

# **Analogue Circuit Fundamentals**

## Transistor

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# Wire (Revision)

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- Voltage same at both ends
- All the current that comes in one end goes out the other

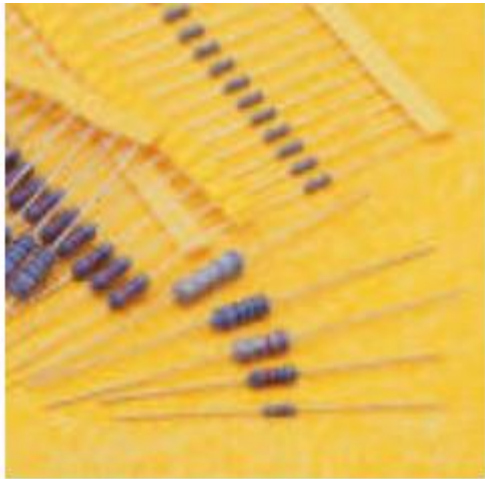


# Resistors (Revision)

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- Voltage linearly proportional to current

$$v_r(t) = i_r(t) \cdot r$$



# Capacitors (Revision)

- Voltage proportional to charge
- Current is rate of change of charge  $dq/dt$ , so **current is proportional to the rate of change in the voltage.**
- Or, **voltage is integral of current.**

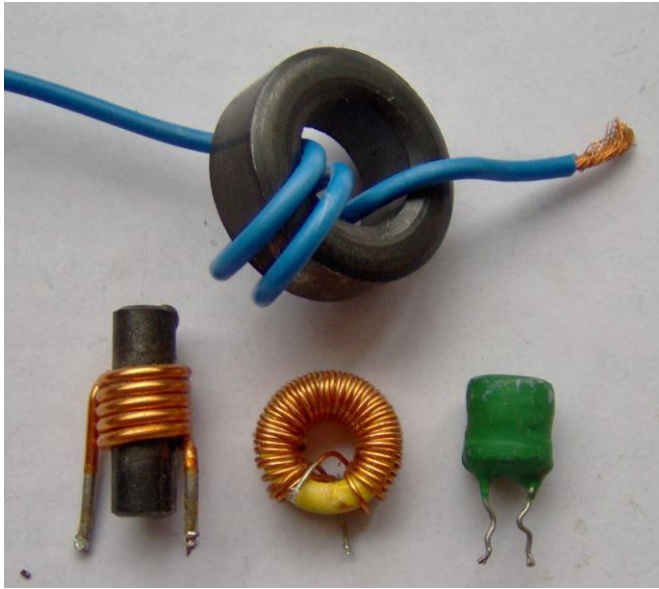


$$i_c(t) = C \frac{dv_c(t)}{dt}$$

# Inductors (Revision)

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- Voltage proportional to rate of change of current with time

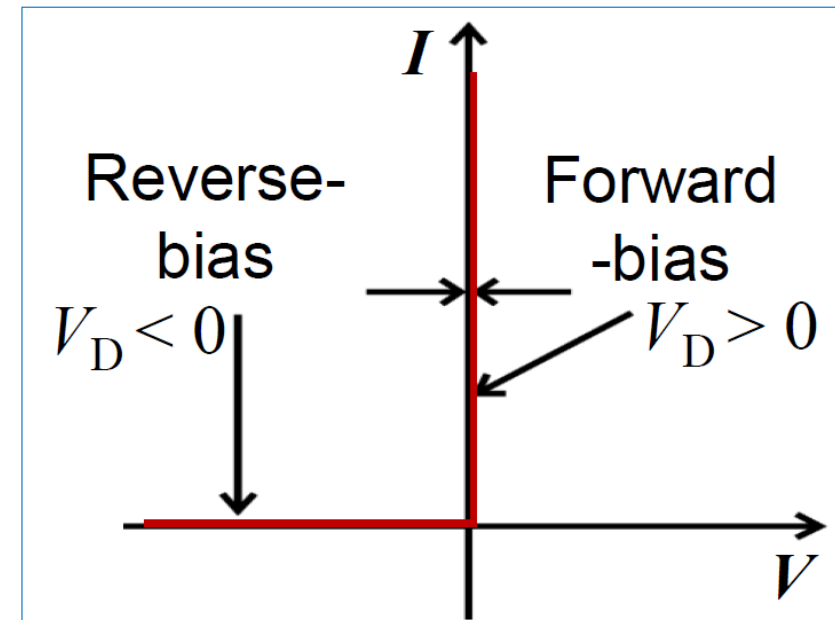
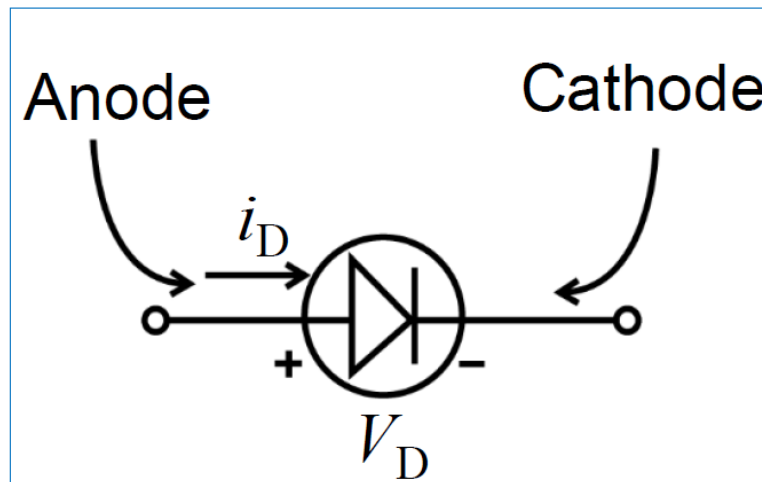


$$v_L(t) = L \frac{di_L(t)}{dt}$$

# Diode (Revision)

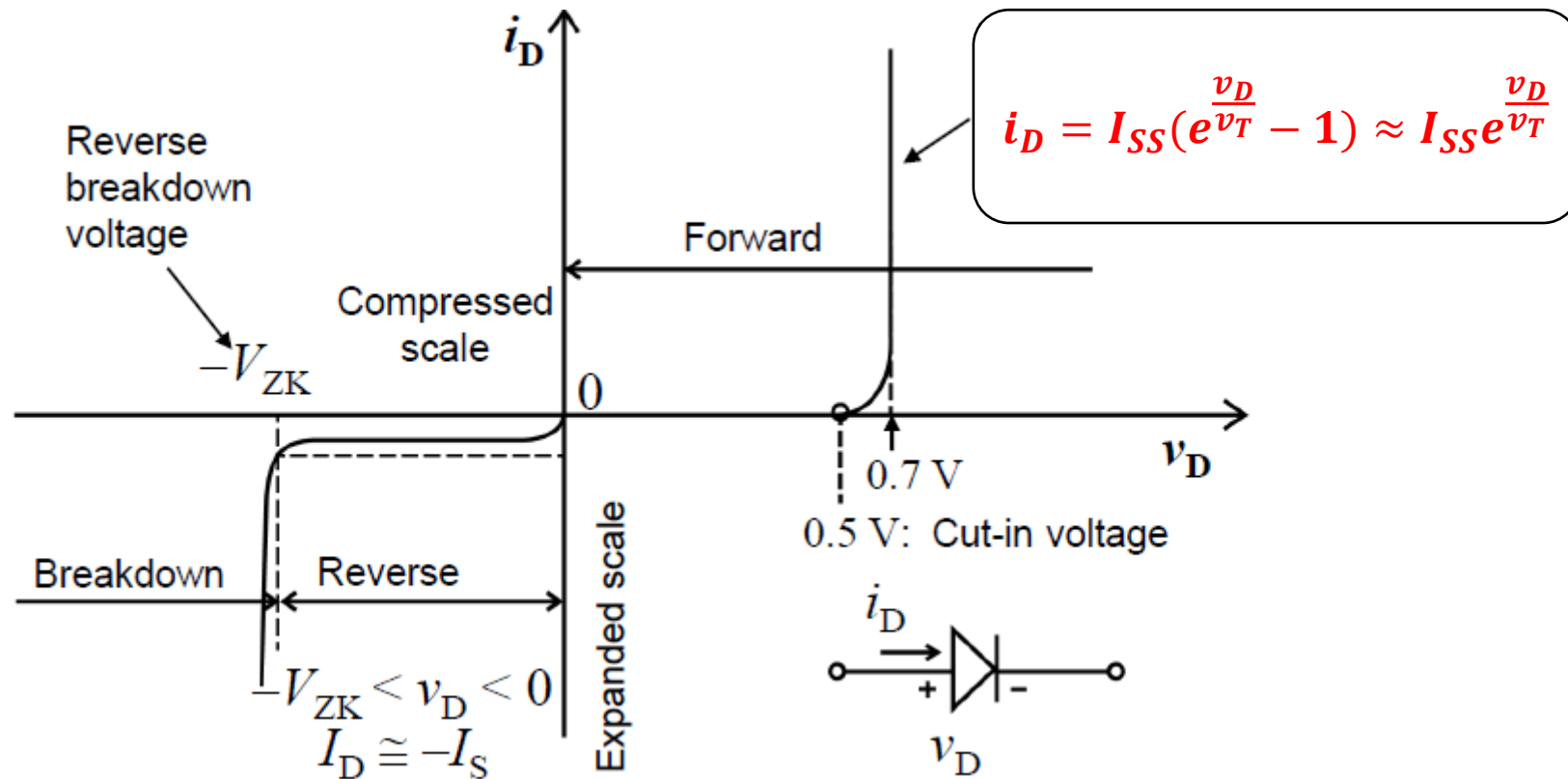
- A two-terminal device.

Forward-bias:  $V_D = 0 \Rightarrow$  Diode behaves like a short circuit.



# Diode (Revision)

- Non-ideal case

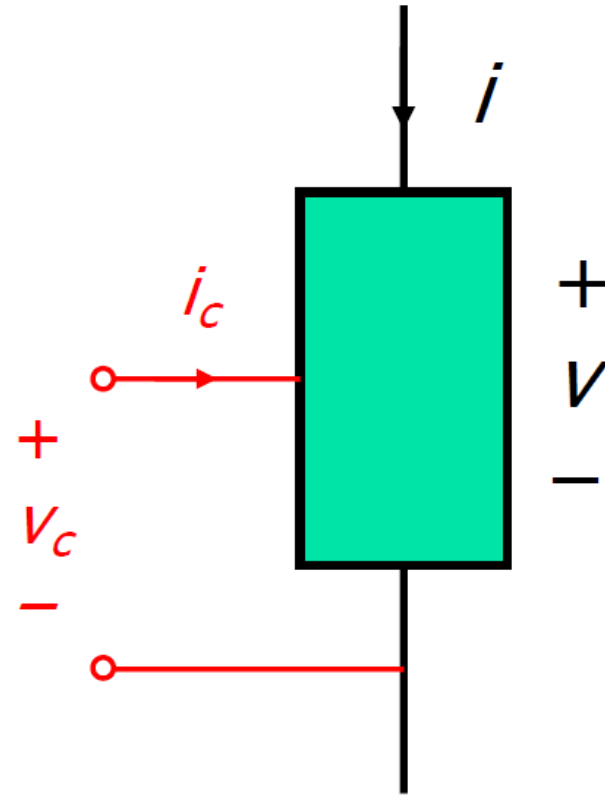


# What is a transistor?

Three-terminal device

whose voltage-current  
relationship is controlled by a  
third voltage or current

Transistor is a voltage/current  
controlled current source



# Types of transistors

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- According to the physics of the device, we can classify transistors into two main classes:

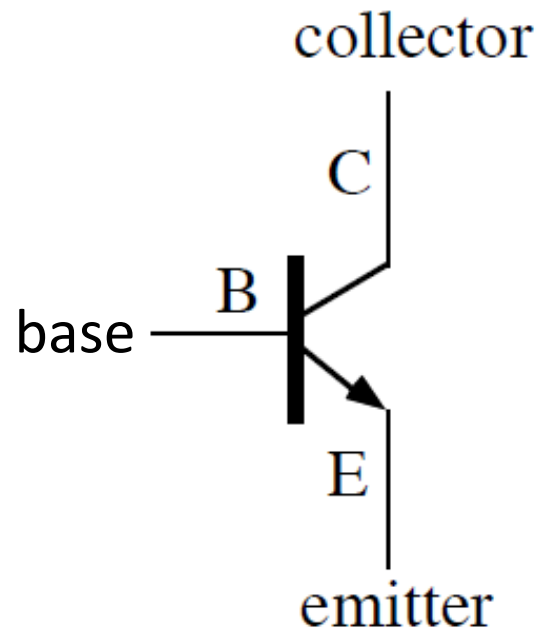
## Bipolar junction transistors (BJT)

Diode-based device which is usually blocked unless the control terminals are forward-biased. So, the control is a current, and BJT is a current amplifier by nature.

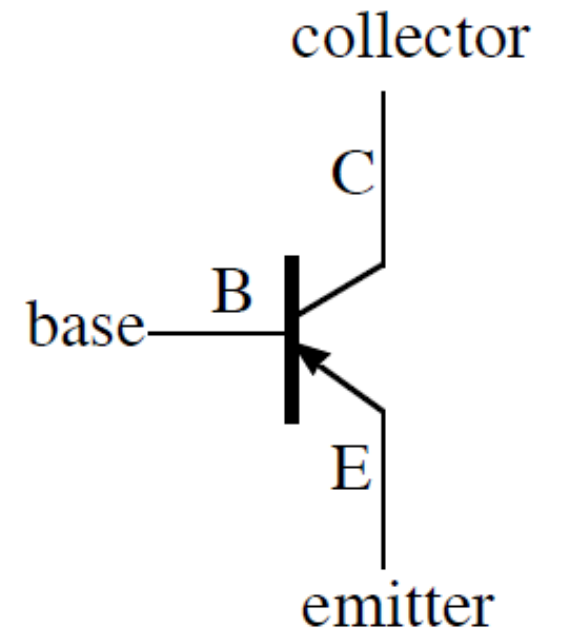
## Field effect transistors (FET)

Conduction is controlled by electric field which is produced by voltage applied to the control terminals. So, the control draws no current and FET is a voltage-controlled device.

# Bipolar junction transistor (BJT)



## NPN Transistor

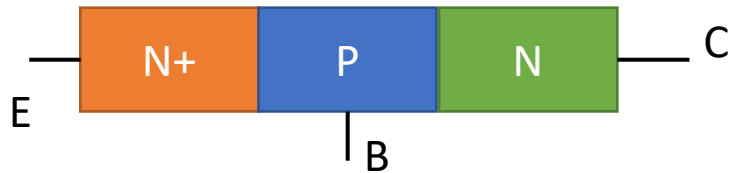


## PNP Transistor

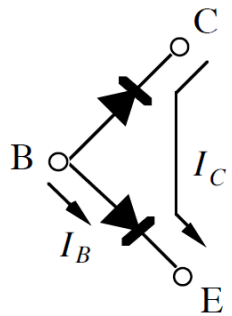
### Schematic Symbol

# Bipolar junction transistor (BJT)

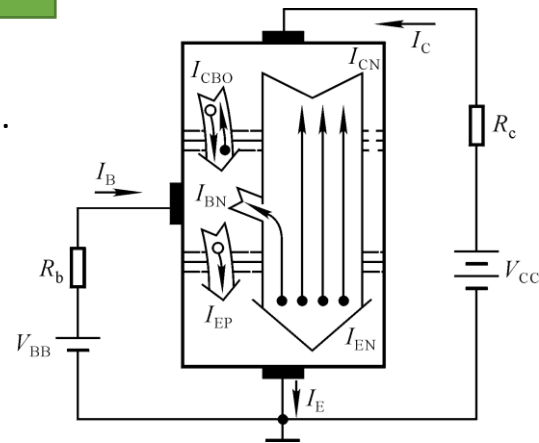
Considering NPN transistor:



\* The base region is very thin.



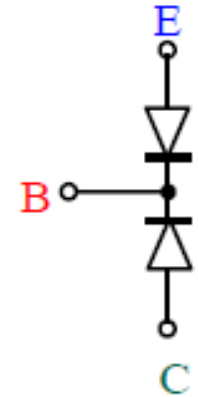
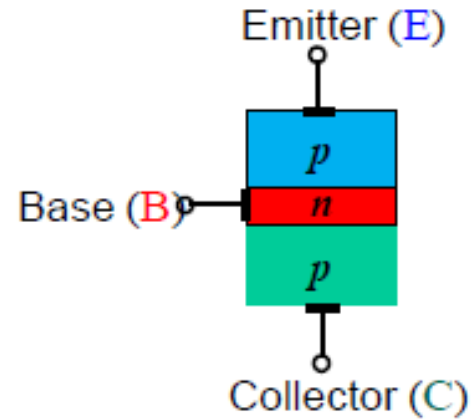
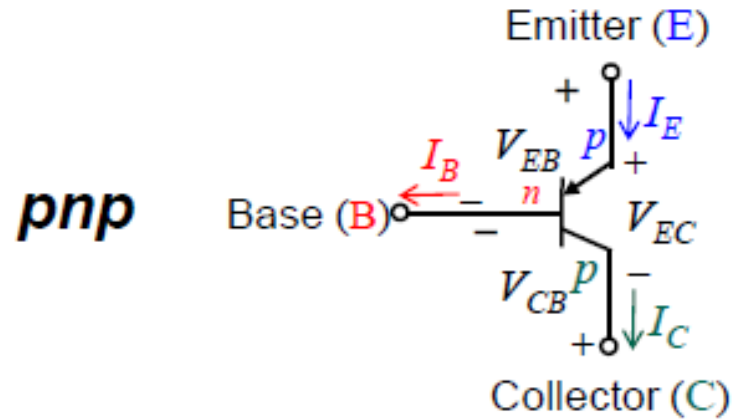
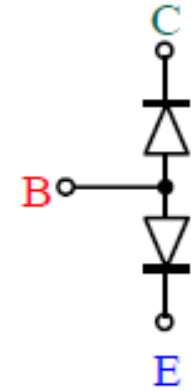
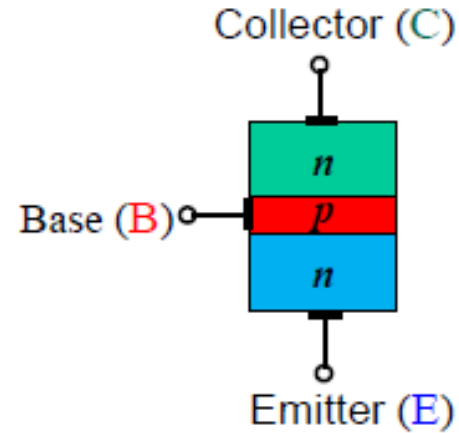
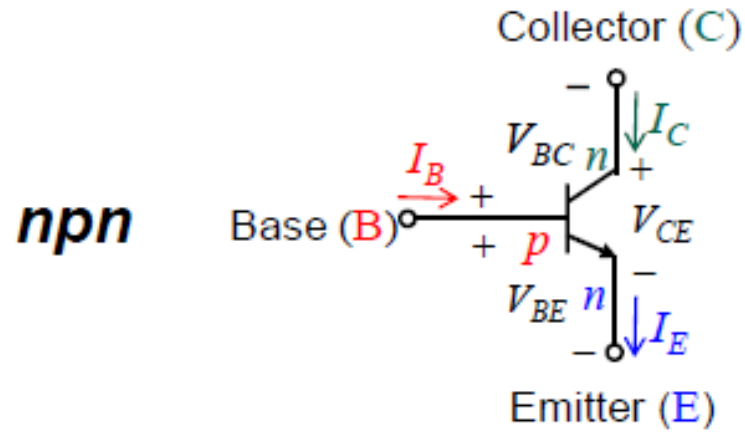
Simplified model



Idealized structure

- The collector-base junction is reverse-biased. So, no current can flow down.
- If the base-emitter junction is forward biased ( $\approx 0.6/0.7V$ ), then the diode “contact potential barrier” can be overcome. Electrons can go to base — called base injection.
- These electrons are minority carriers, which are strongly attracted/captured by the collector. Hence, current flows down from collector to emitter.
- **THUS, we use a small base current to induce a large collector current.**

# NPN and PNP BJT



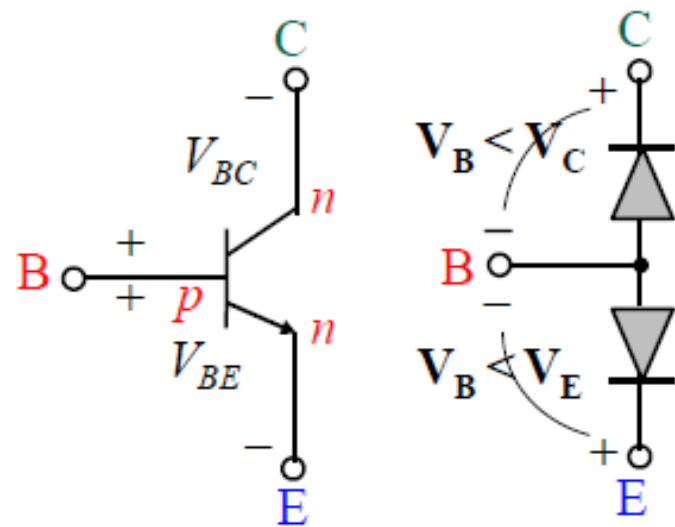
# Summary: Region of Operation of BJT

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|                  | BEJ forward bias         | BEJ reverse bias                            |
|------------------|--------------------------|---------------------------------------------|
| BCJ forward bias | Saturation<br>ON switch  | Reverse Active<br>Not used (weak amplifier) |
| BCJ reverse bias | Active<br>Good amplifier | Cut-off<br>OFF switch                       |

Current conservation equation:  $I_E = I_B + I_C$

# Operation Regions of BJT

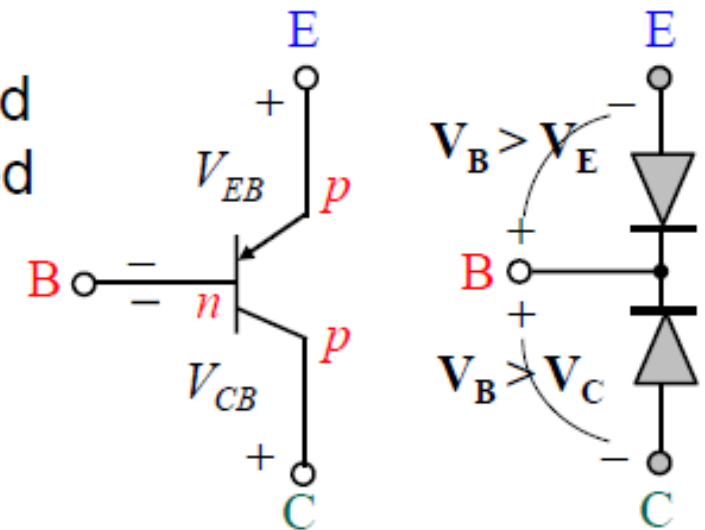


## Cutoff region

BEJ (npn) reverse biased  
BCJ (npn) reverse biased

$$I_C = 0$$

$\Rightarrow$  **Open Switch**



**Note:** The junctions refer to EBJ and CBJ for pnp transistor.

# Operation Regions of BJT

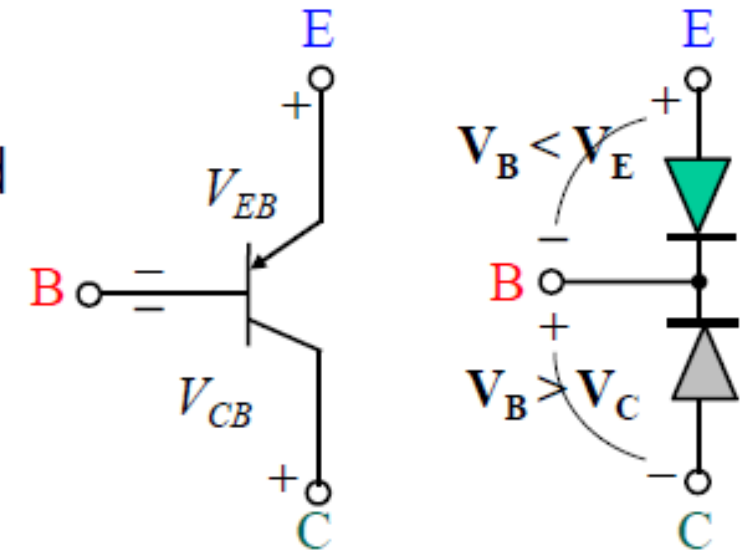
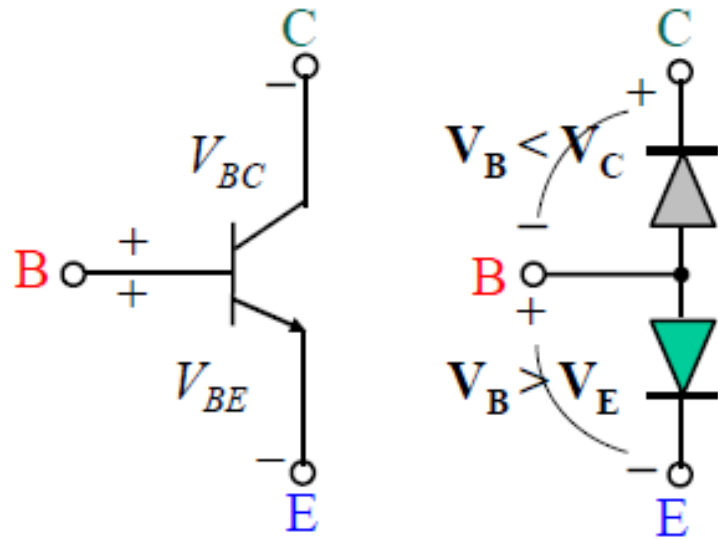
## Forward-active region

BEJ (npn) forward biased  
BCJ (npn) reversed biased

$$V_{BE} \approx 0.7 \text{ V}$$
$$I_C = \beta I_B = \alpha I_E$$

⇒ **Good amplifier**

$$\alpha = \beta / (\beta + 1)$$



**Note:** The junctions refer to EBJ and CBJ for pnp transistor.

# Operation Regions of BJT

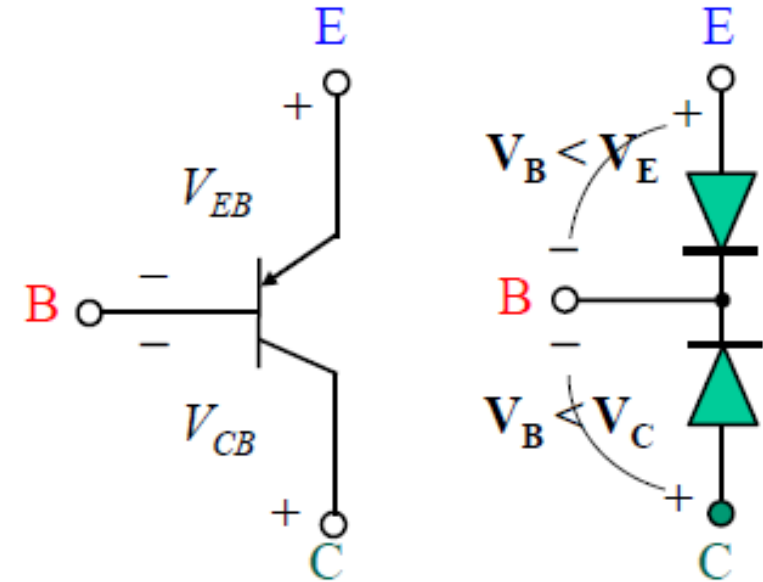
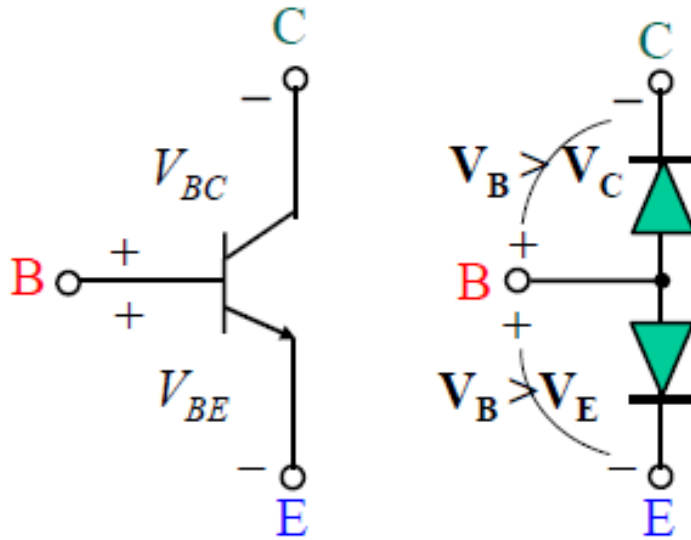
## Saturation region

BEJ (npn) forward biased  
BCJ (npn) forward biased

$\Rightarrow$  **Closed switch**

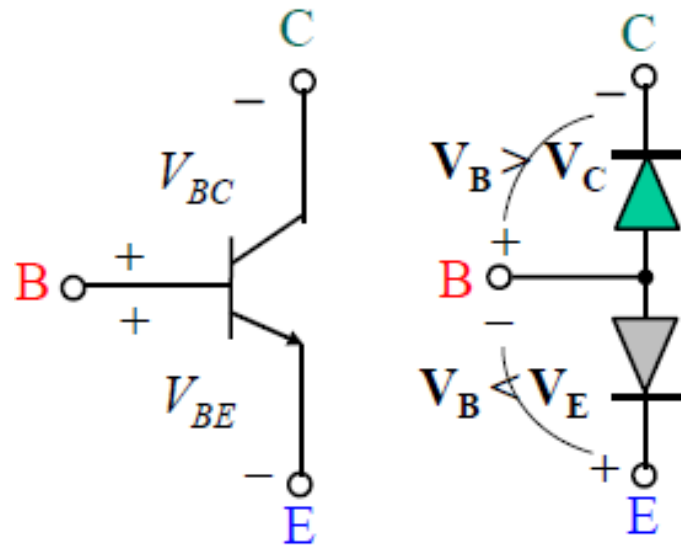
$$\Rightarrow V_{BE} \approx 0.7 \text{ V}$$
$$V_{BC} = 0.4 \sim 0.5 \text{ V}$$

$$\Rightarrow V_{CE(SAT)} = 0.2 \sim 0.3 \text{ V}$$



**Note:** The junctions refer to EBJ and CBJ for pnp transistor.

# Operation Regions of BJT

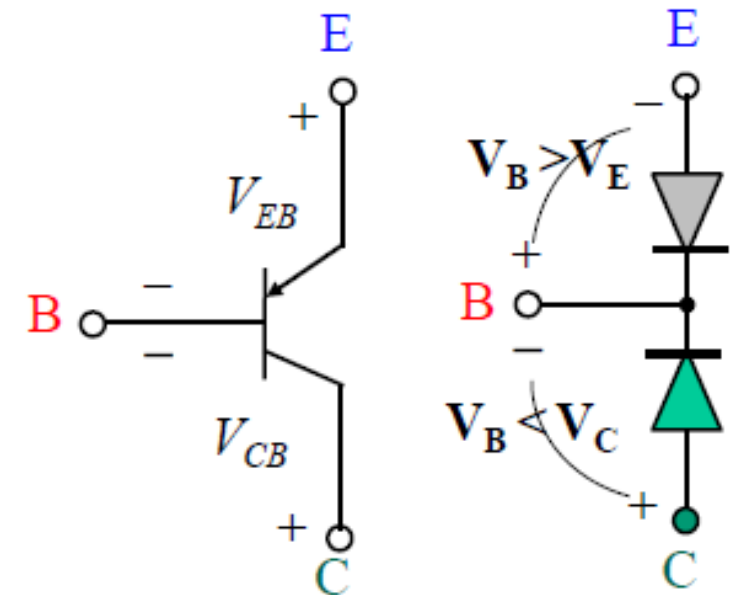


## Reverse-active region

BEJ (npn) reverse biased  
BCJ (npn) forward biased

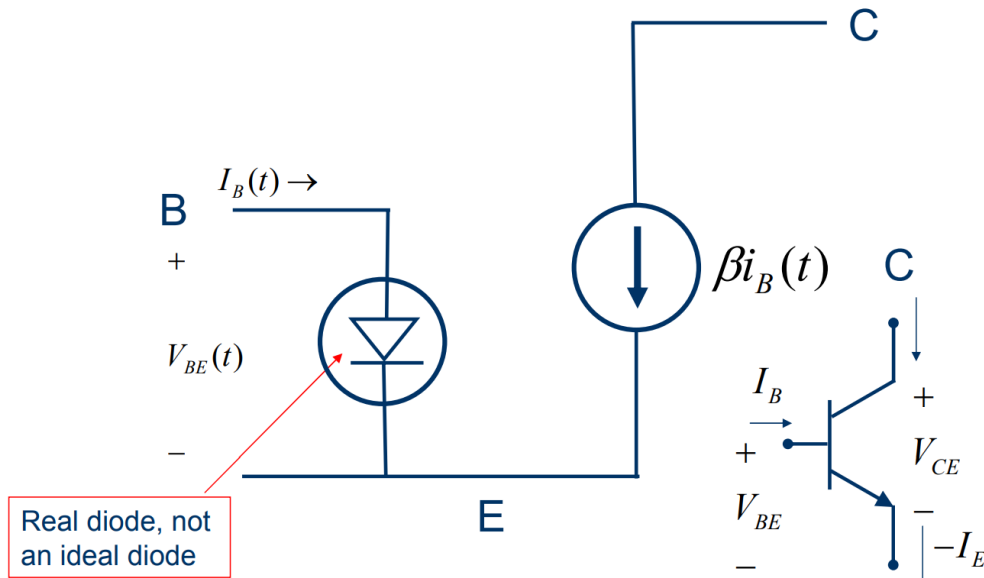
⇒ **Weak amplifier**

⇒ **Normally not use**



**Note:** The junctions refer to EBJ and CBJ for pnp transistor.

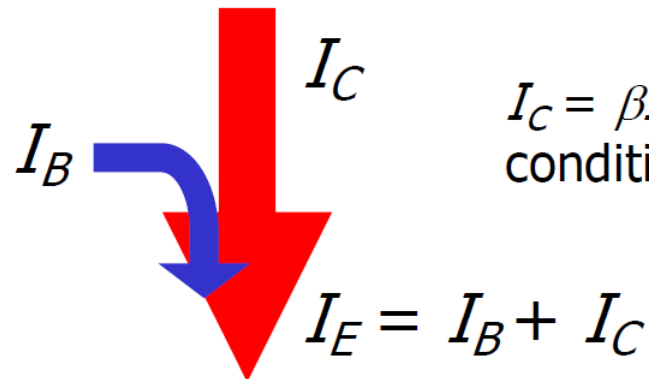
# Some properties



$V_{BE} \approx 0.6/0.7V$  when the transistor turns on.

Never try to stick a large voltage across  $V_{BE}$  because it may produce enormous current or may just kill the device!

$\beta$  is a "bad" parameter. Don't trust the databook. Its value can vary to  $\pm 50\%$  or more.



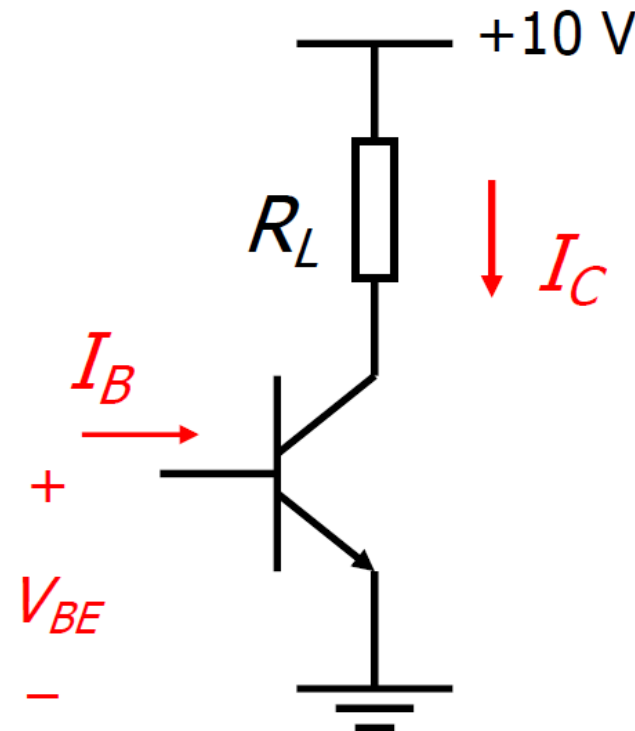
$I_C = \beta I_B$  holds only under some carefully set conditions. We'll look at it later.

# Typical operations in circuit

1. Cut-off
2. Active operation
3. Saturation

Determining factors:

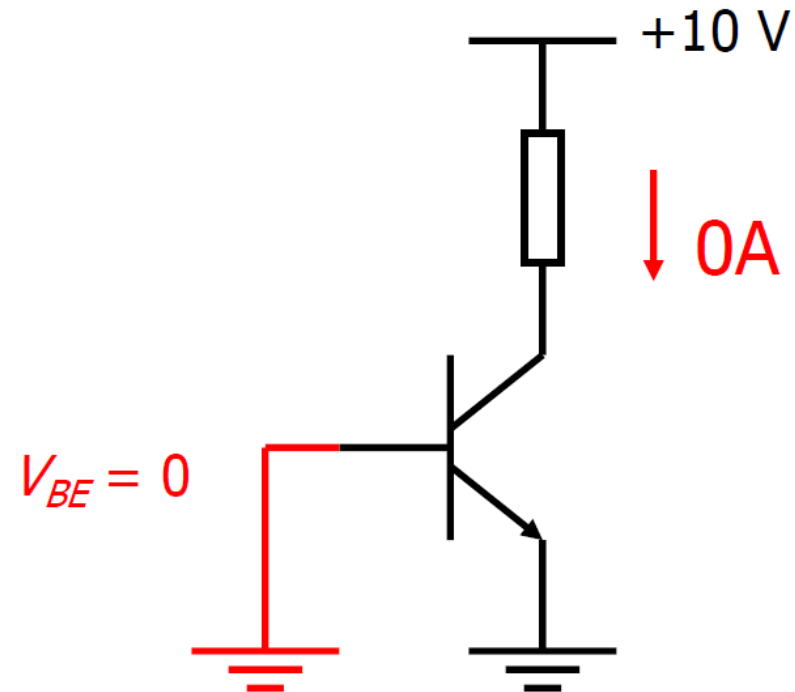
- How large is  $I_B$  or  $V_{BE}$
- How large is  $R_L$



# Cut-off

When the B-E junction is not forward-biased, the transistor is basically not doing anything.

This is called **CUT-OFF**.



# Active operation (for ideal transistor)

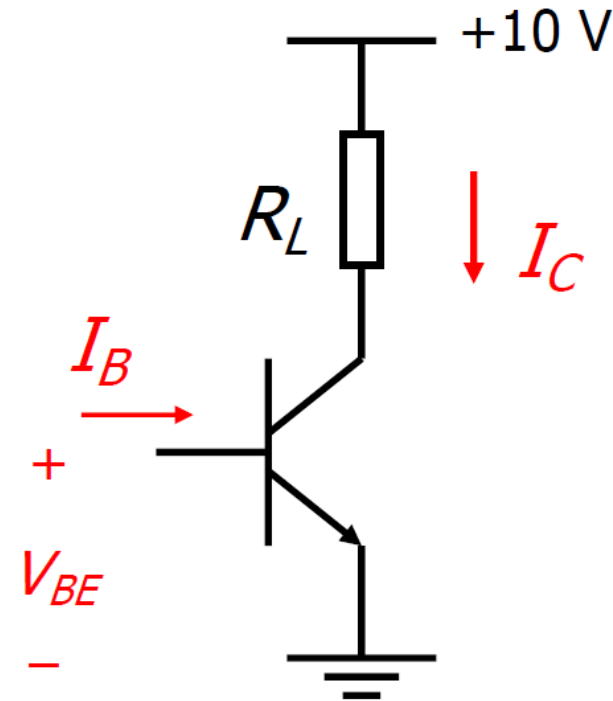
When the following holds:

$$I_C = \beta I_B$$

the BJT is said to be in active operation.

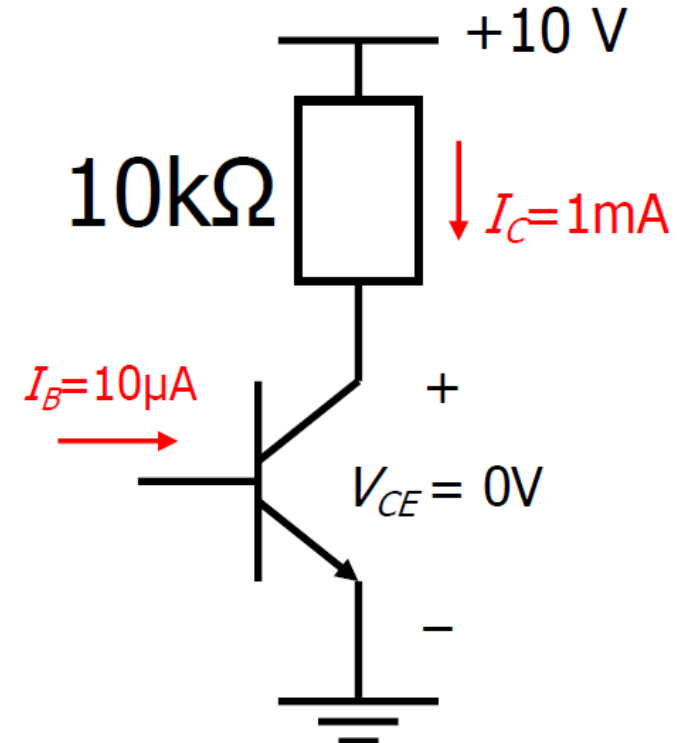
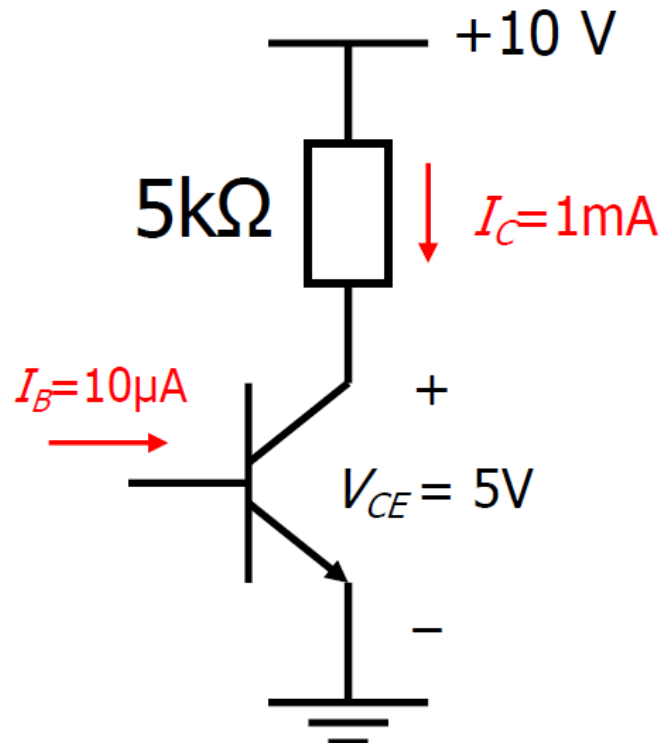
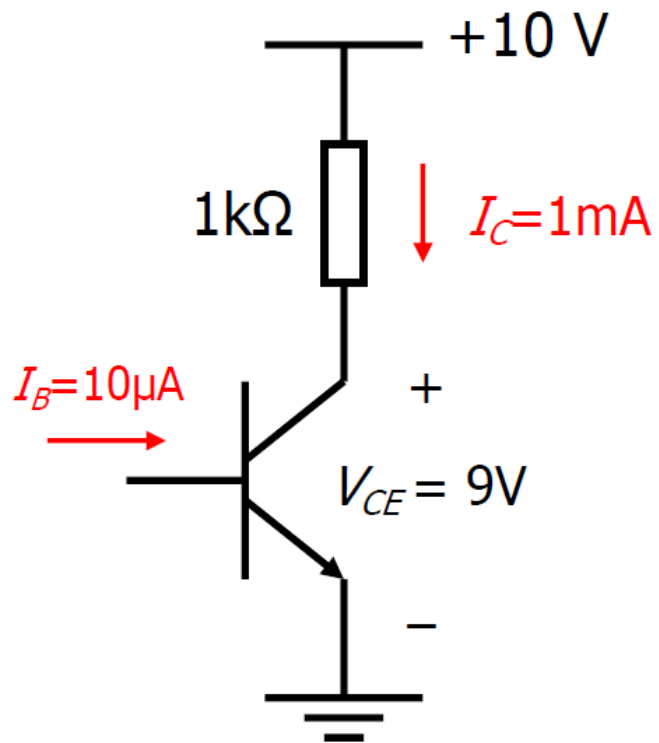
This is the case of current amplification.

But we need  $I_C R_L < 10V$



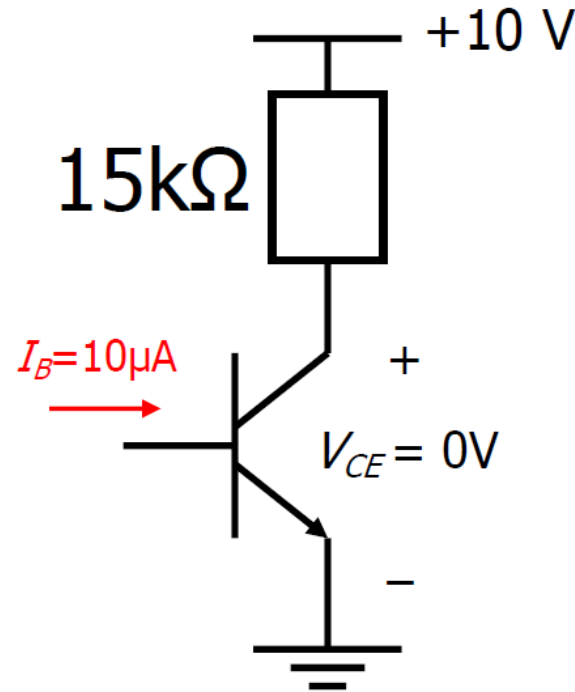
# Active operation (for ideal transistor)

Let  $\beta = 100$ .



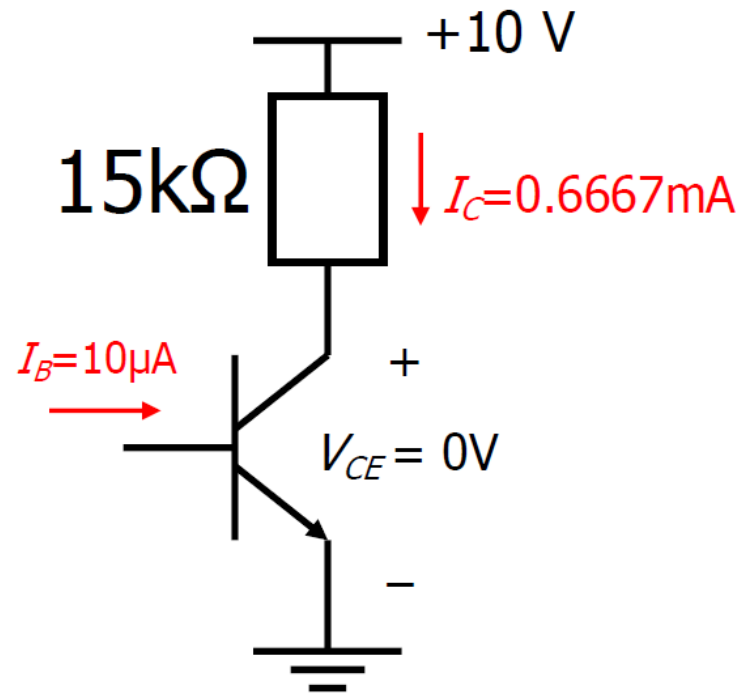
# Saturation (for ideal transistor)

When  $V_{CE}$  is reduced to 0, the BJT is saturated.



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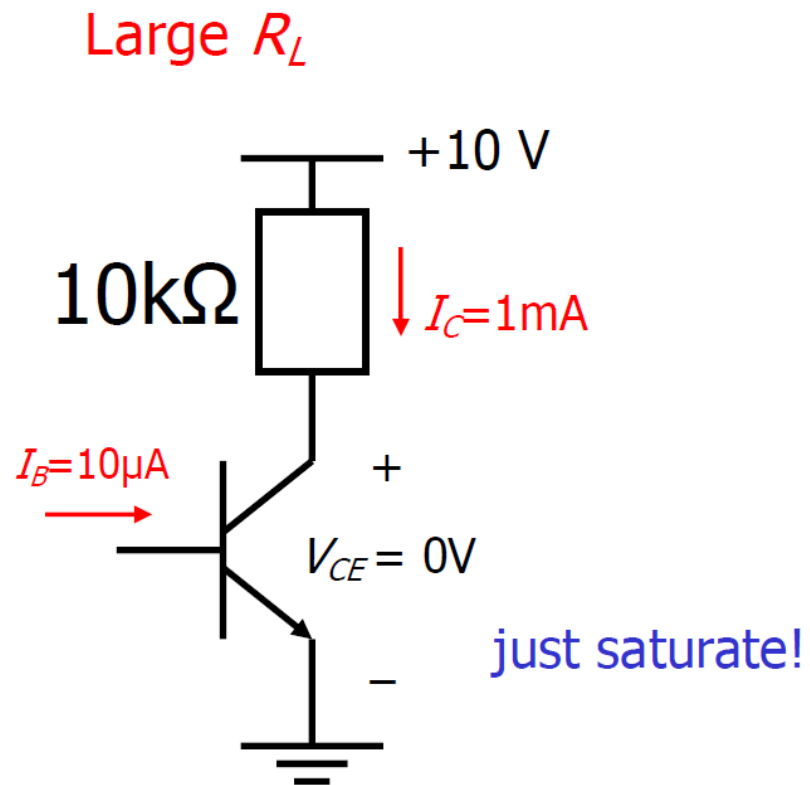
$I_C$  cannot be 1mA!!  
In fact, it must drop in order to make up for the total voltage.

In this case,

$$I_C = 10\text{V}/15\text{k}\Omega = 0.6667\text{mA}$$

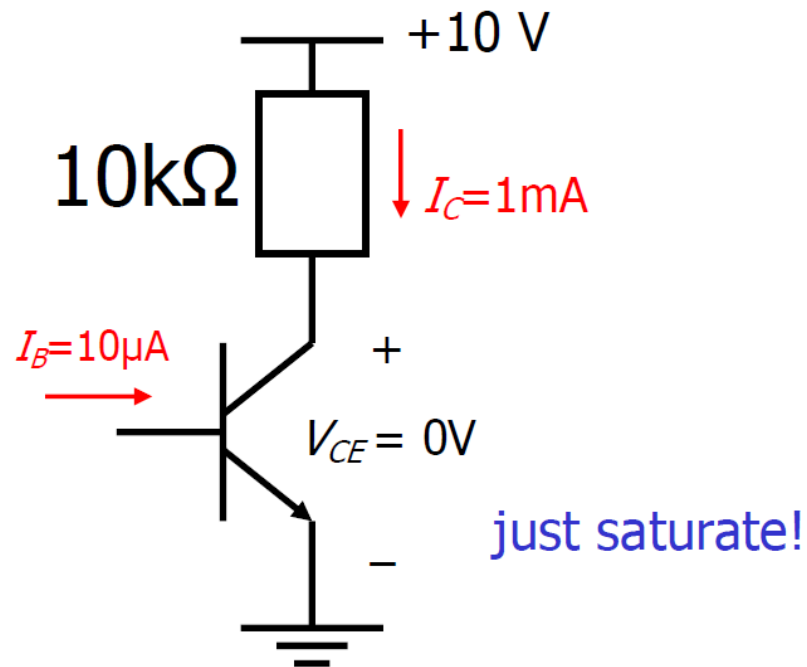
$$~~I_C = \beta I_B~~$$

# What makes it saturate?

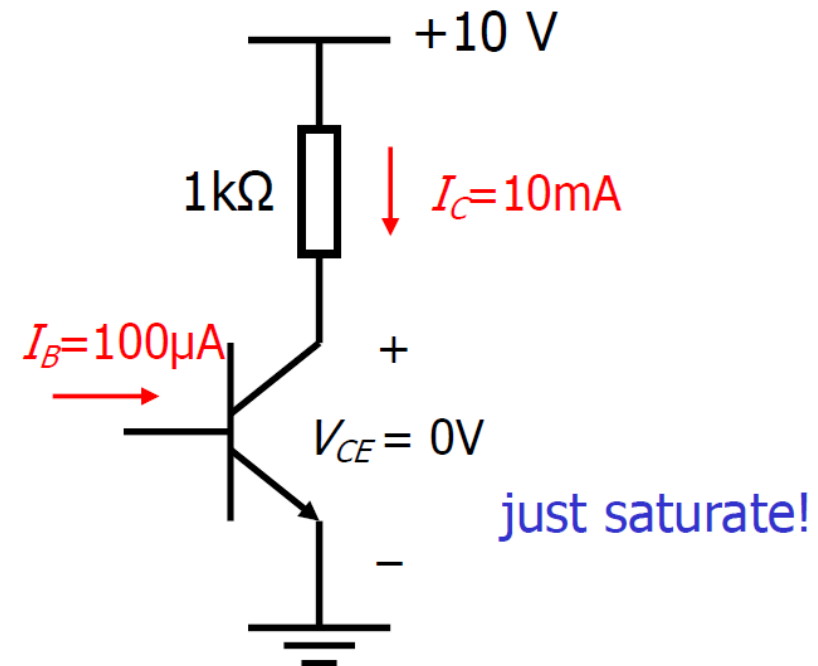


# What makes it saturate?

Large  $R_L$



Large  $I_B$



# BJT as switch

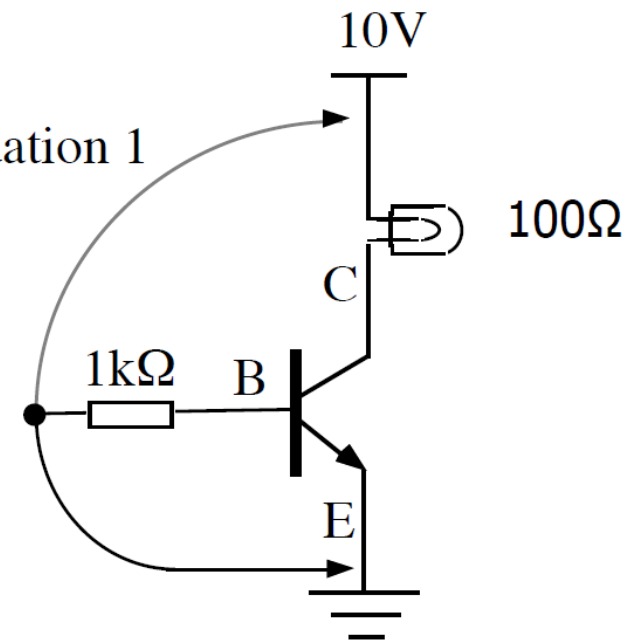
## Saturation

$$I_B = \frac{(10 - 0.7)V}{1k\Omega} = 9.3mA$$

$I_C = 100 \times 9.3 = 0.93A$  which is too large and surely saturates the BJT!!! So,  $I_C \approx 0.1A$ .

Light bulb turns on.

Situation 1



# BJT as switch

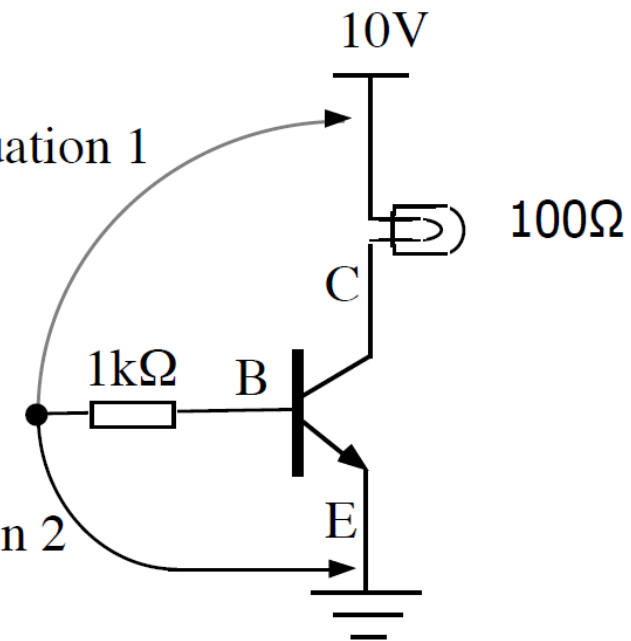
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Light bulb turns on.

Situation 1



Situation 2

## Cut-off

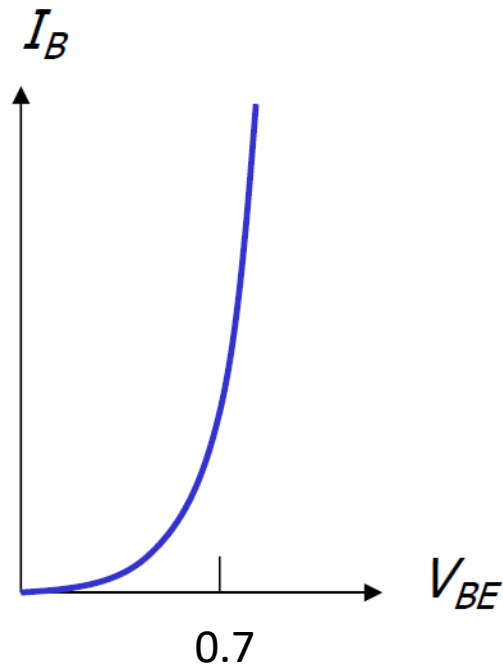
$I_B = I_C = 0$ . Light bulb turns off.

# BJT characteristics

## Input characteristic ( $I_B$ versus $V_{BE}$ )

Obviously,  $V_{BE}$  and  $I_B$  are related by diode characteristic.

$$I_B = I_{SS} \left( e^{V_{BE} / V_T} - 1 \right)$$



**thermal voltage**

Boltzman's constant

absolute temperature

$$V_T = \frac{kT}{q} \approx 25 \text{ mV @room temp}$$

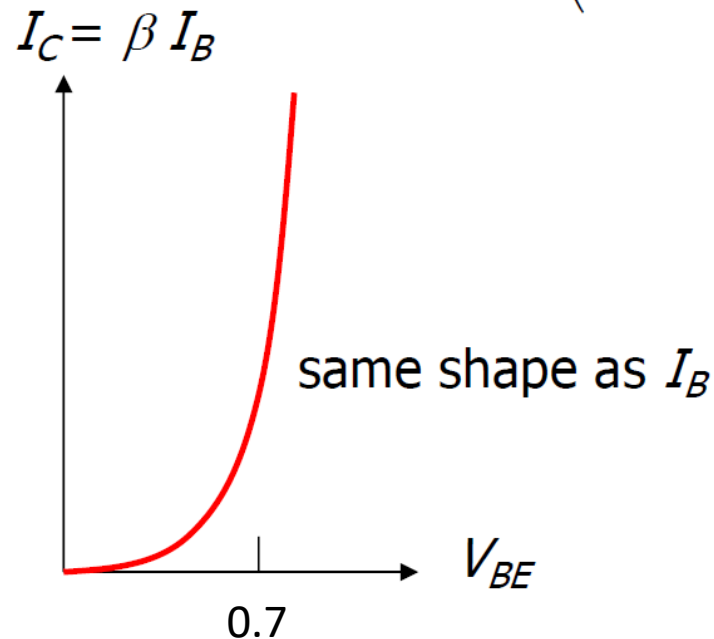
electronic charge

# BJT characteristics

## Transfer characteristic ( $I_C$ versus $V_{BE}$ )

Also,  $I_C$  is just  $I_B$  multiplied by  $\beta$ .

$$I_C = \beta I_{SS} \left( e^{V_{BE} / V_T} - 1 \right) = I_S \left( e^{V_{BE} / V_T} - 1 \right)$$



**thermal voltage**

Boltzman's constant

absolute temperature

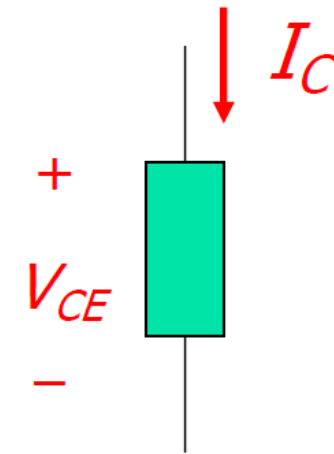
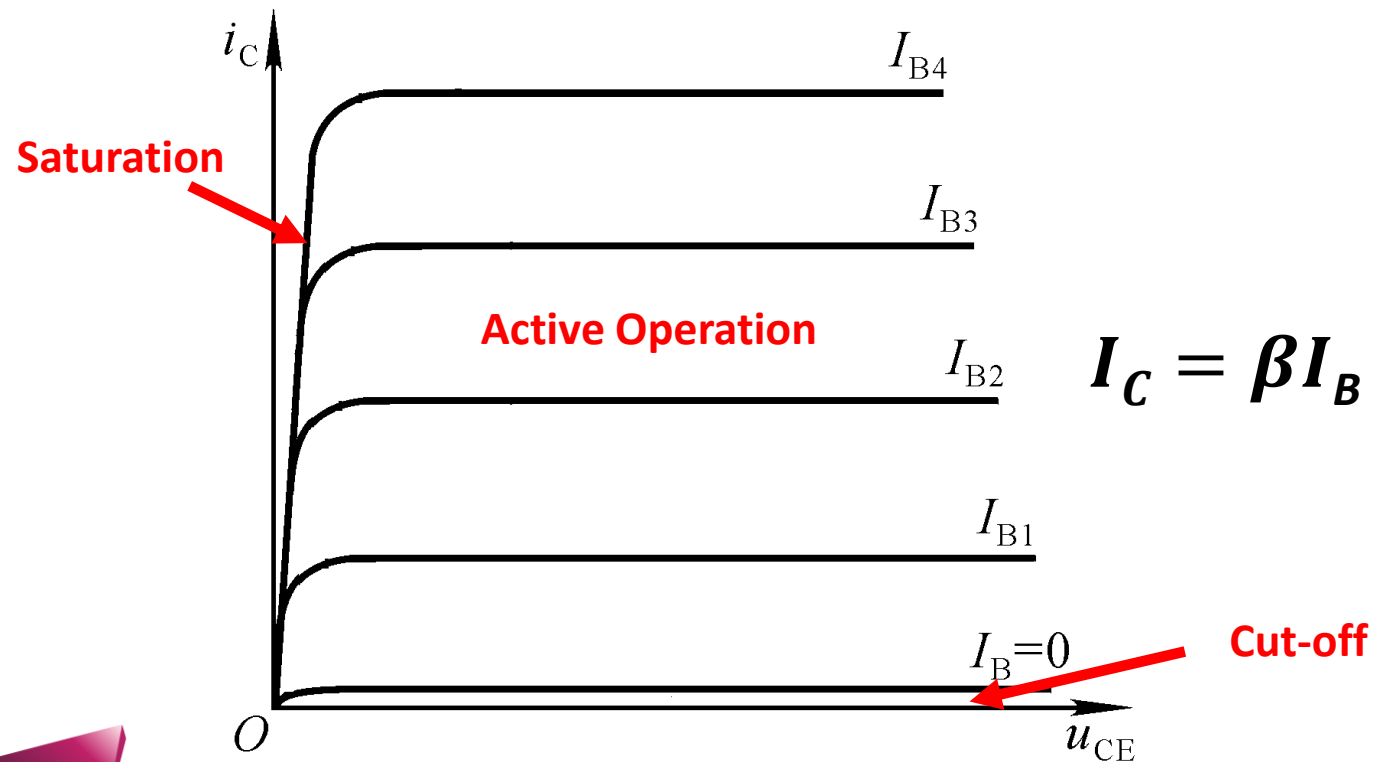
$$V_T = \frac{kT}{q} \approx 25 \text{ mV @room temp}$$

electronic charge

# BJT characteristics

## Output characteristic ( $I_C$ versus $V_{CE}$ )

$I_C$  is nearly flat unless near saturation.



Not Ohm's law!!

# BJT characteristics

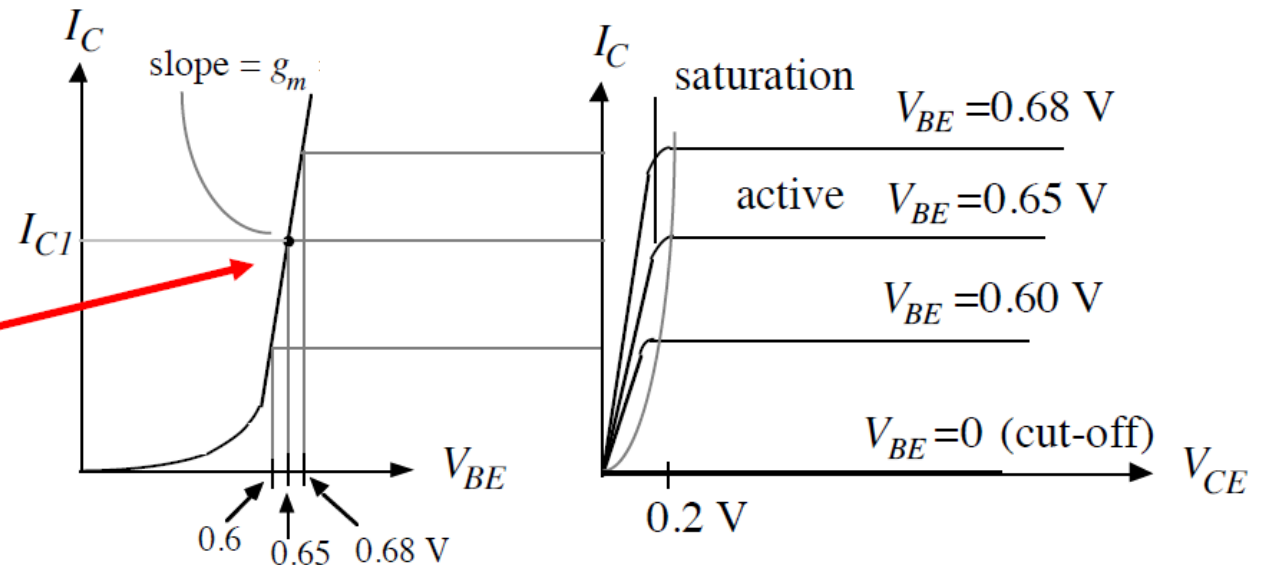
**Ideally:**  $V_{BE} \approx 0.6/0.7$

**In practice:**  $V_{BE}$  can be variant, a range of  $V_{BE}$  corresponds to a range of  $I_C$ . (Small signal model)

Transconductance:

$$g_m = \frac{\Delta I_C}{\Delta V_{BE}}$$

= slope  
on the transfer char.



# BJT characteristics

---

Transconductance

$$g_m = \frac{\Delta I_C}{\Delta V_{BE}}$$

A simple differentiation gives

$$g_m = \frac{dI_C}{dV_{BE}} = \frac{d}{dV_{BE}} \left( \beta I_{SS} (e^{V_{BE}/V_T} - 1) \right)$$

# BJT characteristics

Transconductance

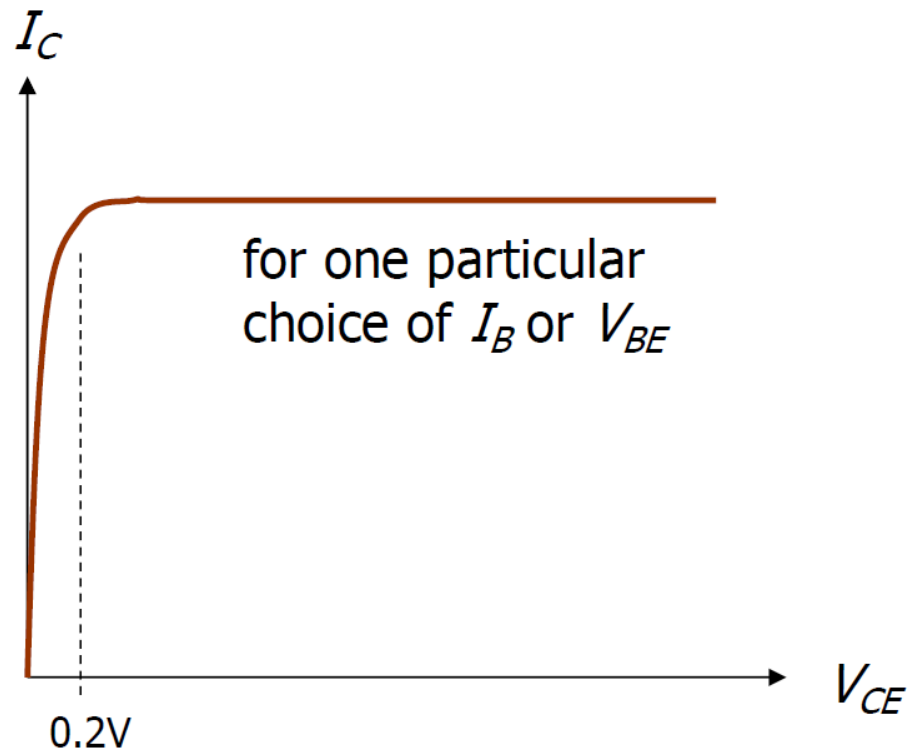
$$g_m = \frac{\Delta I_C}{\Delta V_{BE}}$$

A simple differentiation gives

$$\begin{aligned} g_m &= \frac{dI_C}{dV_{BE}} = \frac{d}{dV_{BE}} \left( \beta I_{SS} (e^{V_{BE}/V_T} - 1) \right) \\ &= \beta I_{SS} (e^{V_{BE}/V_T}) \frac{1}{V_T} \\ &\approx \frac{I_C}{V_T} \quad \text{or} \quad \frac{I_C}{25\text{mV}} \quad \text{At room temp} \end{aligned}$$

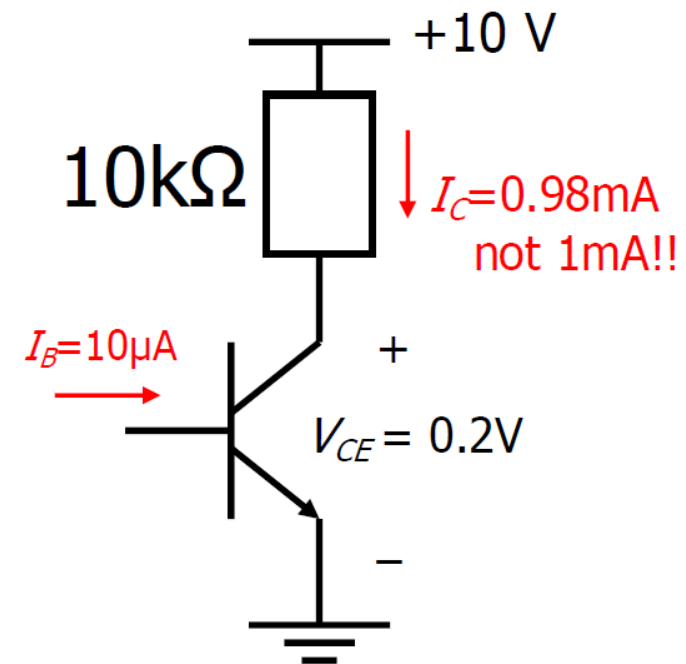
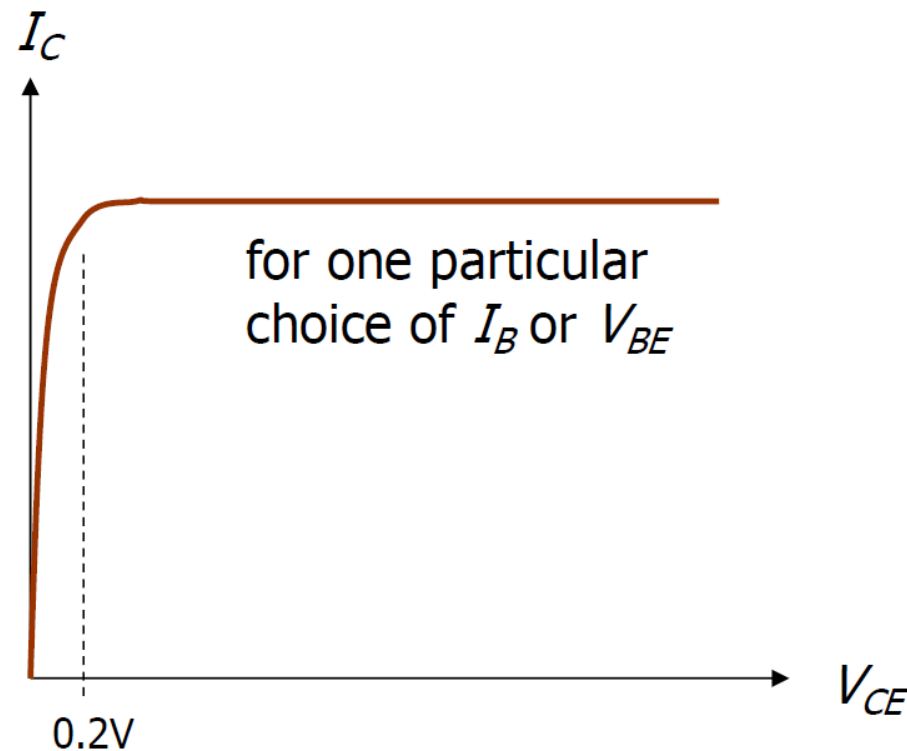
# BJT characteristics

At saturation,  $V_{CE}$  is not really 0, it is about 0.2 V.



# BJT characteristics

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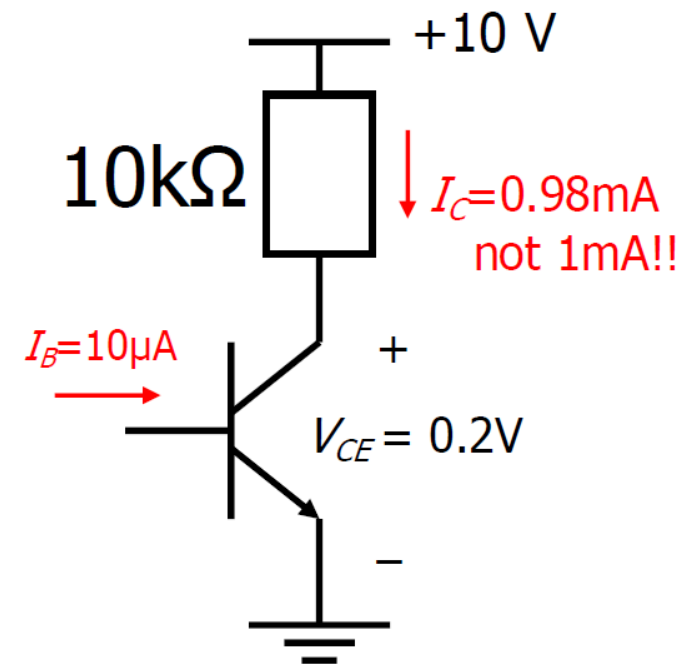
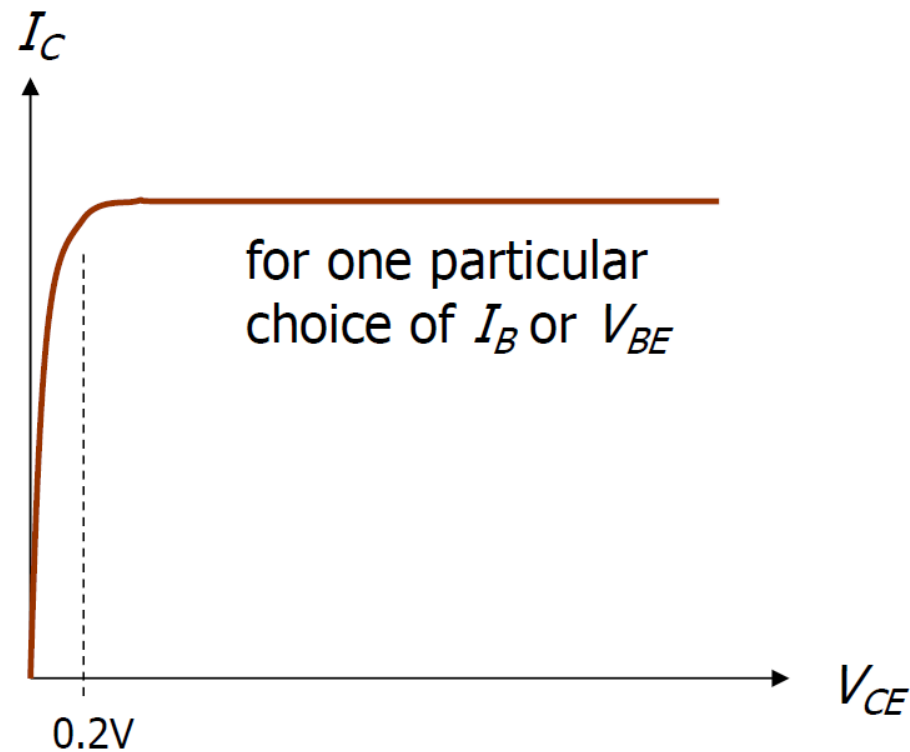


In our course, we treat the BJT to be ideal unless mentioned otherwise in the question.

**However, in practice, we should let  $V_{BE} < V_{CE}$  ( $V_{CE} > 0.7V$ ) to keep collector-base junction reverse-biased!!**

# BJT characteristics

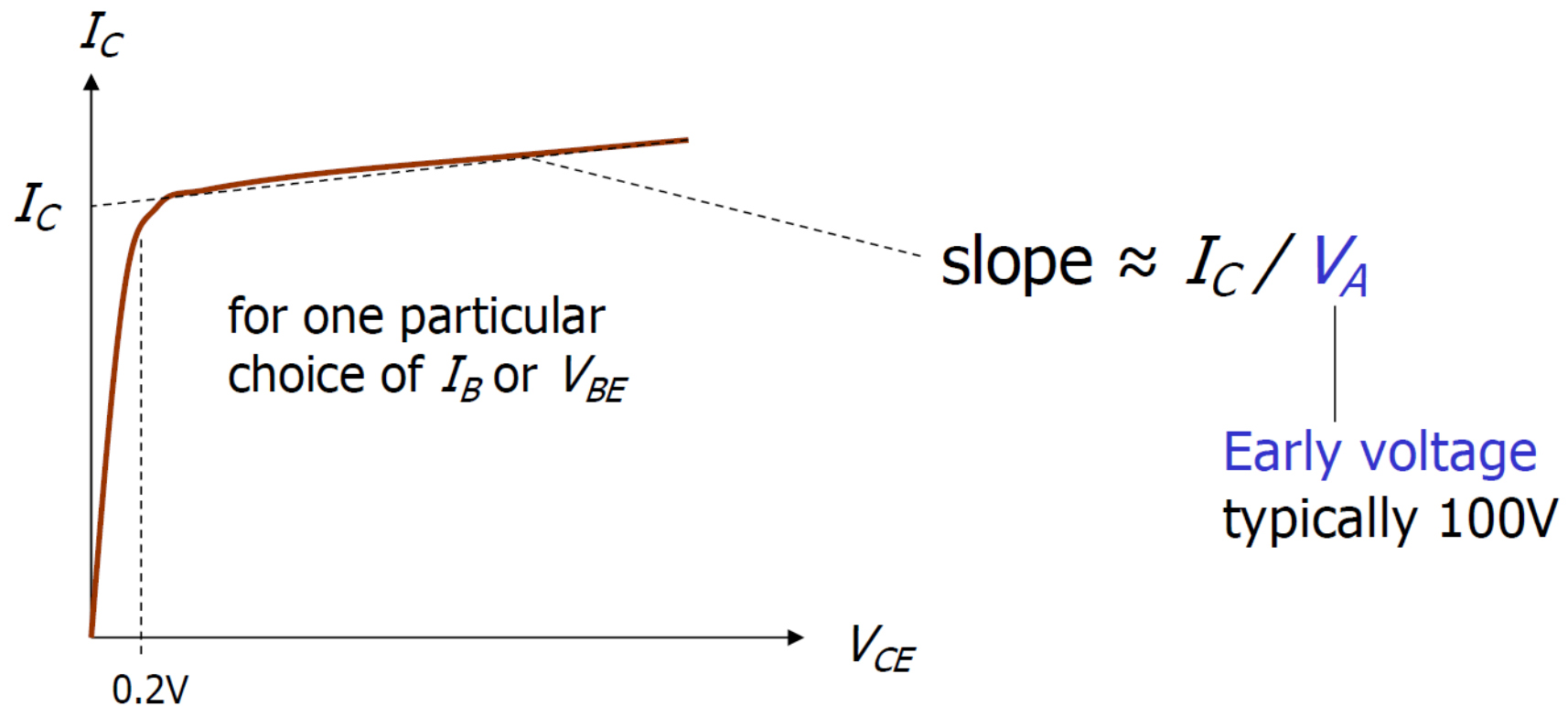
At saturation,  $V_{CE}$  is not really 0, it is about **0.2 V**.



**For Exam/Quiz/Homework, we have  $V_{CE} \geq 0.7V$ , unless the transistor is assumed to be ideal.**

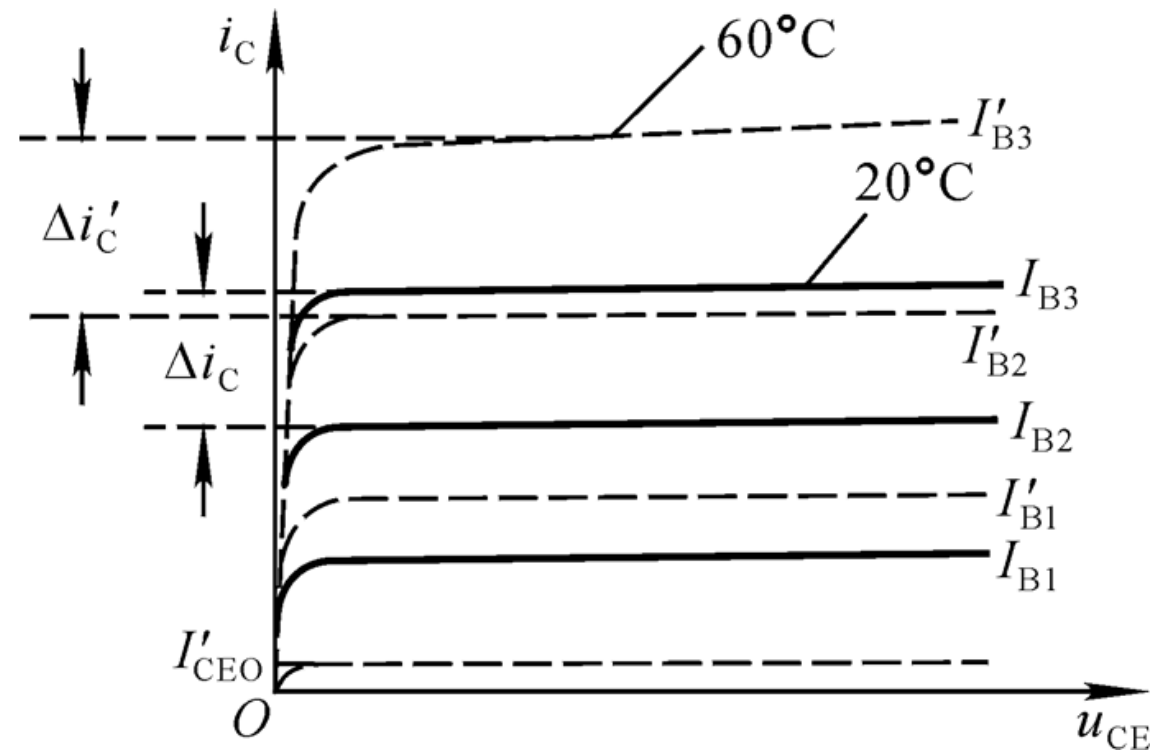
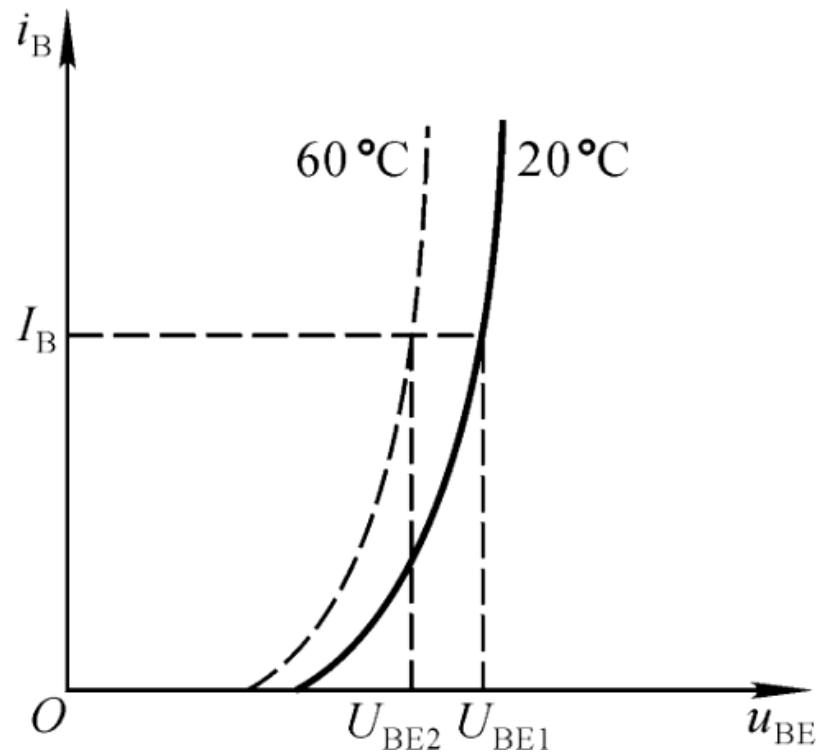
# BJT characteristics

In active region,  $I_C$  is not really flat. It goes up gently! This is called **Early Effect**!



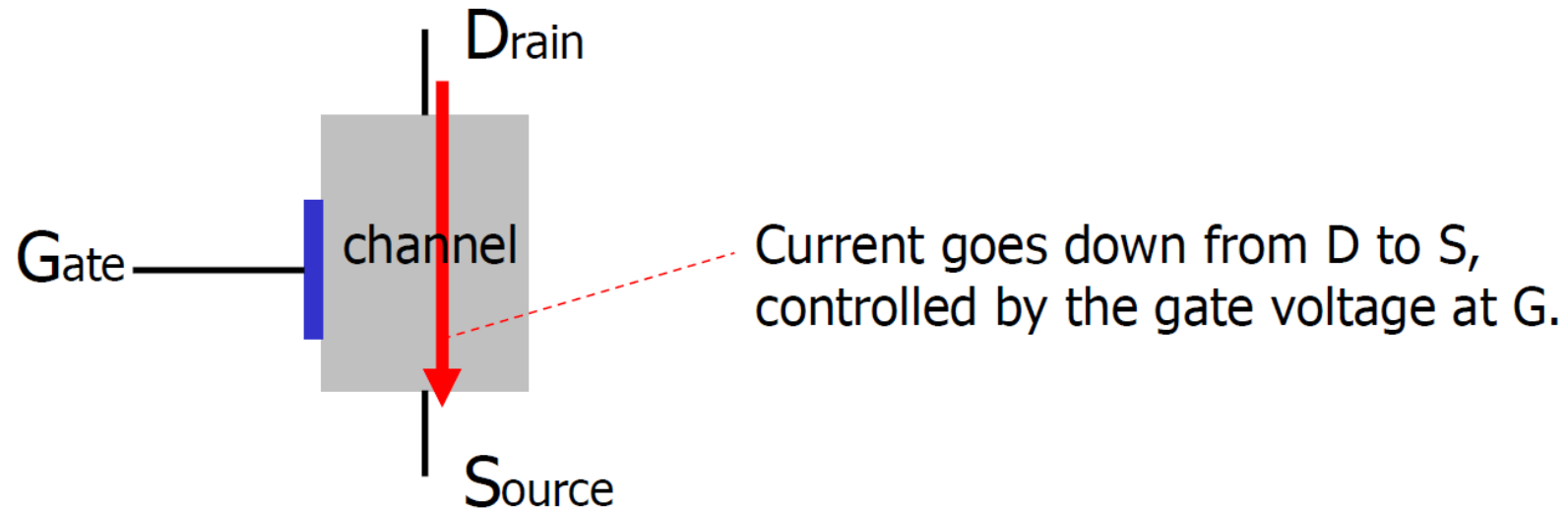
# BJT characteristics

# Temperature



# Field Effect Transistors (FET)

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Two kinds of channels:

n-channel FET  
p-channel FET

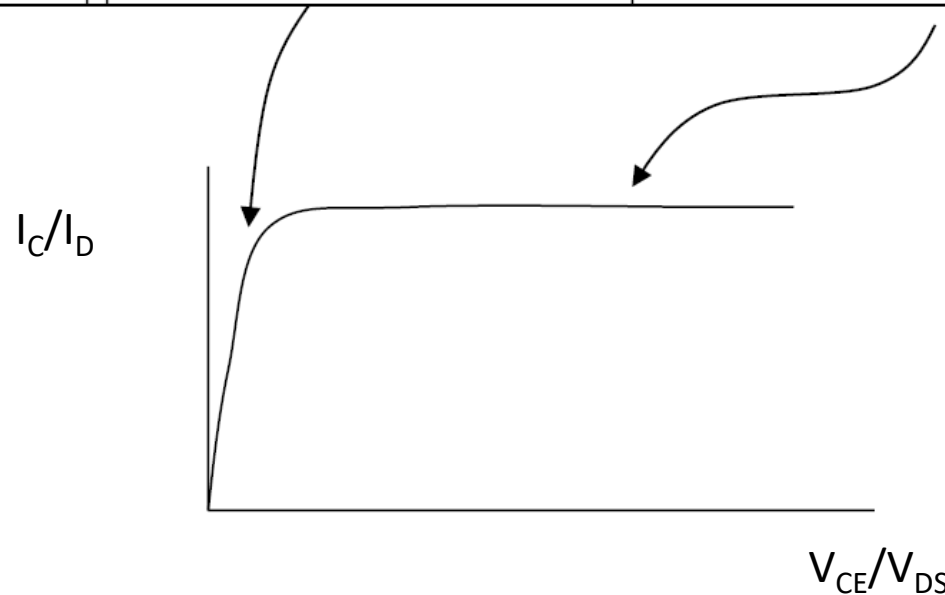
Two kinds of gate electrodes:

Junction FET (JFET)  
Metal-oxide-semiconductor FET (MOSFET)

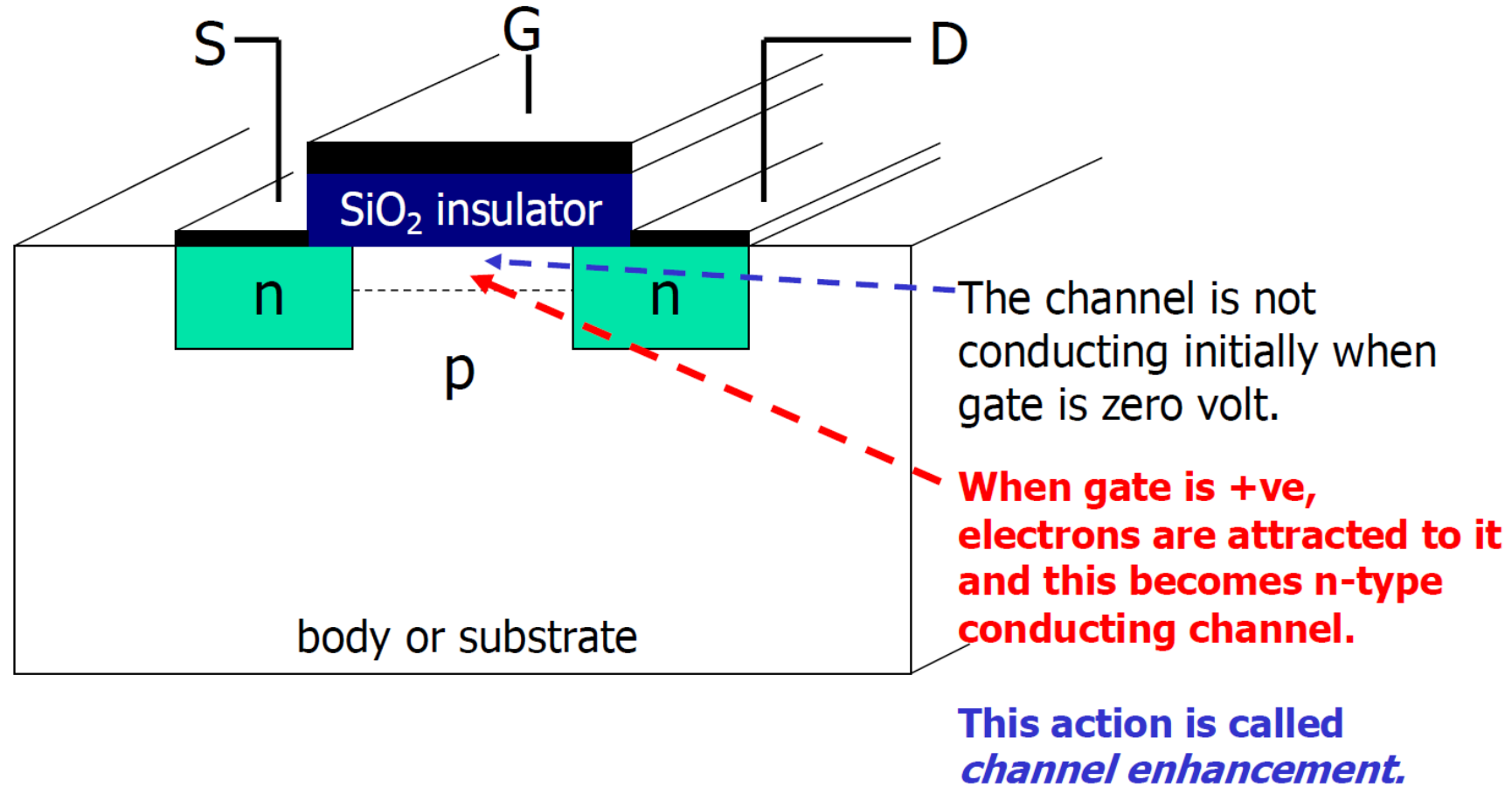
# Terminology confusion

FET also has three types of operations.

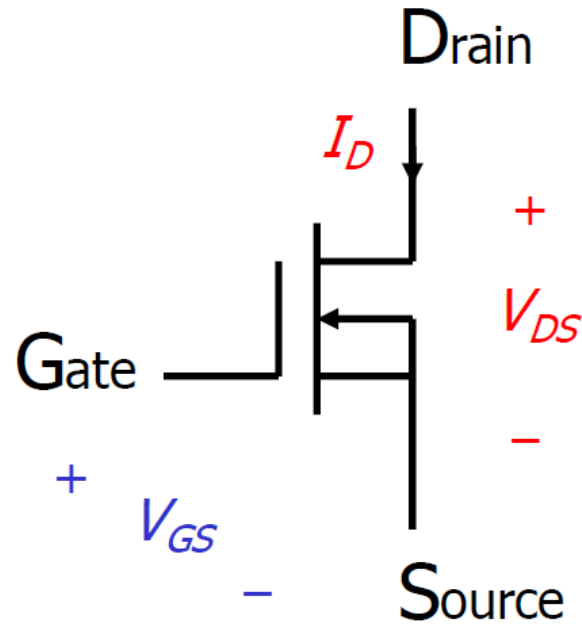
|     |                   |                   |         |
|-----|-------------------|-------------------|---------|
| BJT | saturation region | active region     | cut-off |
| FET | triode region     | saturation region | cut-off |



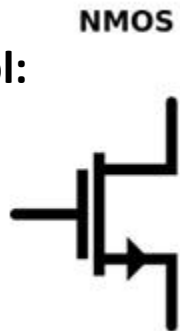
# n-channel MOSFET



# n-channel MOSFET characteristic



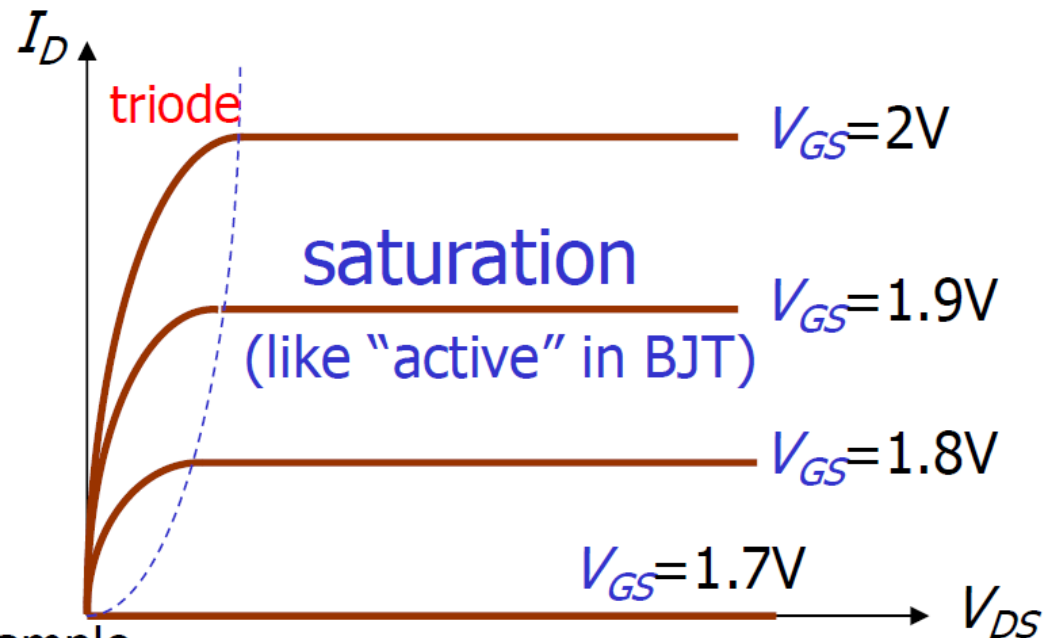
Other symbol:



Characteristics:

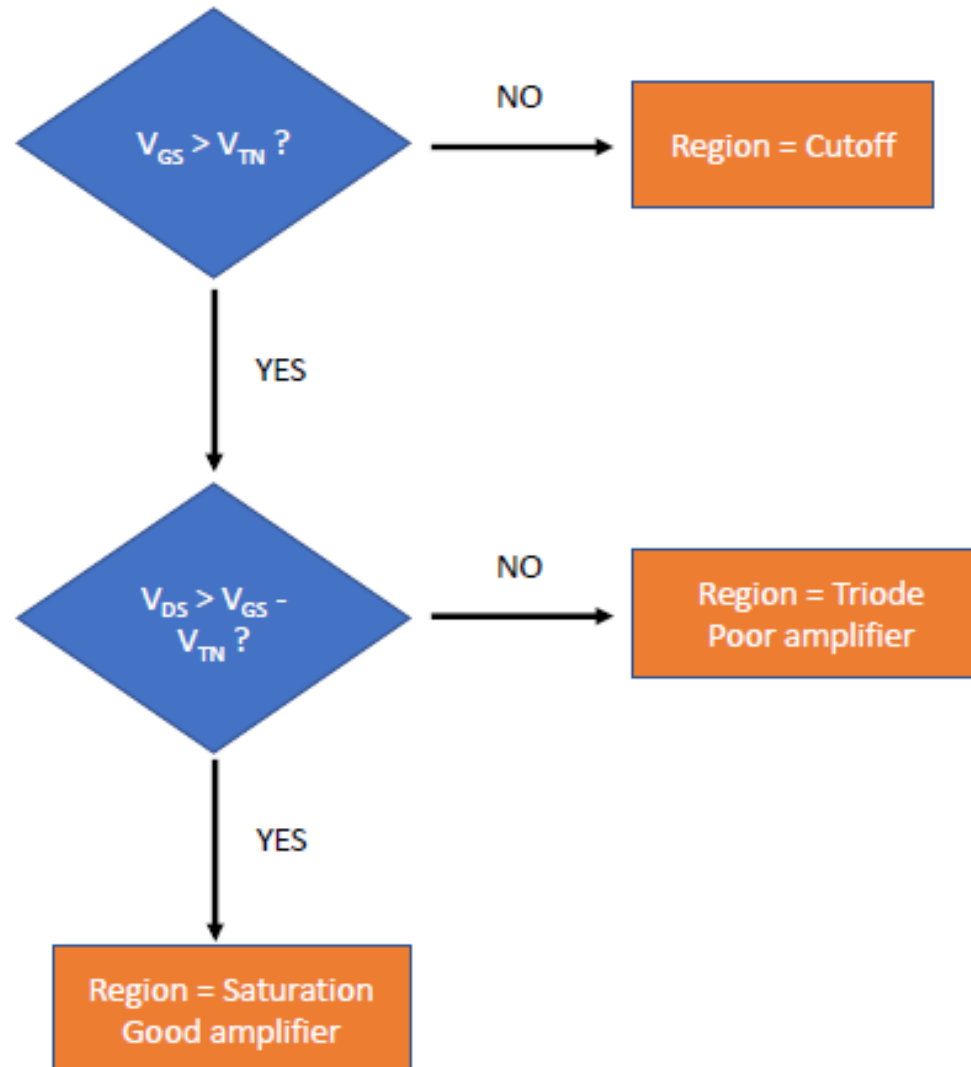
Gate current = 0 (always)

The channel conduction is determined by  $V_{GS}$

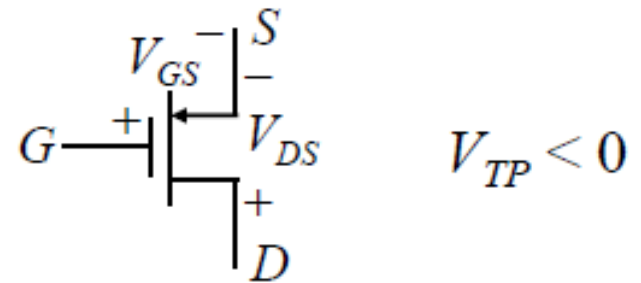
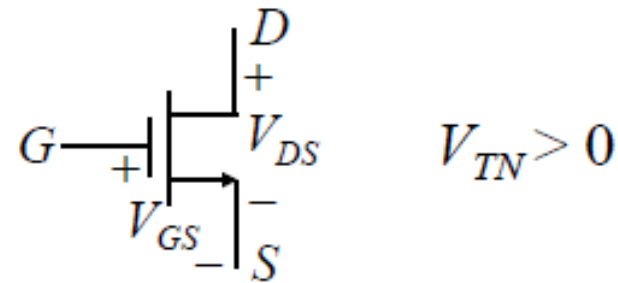


Threshold voltage  
 $V_{th} = 1.7 \text{ V}$ , for example.

# Summary: Region of operation of NMOS

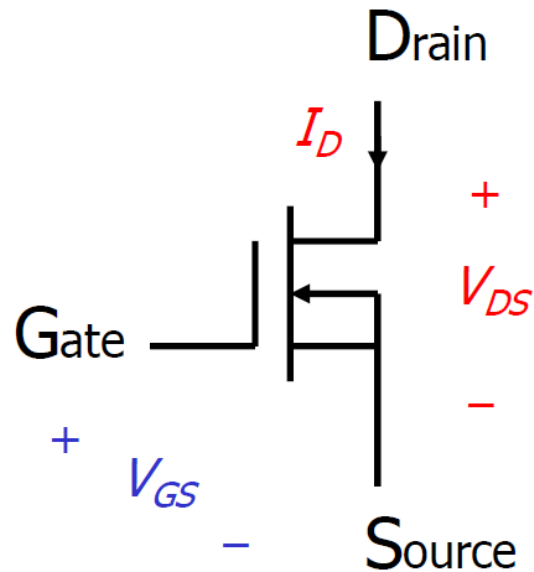


# MOSFET Biasing for Different Region of Operation

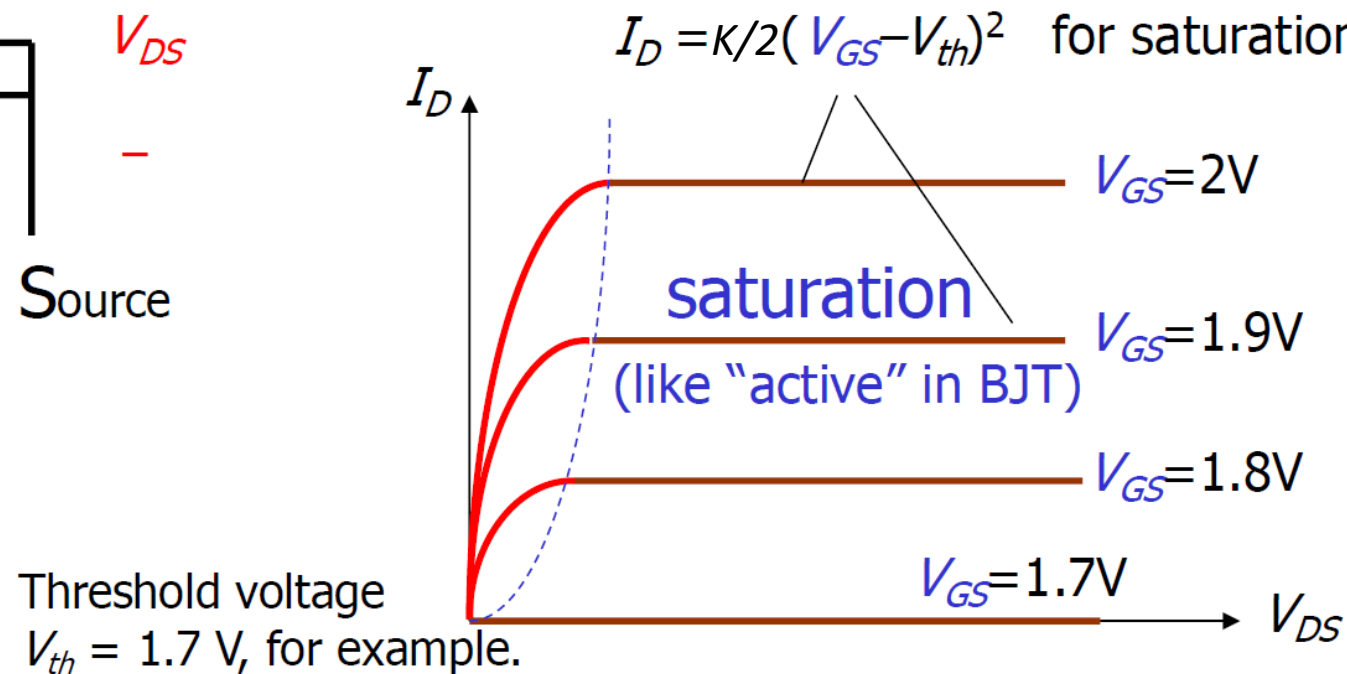


| Region     | NMOS                                                                                                                        | PMOS                                                                                                                                          |
|------------|-----------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------|
| Cutoff     | $V_{GS} < V_{TN}$<br>$I_D = 0$                                                                                              | $ V_{GS}  <  V_{TP} $<br>$I_D = 0$                                                                                                            |
| Triode     | $V_{GS} \geq V_{TN}$ and $V_{DS} < V_{GS} - V_{TN}$<br>$I_D = K_n \left( V_{GS} - V_{TN} - \frac{V_{DS}}{2} \right) V_{DS}$ | $ V_{GS}  \geq  V_{TP} $ and $ V_{DS}  <  V_{GS}  -  V_{TP} $<br>$I_D = K_p \left(  V_{GS}  -  V_{TP}  - \frac{ V_{DS} }{2} \right)  V_{DS} $ |
| Saturation | $V_{GS} \geq V_{TN}$ and $V_{DS} \geq V_{GS} - V_{TN}$<br>$I_D = \frac{K_n}{2} (V_{GS} - V_{TN})^2$                         | $ V_{GS}  \geq  V_{TP} $ and $ V_{DS}  \geq  V_{GS}  -  V_{TP} $<br>$I_D = \frac{K_p}{2} ( V_{GS}  -  V_{TP} )^2$                             |

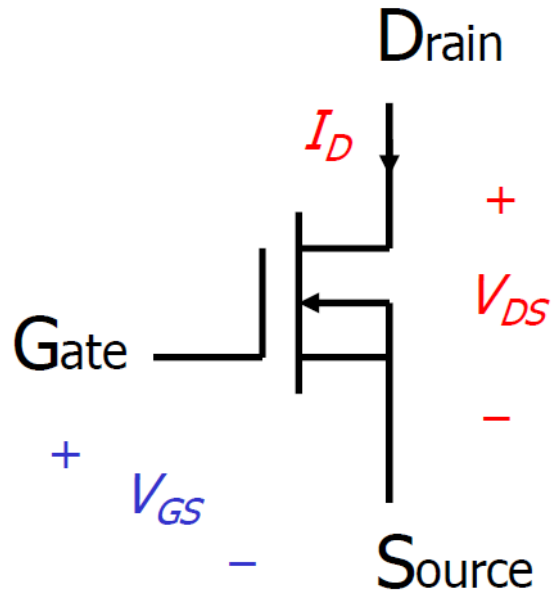
# Saturation region



The saturation current is proportional to  $(V_{GS} - V_{th})^2$ .

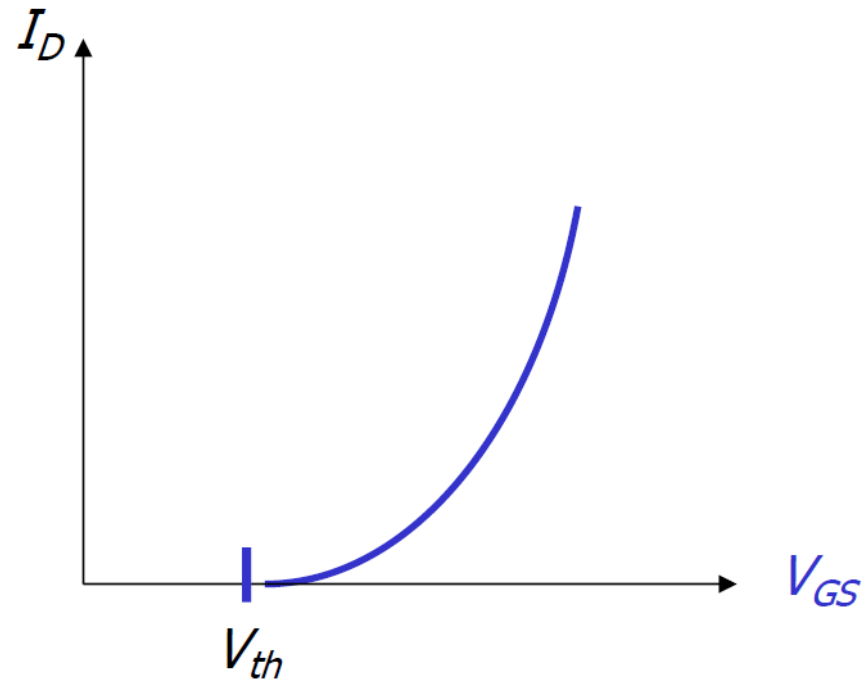


# Saturation region



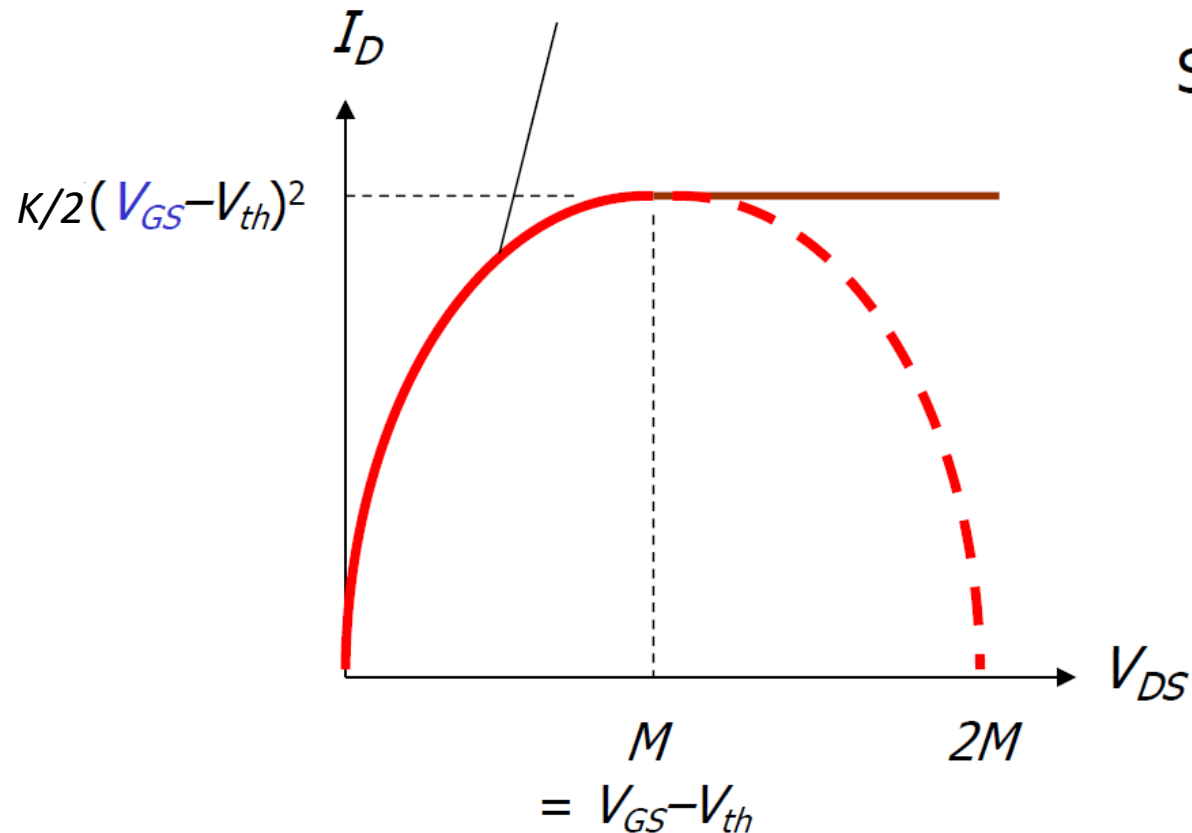
$$I_D = K/2 (V_{GS} - V_{th})^2 \quad \text{for saturation region}$$

If we plot the saturation  $I_D$  versus  $V_{GS}$ , we have a quadratic (parabolic) curve.



# Triode region

Triode region — like a quadratic (parabolic) function



So, the equation is:

$$y = a x (2M - x)$$

||

$$I_D = a V_{DS} (2M - V_{DS})$$

Obviously,  $M = V_{GS} - V_{th}$ ,  $a = K/2$

$$I_D = K/2 V_{DS} [2 (V_{GS} - V_{th}) - V_{DS}]$$

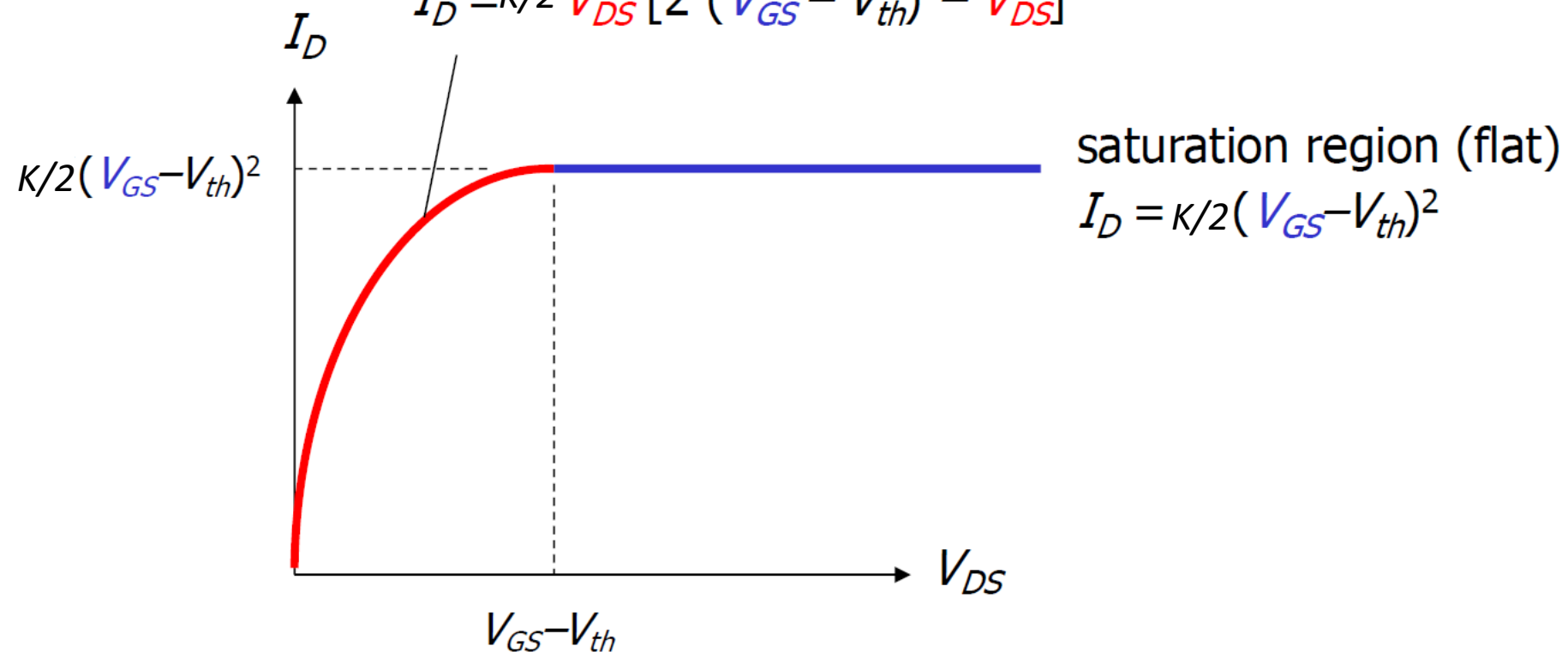
for triode region

# n-channel MOSFET characteristic

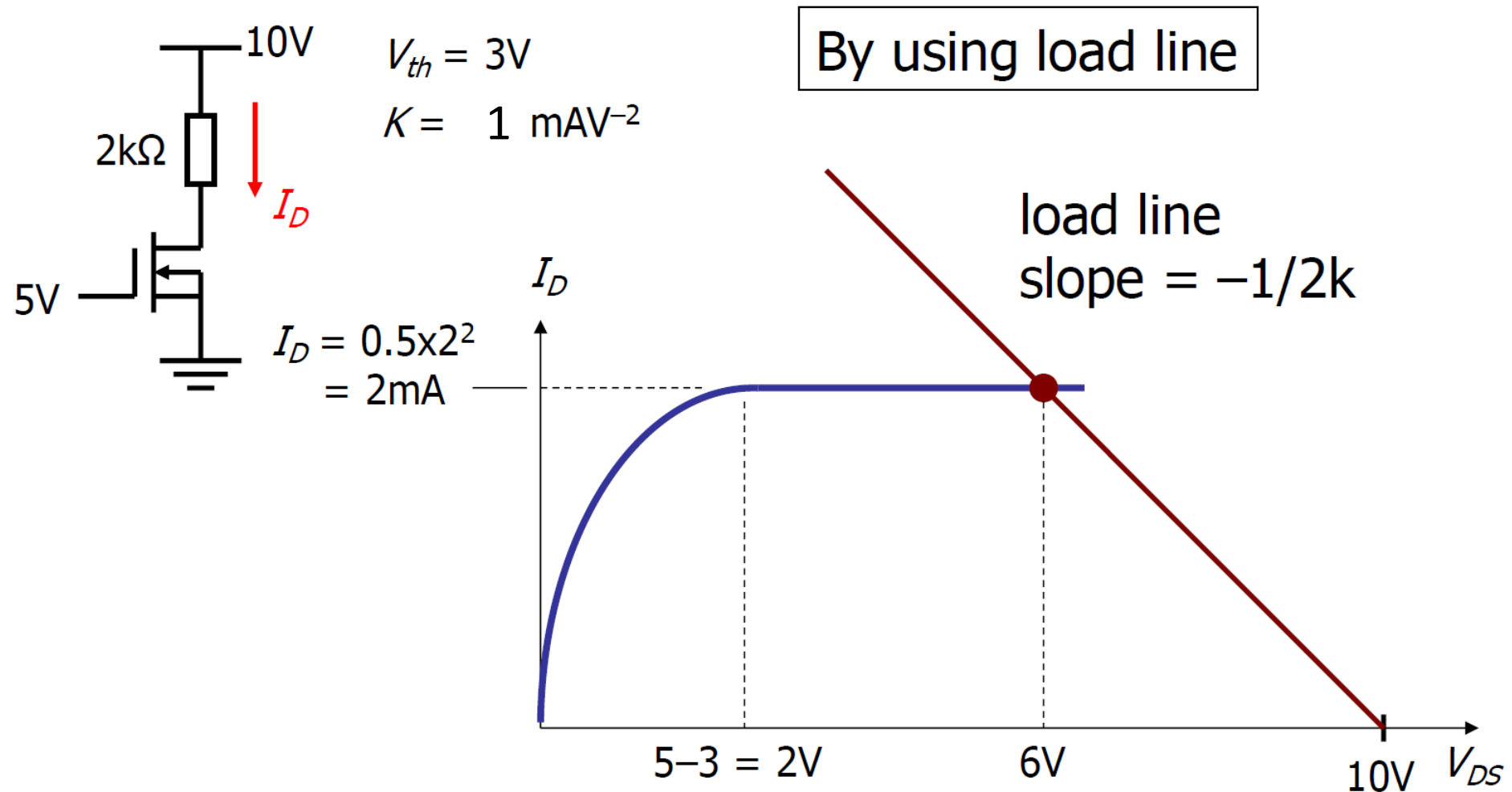
Complete model summary:

triode region (quadratic in  $V_{DS}$ )

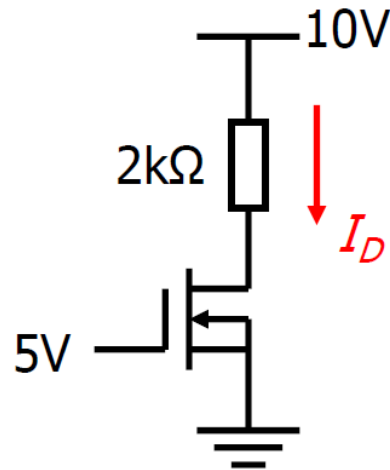
$$I_D = k/2 V_{DS} [2 (V_{GS} - V_{th}) - V_{DS}]$$



# Example (biasing in saturation)



# Example (biasing in saturation)



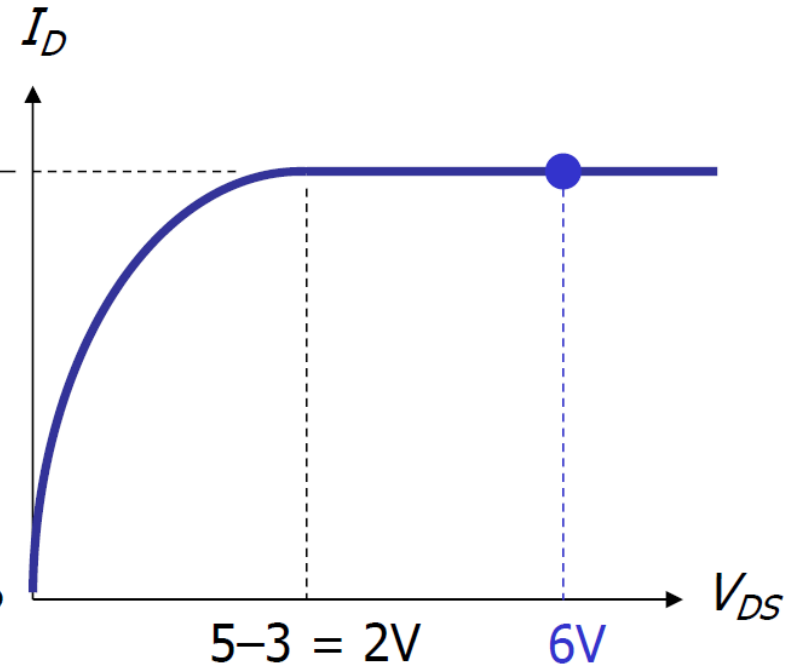
$$V_{th} = 3V$$

$$K = 1 \text{ mA}V^{-2}$$

By analysis

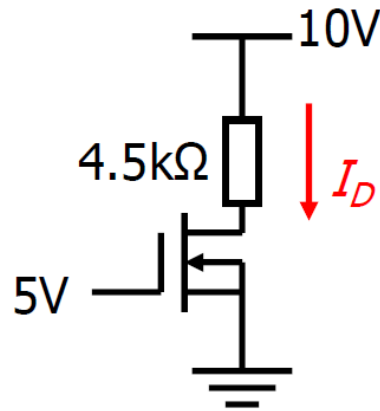
$$I_D = 0.5 \times 2^2 \\ = 2\text{mA}$$

$$V_{DS} = 10 - 2 \times 2 \\ = 6V \\ \text{which is } > 2 \\ \text{OKAY!}$$



What happen if a 4.5kΩ is used?

# Example (biasing in saturation)

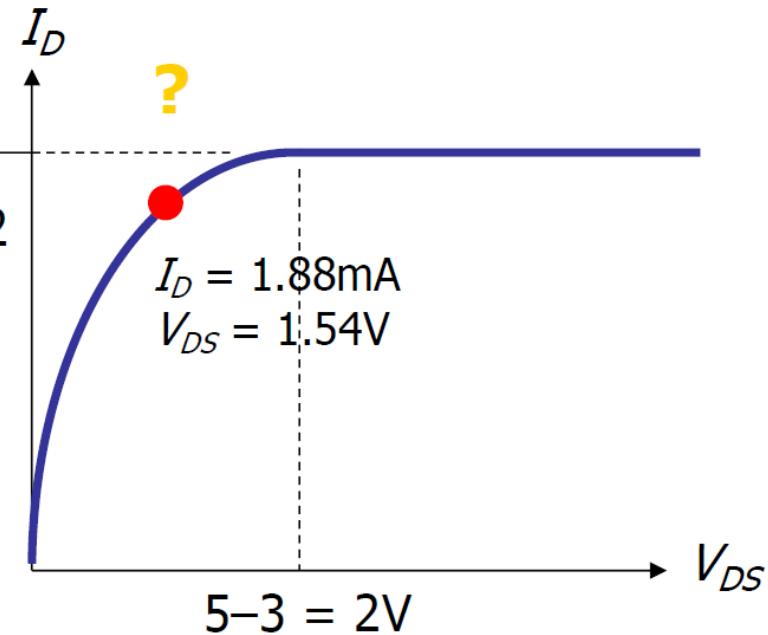


$$V_{th} = 3V$$
$$K = 1 \text{ mA/V}^2$$

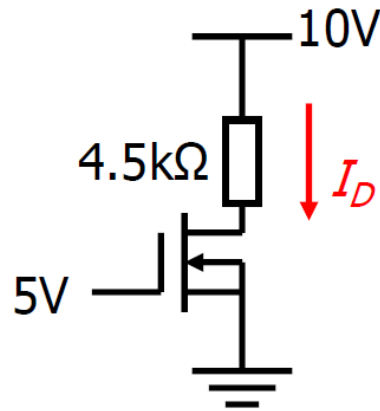
$$I_D = 0.5 \times 2^2$$
$$= 2\text{mA}$$

$$V_{DS} = 10 - 4.5 \times 2$$
$$= 1V$$

Oops!!



# Example (biasing in saturation)



$$V_{th} = 3V$$

$$K = 1 \text{ mA/V}^2$$

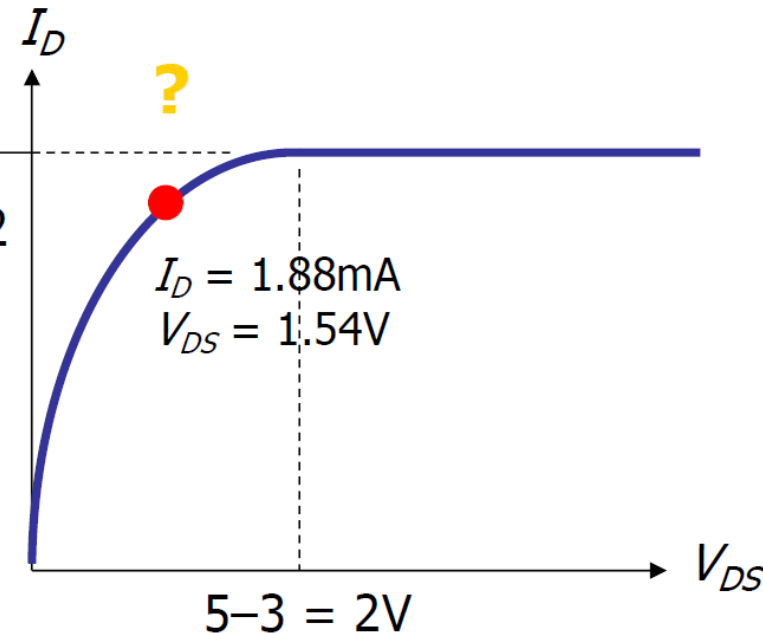
$$I_D = 0.5 \times 2^2$$

$$= 2\text{mA}$$

$$V_{DS} = 10 - 4.5 \times 2$$

$$= 1V$$

Oops!!



So, it is in the triode region.

$$I_D = K/2 V_{DS} [2 (V_{GS} - V_{th}) - V_{DS}]$$

$$= 0.5 V_{DS} (4 - V_{DS})$$

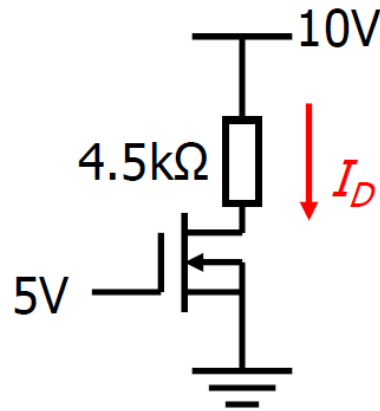
$$= 0.5 (10 - 4.5 I_D) (4 - 10 + 4.5 I_D)$$

i.e.,  $10.125 I_D^2 - 35 I_D + 30 = 0$

$$I_D = 1.8845\text{mA} \text{ or } 1.5742\text{mA}$$

And 1.88mA gives  $V_{DS} = 10 - 4.5 \times 1.88 = 1.54V$ .  
But 1.57mA gives  $V_{DS} = 10 - 4.5 \times 1.57 = 2.95V$ !!

# Example (biasing in saturation)



$$V_{th} = 3V$$

$$K = 0.5 \text{ mA/V}^2$$

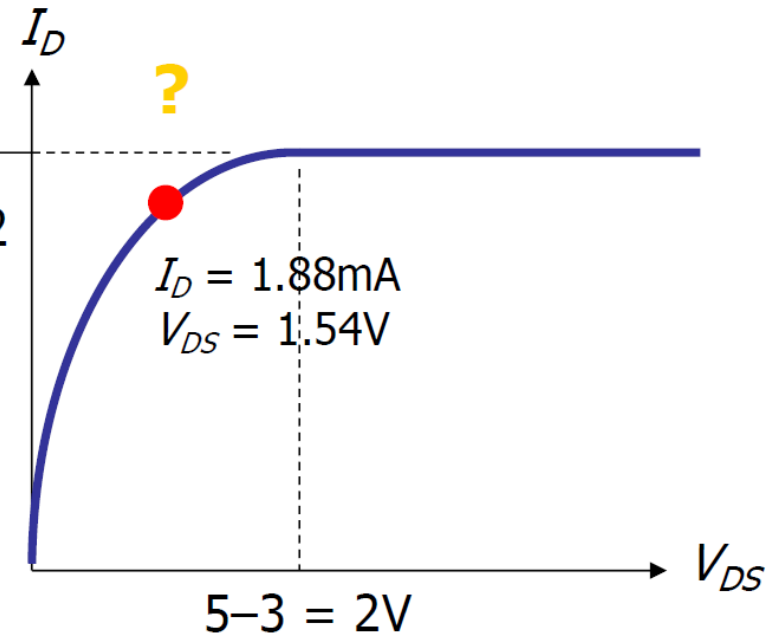
$$I_D = 0.5 \times 2^2$$

$$= 2 \text{ mA}$$

$$V_{DS} = 10 - 4.5 \times 2$$

$$= 1 \text{ V}$$

Oops!!



So, it is in the triode region.

$$I_D = K/2 V_{DS} [2 (V_{GS} - V_{th}) - V_{DS}]$$

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# Enhancement and depletion MOSFET

---

What we have just studied is the **enhancement MOSFET**.

**Enhancement** — the channel is originally not conducting when gate voltage is 0, and we have to apply a positive gate voltage (bigger than a threshold  $V_{th}$ ) to make it conduct (enhance it).

**Depletion** — In fact, we also have another kind of MOSFET, in which the channel can conduct even when gate voltage is not applied. Then, we need to apply reverse gate voltage to cut it off. This is called **depletion MOSFET**.

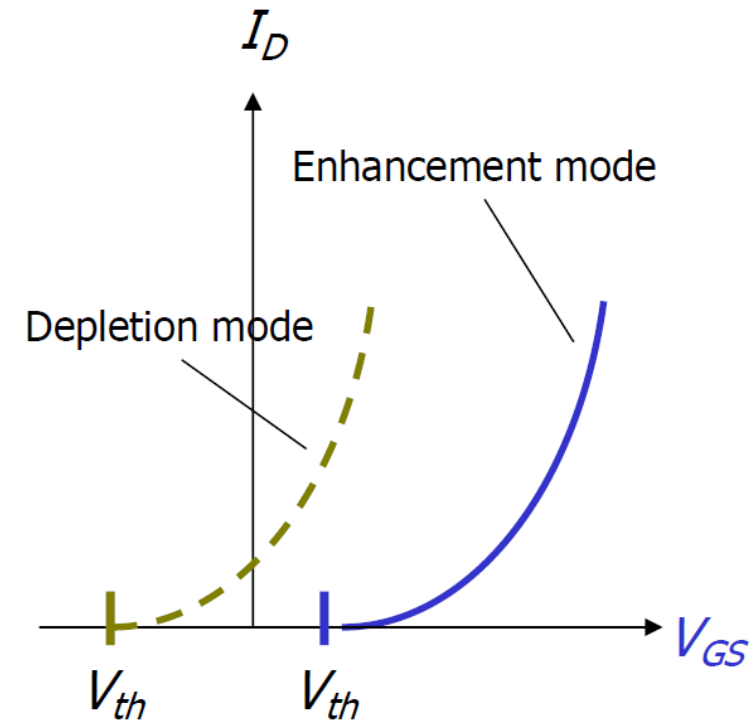
NOTE THAT DUE TO A SEMICONDUCTOR DOPING PROPERTY,  
For n-channel MOSFET, both enhancement and depletion types can be made.  
For p-channel MOSFET, only enhancement type can be made.

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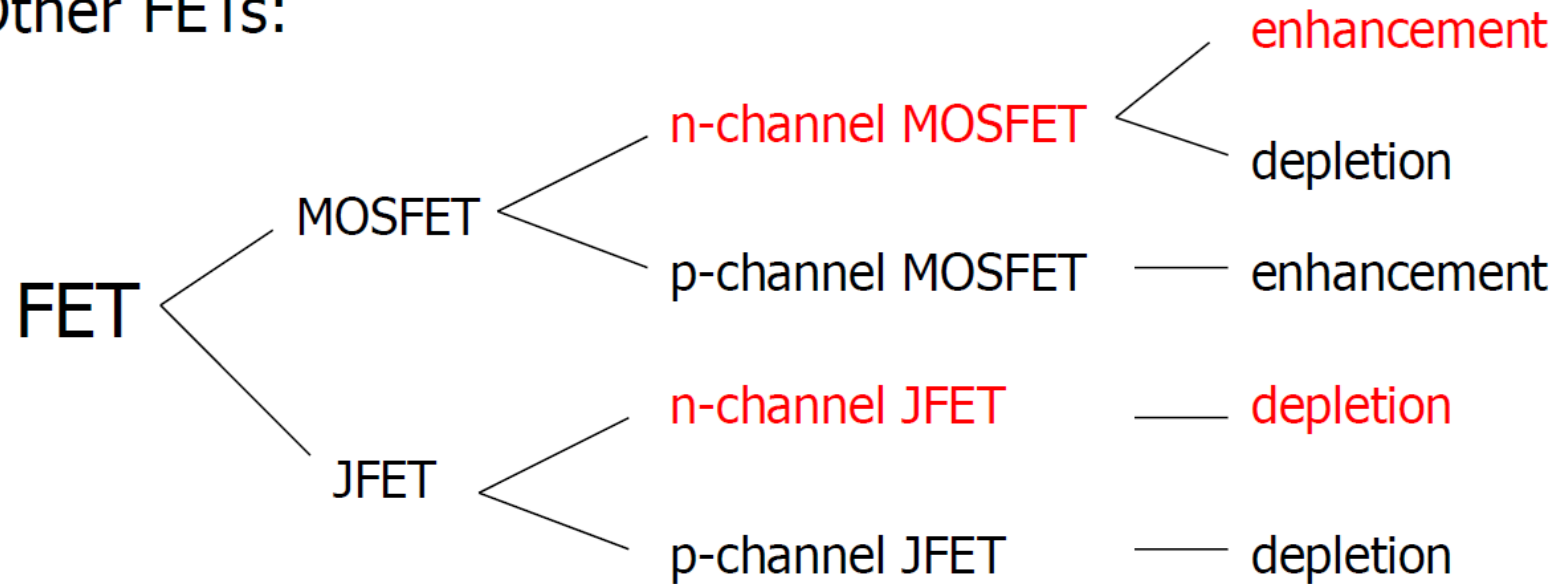


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For p-channel MOSFET, only enhancement type can be made.

# Other FETs

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Other FETs:



# p-channel FETs

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Operation is almost the same as n-channel FETs.

Voltage polarity and current direction reversed.

BUT... for p-channel devices,

the carriers are holes (not electrons). So, mobility is lower and minority carrier lifetime shorter.

Consequence: p-channel devices are usually POORER!  
higher threshold voltage, higher resistance, and lower current capability.