'V_{CE} - I_C' characteristics for BJT (base currents: $I_{B1} < I_{B2} < I_{B3} < I_{B4} < I_{B5} < I_{B6} < I_{B7}$) . Operating points for switching action: A (on) & B (off).

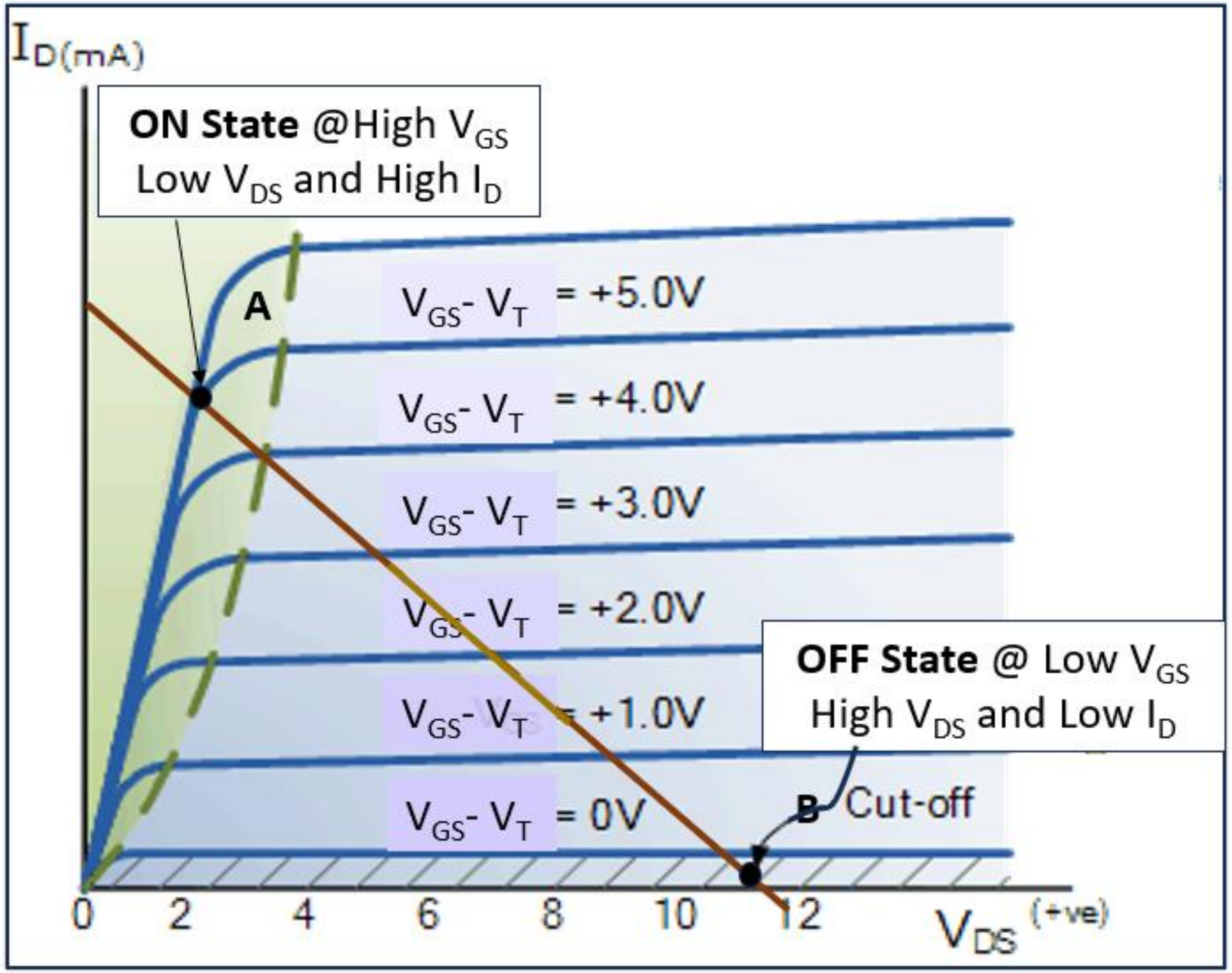
Switching Characteristics of N-Channel Enhancement-Mode MOSFET (on V_{DS}-I_D Plane)



- Enhancement MOSFET starts conducting when the drain-source channel is formed.
- N-Channel MOSFET: N-channel is formed.
- V_T is the minimum value of V_{GS} for the channel formation. $V_{GS} > V_T$ for MOSFET to be ON. Channel resistance decreases as V_{GS} increases further.

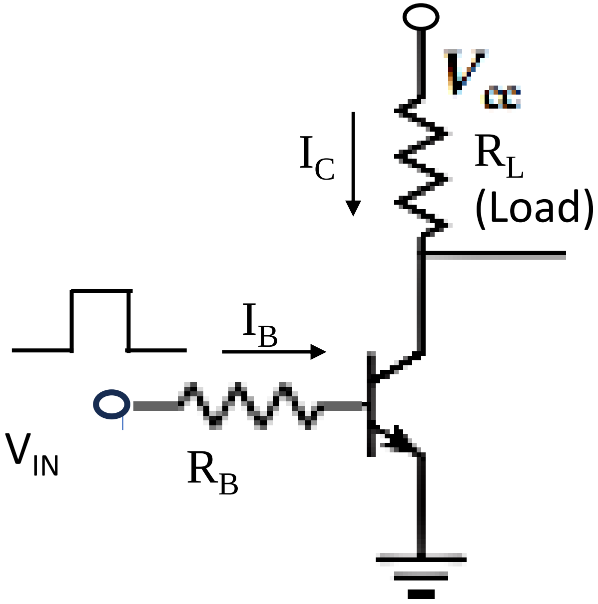
OFF: $V_{GS} < V_T$. $I_G \approx 0$. $I_D \approx 0$. $V_{DS} \approx V_{DD}$

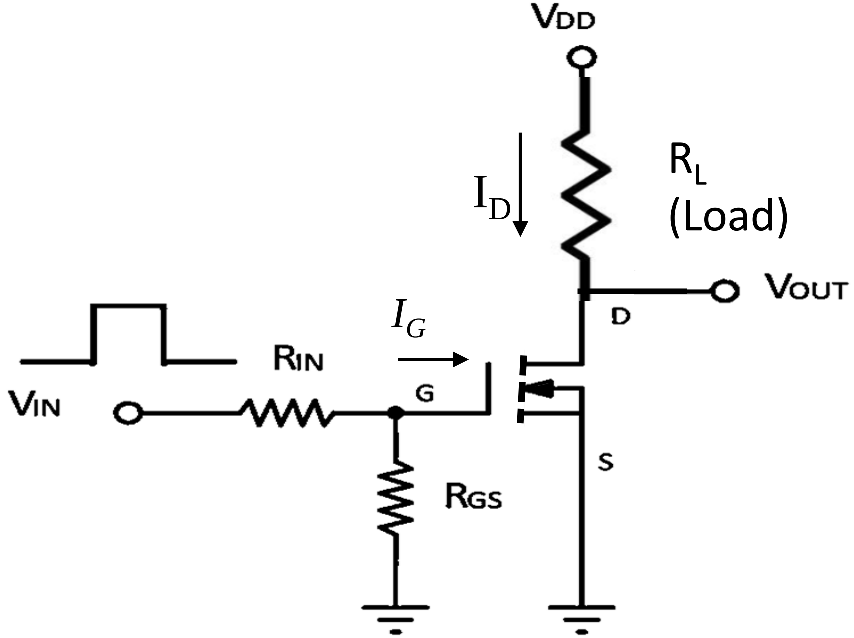
ON: $V_{GS} > V_T$ + a few V.
$I_G \approx 0$. $V_{DS} \approx 0$. $I_D \approx V_{DD} / R_L$.



Typical 'V_{DS}-I_D' characteristics for N channel Enhancement mode MOSFET
A & B: operating points for switching action

BJT & MOSFET Switching with Vin as Control Input





Switch circuit using NPN BJT & control input V_{in}.

R_B is for limiting I_B.

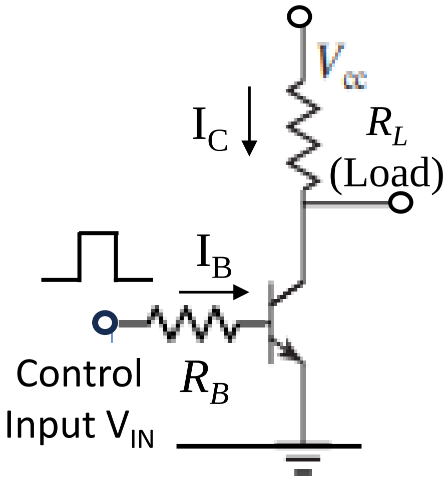
OFF: $I_B \approx 0$.
ON: $I_B > I_C/\beta$.

Switch circuit using N-Channel MOSFET & control input V_{in}.

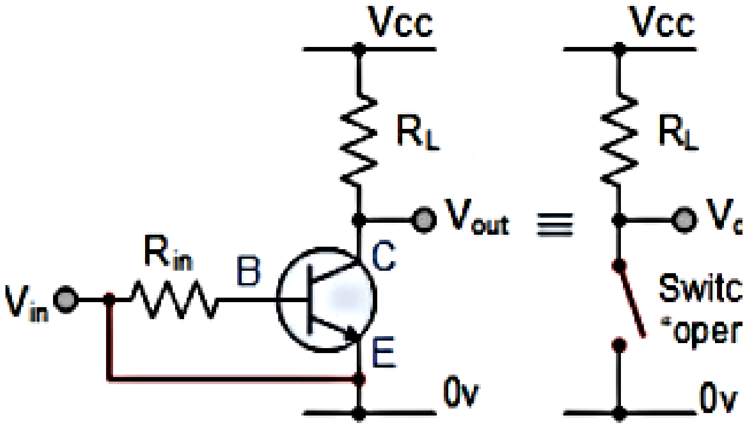
R_{in} and R_{GS} are for voltage attenuation, if V_{in}-peak is large.

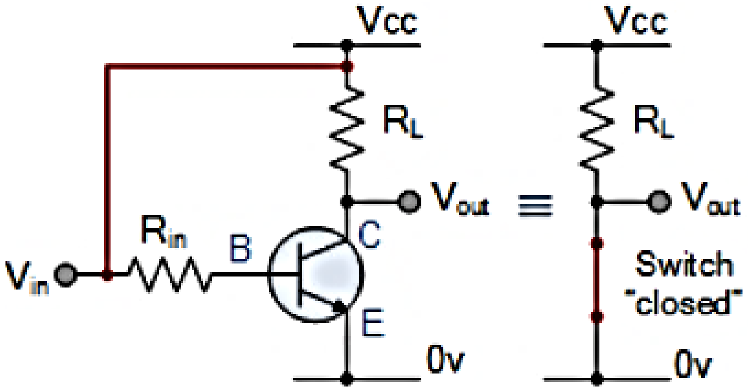
OFF: $V_{GS} < V_T$.
ON: $V_{GS} > V_T$ + a few V.

BJT Switching Operation



BJT (NPN) circuit with control input Vin (binary levels: 0, V_{CC}).





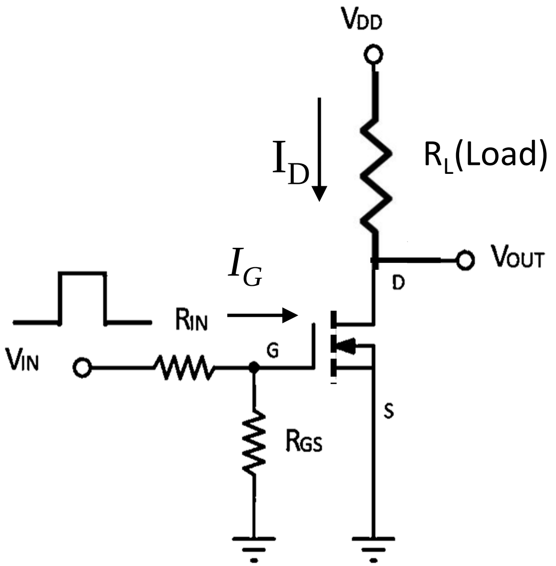
(a) $V_{in} = 0$

- $V_{BE} = 0 < 0.5$ V .
- BJT operates as open switch.
  $I_B \approx 0$. $V_{CE} \approx V_{CC}$. $I_C \approx 0$.
- BE junction is not forward biased. BC junction is reverse biased.

(b) $V_{in} = V_{CC}$

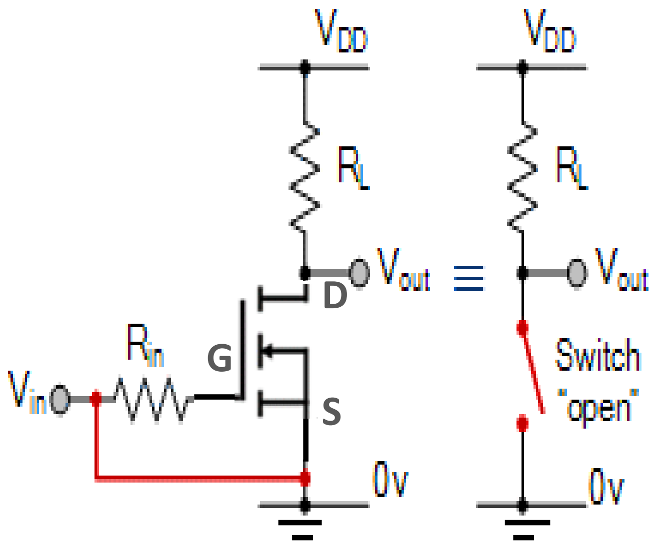
- BE junction is forward biased, with I_B limited by R_B , with V_{BE} reaching its saturation value V_{BES} (≈ 0.8 V). Collector voltage drops until BC junction gets forward biased with V_{BE} reaching its saturation value V_{CES} (≈ 0.2 V).
- BJT operates as closed switch.
- $V_{BE} = 0.8$ V. $V_{out} = V_{CES} = 0.2$ V .
  $I_B = (V_{CC} - 0.8) / R_B$.
  $I_C = (V_{CC} - V_{CES}) / R_L$.

MOSFET Switching Operation



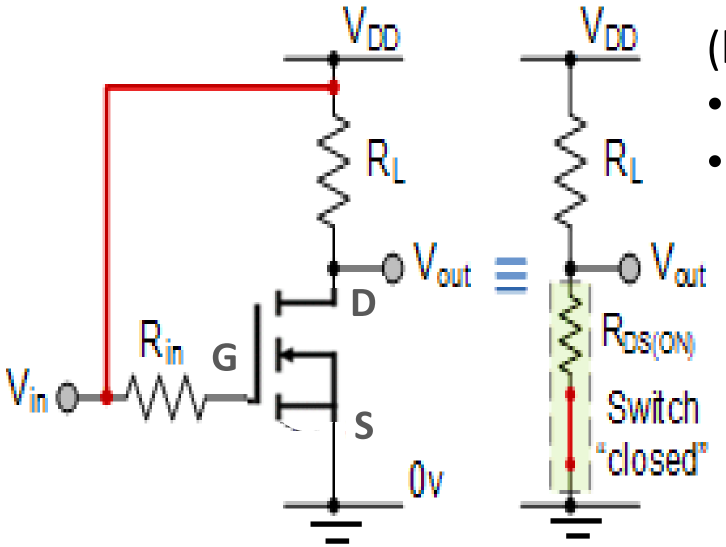
MOSFET (N-channel) circuit with control input V_{in} (binary levels: 0, V_{DD}).
Usually R_{in} is short and R_{GS} is open

Let V_{DD} = 12 V, V_T = 2 V, R_{IN} = 0, R_{GS} = ∞.



(a) $V_{in} = 0$

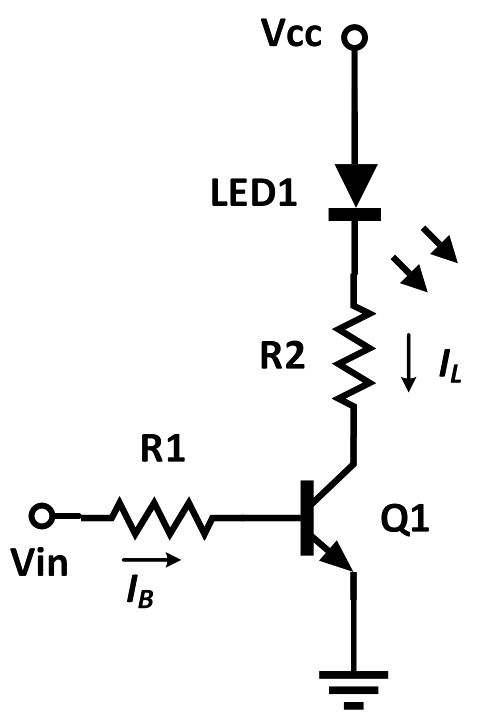
- $V_{GS} = 0 < V_T$.
- MOSFET operates as open switch.
  $I_G \approx 0$. $V_{DS} \approx V_{DD}$. $I_D \approx 0$.



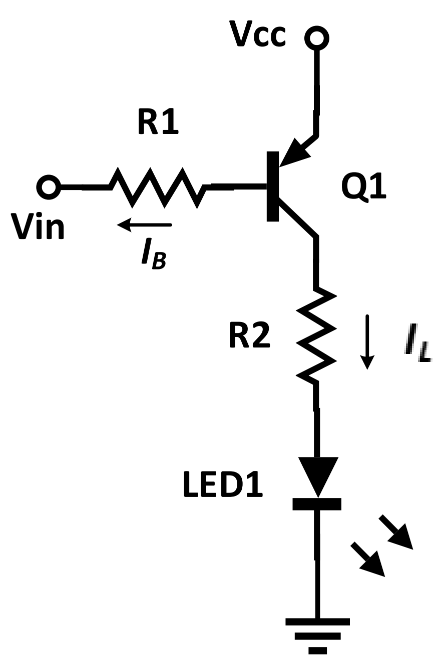
(b) $V_{in} = V_{DD}$

- V_{GS} = 12 V $> V_T$.
- MOSFET operates as closed switch.
  $I_G \approx 0$. $V_{DS} \approx 0$. $I_D = V_{DD}/R_L$.

NPN
Switch for
Load
Connected
to +ve
Supply End



PNP
Switch for
Load
Connected
to –ve
Supply
End



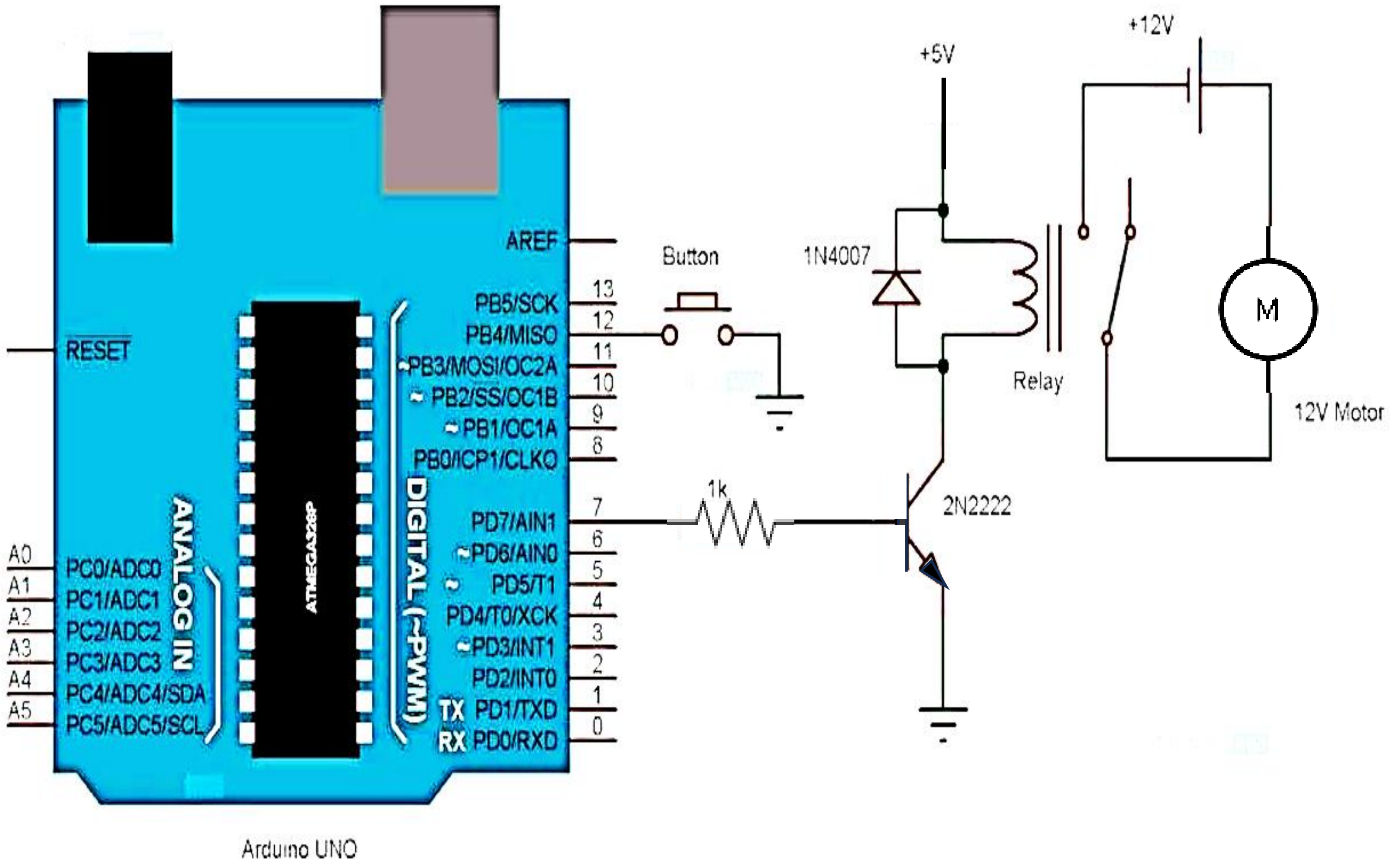
$V_{cc} = 5$ V. V_{in}: 0 (LED off), 5 V (LED on). $\beta > 50$.
I_L for full brightness = 10 mA. LED drop = 2 V.

$I_L = [V_{CC} - V_{LED} - V_{CES}]/R_2 = [5 - 2 - 0.2]/R_2 > 10$ mA
$\Rightarrow R_2 < 2.8/10$ k$\Omega = 280\ \Omega$.
Let $R_2 = 270\ \Omega. \Rightarrow I_L = 10.3$ mA.
$I_B = [(V_{in})_{\text{high}} - V_{BES} - 0]/R_1 > I_L/\beta_{\min}$
$\Rightarrow (5 - 0.8 - 0)/R_1 > 10.3/50 \Rightarrow R_1 < 20.38$ kΩ.
Let $R_1 = 18$ kΩ.

$V_{cc} = 5$ V. V_{in} : 0 (LED on), 5 V (LED off). $\beta > 50$.
I_L for full brightness = 10 mA. LED drop = 2 V.

$I_L = [V_{CC} - V_{ECS} - V_{LED}]/R_2 = [5 - 0.2 - 2]/R_2 > 10$ mA
$\Rightarrow R_2 < 2.8/10$ k$\Omega = 280\ \Omega$.
Let $R_2 = 270\ \Omega, \Rightarrow I_L = 10.3$ mA.
$I_B = [V_{CC} - V_{EBS} - (V_{in})_{\text{low}}]/R_1 > I_L/\beta_{\min}$
$\Rightarrow (5 - 0.8 - 0)/R_1 > 10.3/50 \Rightarrow R_1 < 20.38$ kΩ.
Let $R_1 = 18$ kΩ.

Relay Switching Using Micro-Controller (Arduino)



Arduino Relay Control Circuit Diagram

Source: https://www.electronicshub.org/arduino-relay-control/

Example

Control of a relay with 'Arduino' digital output pin (PD7) and NPN transistor (2N2222).

Relay coil current = 60 mA.
Transistor β_{min} = 30.

Set the pin PD7 to 'Hi'. It will put the transistor in ON state, allowing current to flow through the relay coil making the relay ON.
I_B > Relay current / β_{min} = 2 mA.

Diode connected in parallel with the relay avoids sudden change of current in the relay coil.

Questions and Discussions