Regions of Operation of BJT and MOSFET

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EE2002 Analog Electronics

Lesson Objectives

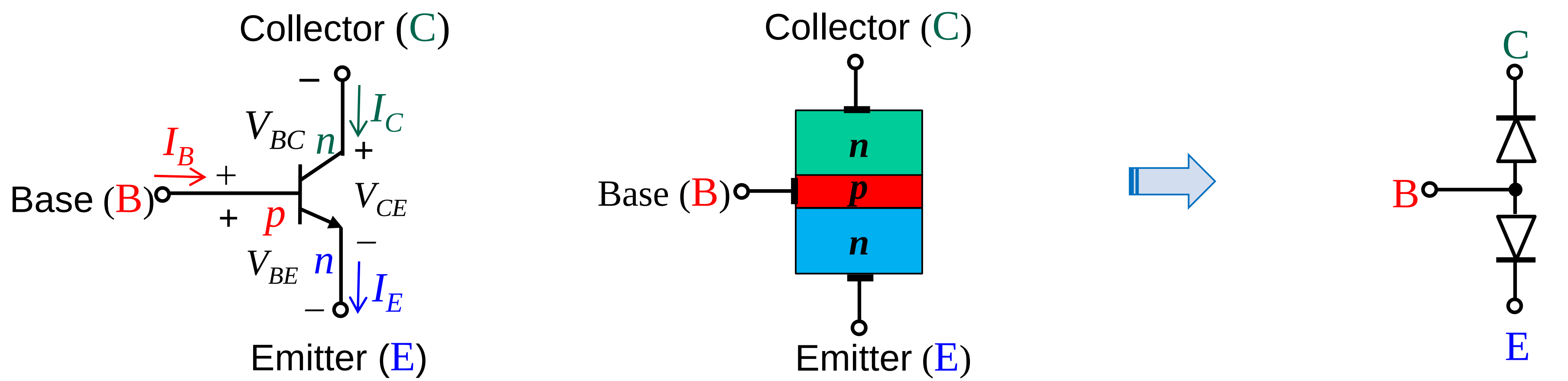
At the end of this lesson, you should be able to:

- Identify the symbols used to represent transistors in circuit schematics
- Identify the three different operation regions of BJT and MOSFET
- Describe the criteria for the different operation regions of BJT and MOSFET
- Discuss the i-v characteristics of MOSFET
- Analyse circuits used to bias BJT and MOSFET transistors into various regions of operation

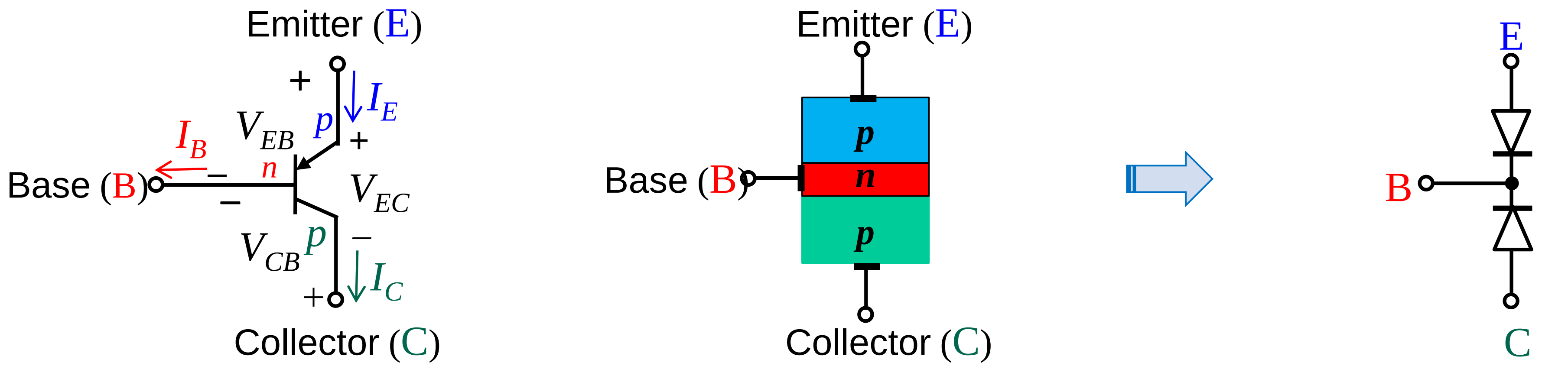
NPN and PNP BJTs

Don't get it

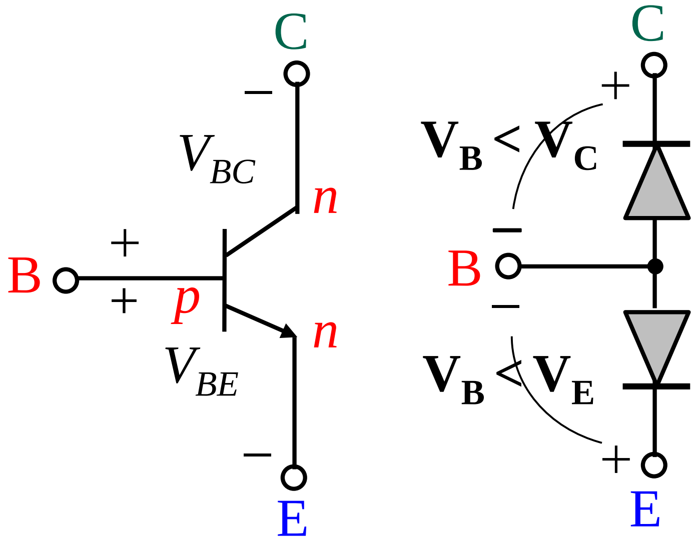
npn



pnp



Operation Regions of BJT

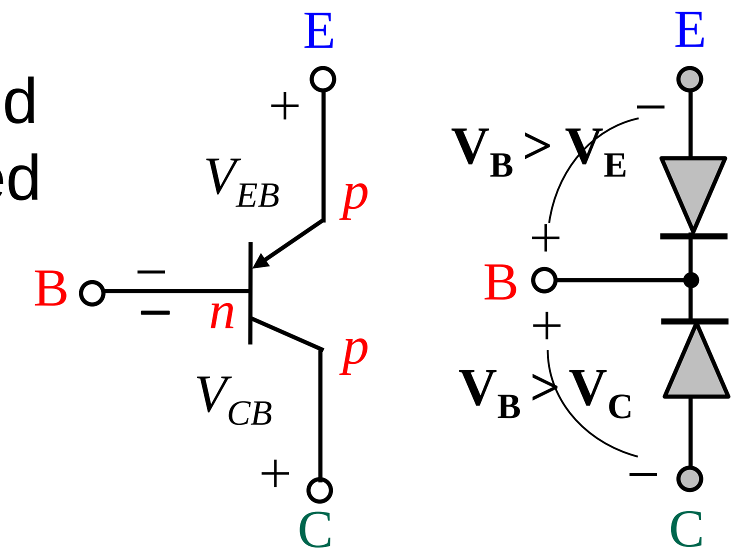


Cutoff region

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

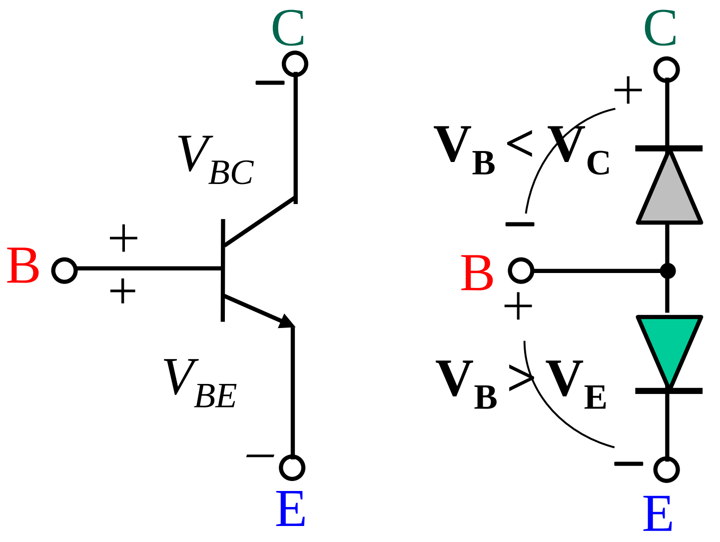
$I_C = 0$

$\Rightarrow$ **Open Switch**



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

Operation Regions of BJT



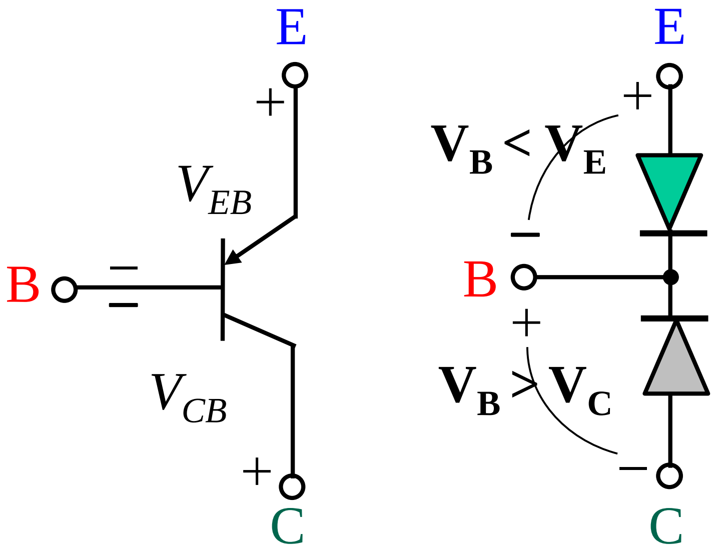
Forward-active region

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

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

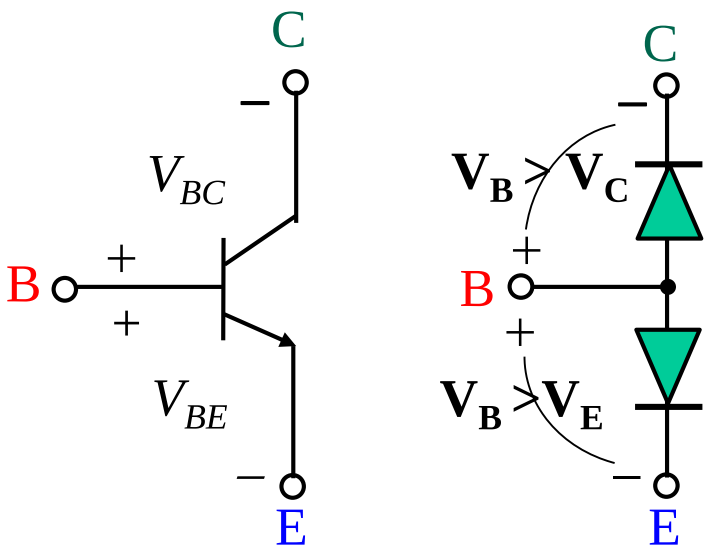
$\Rightarrow$ **Good amplifier**

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



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

Operation Regions of BJT



Saturation region

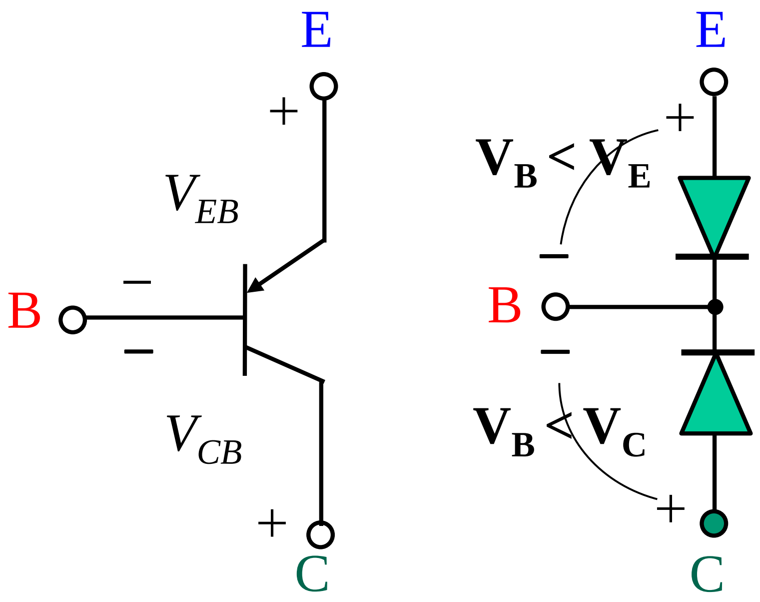
BEJ (npn) forward biased
BCJ (npn) forward biased

⇒ **Closed switch**

$\Rightarrow V_{BE} \approx 0.7\text{ V}$

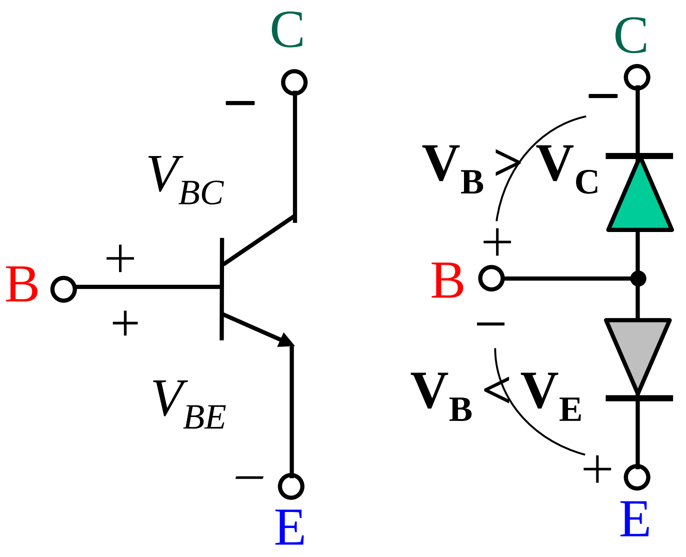
$V_{BC} = 0.4\sim 0.5\text{ V}$

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



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

Operation Regions of BJT

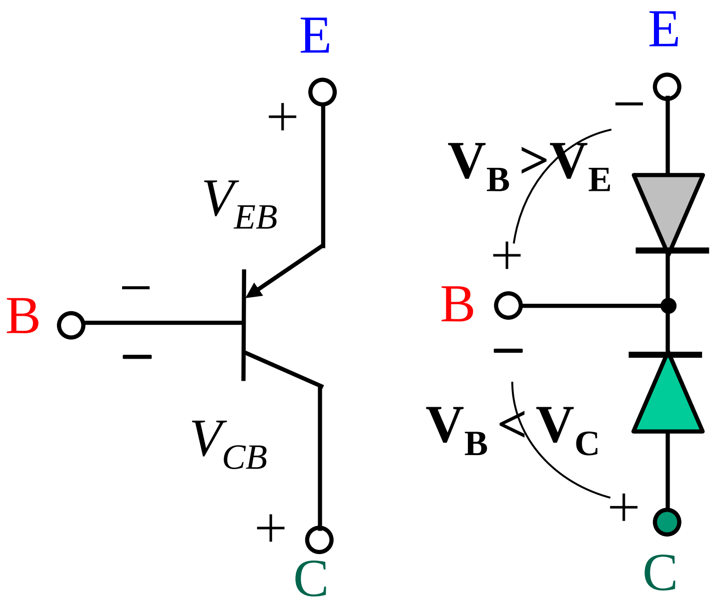


Reverse-active region

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

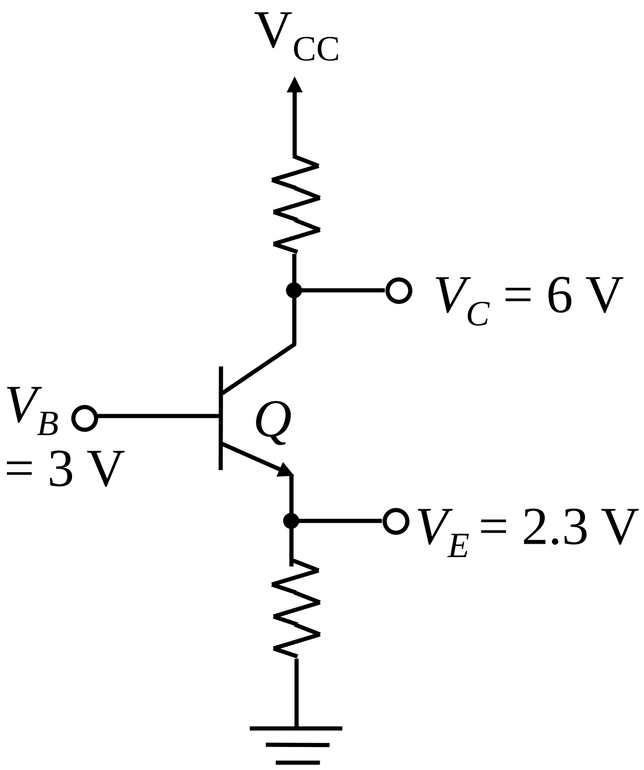
$\Rightarrow$ **Weak amplifier**

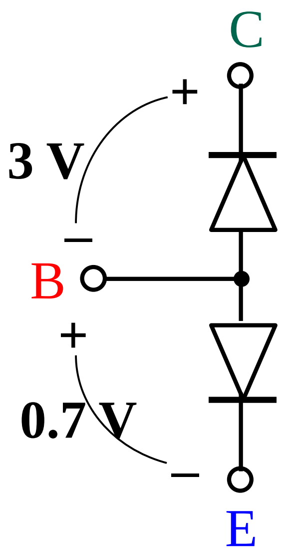
$\Rightarrow$ **Normally not use**



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

BJT Bias Analysis: Active Mode





$$V_{BE} = V_B - V_E = 3 - 2.3 = 0.7 \text{ V}$$

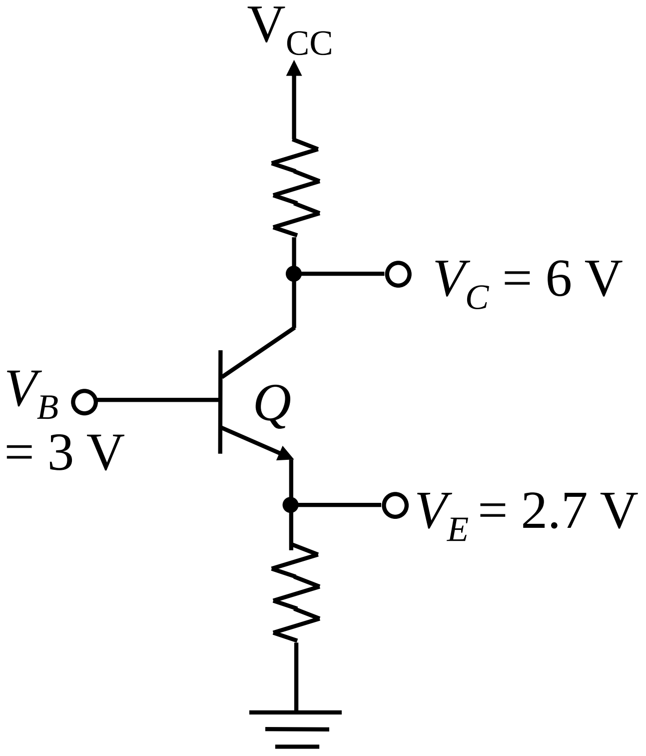
$$V_{BC} = V_B - V_C = 3 - 6 = -3 \text{ V}$$

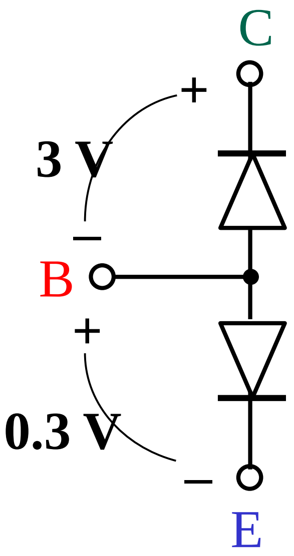
BCJ is reversed biased by 3 V

BEJ is forward biased by 0.7 V

Q in active mode and can be used as linear amplifier.

BJT Bias Analysis: Cutoff Mode





$$V_{BE} = V_B - V_E = 3 - 2.7 = 0.3 \text{ V}$$

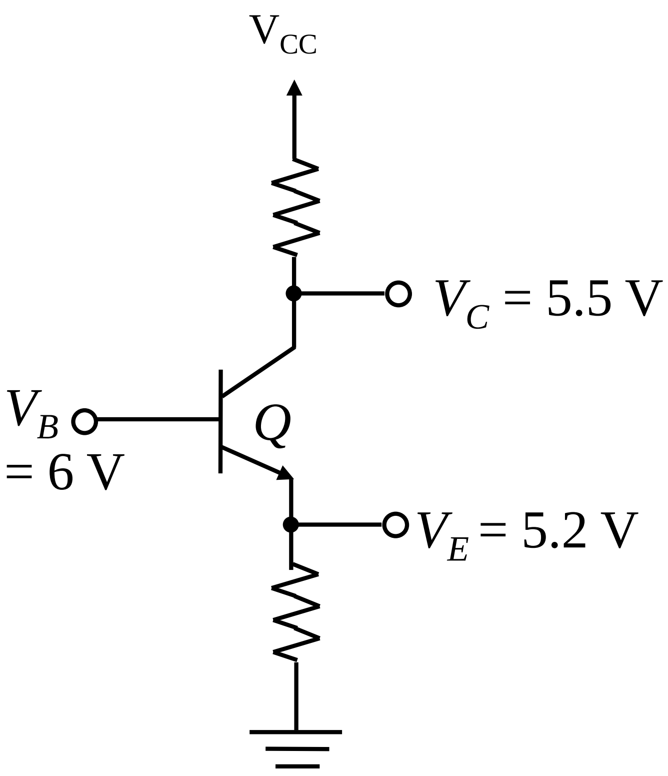
$$V_{BC} = V_B - V_C = 3 - 6 = -3 \text{ V}$$

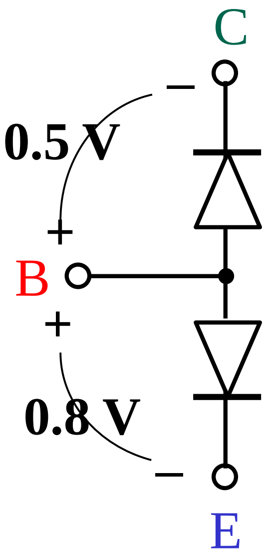
BCJ is reversed biased by 3 V

BEJ is forward biased by 0.3 V but inadequate to turn on BEJ

$\Rightarrow$ Q is cutoff.

BJT Bias Analysis: Saturation Mode





$$V_{BE} = V_B - V_E = 6 - 5.2 = 0.8 \text{ V}$$

$$V_{BC} = V_B - V_C = 6 - 5.5 = 0.5 \text{ V}$$

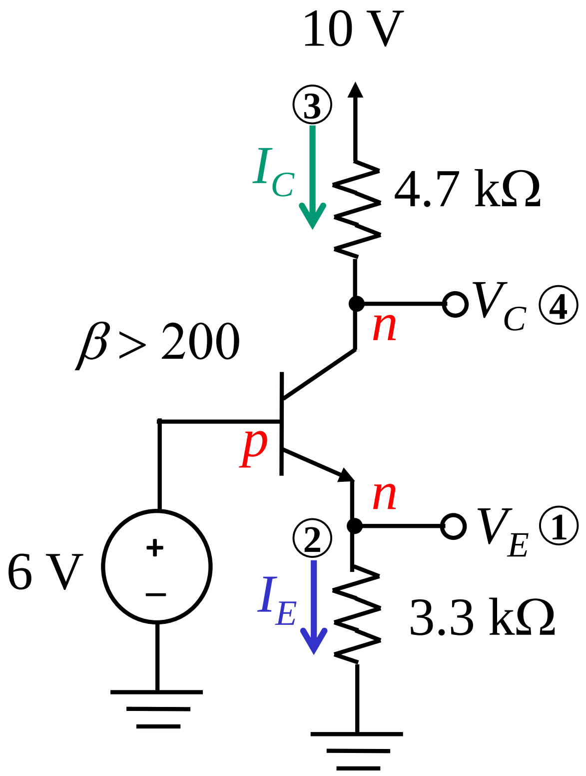
BCJ is forward biased by 0.5 V

BEJ is forward biased by 0.8 V

$$V_{CE} = V_{CB} + V_{BE} = -0.5 + 0.8 = 0.3 \text{ V}$$

Q is in Saturation.

BJT Bias Analysis: Determine DC Node Voltages and Branch Currents



Assume active-mode operation,

$$V_E = V_B - V_{BE}$$
$$= 6 - 0.7$$
$$= 5.3 \text{ V}$$

$$I_E = \frac{5.3}{3.3}$$
$$= 1.6 \text{ mA}$$

Since β is very large,

$$\alpha \approx 1 \Rightarrow I_C \approx I_E = 1.6 \text{ mA}$$

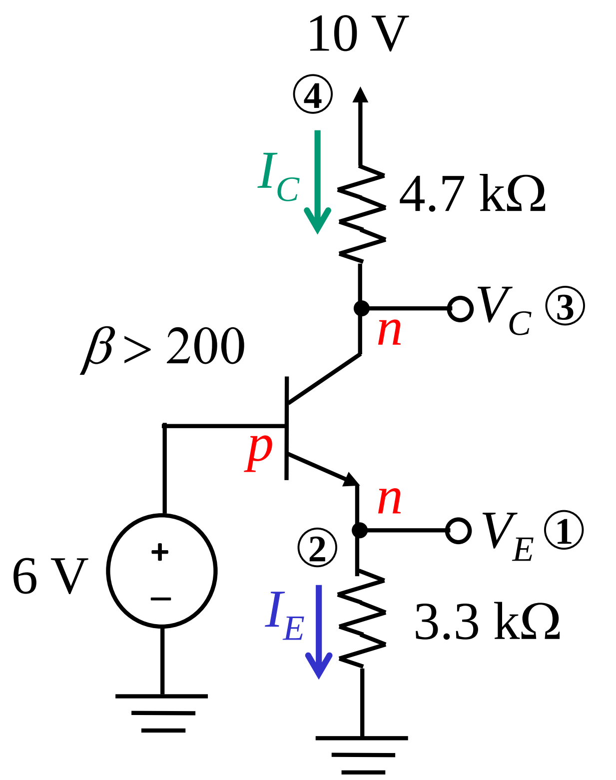
$$V_C = 10 - 1.6 \times 4.7$$
$$= 2.48 \text{ V}$$

$$V_{BC} = V_B - V_C$$
$$= 6 - 2.48$$
$$= 3.52 \text{ V}$$

=> Wrong assumption! Q is in saturation mode.

BJT Bias Analysis: Determine DC Node Voltages and Branch Currents

(Cont.)



In saturation region,
$V_{CE} \approx 0.2$ to 0.3.

Assume $V_{CE(SAT)} = 0.2$ V,

$$V_E = 6 - 0.7 = 5.3 \text{ V} \quad \text{and} \quad I_E = \frac{5.3}{3.3} = 1.6 \text{ mA}$$

$$V_C = V_E + V_{CE(SAT)} = 5.3 + 0.2 = 5.5 \text{ V}$$

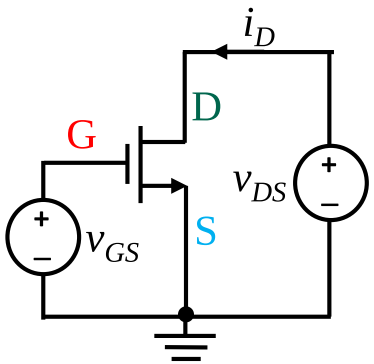
$$I_C = \frac{10 - 5.5}{4.7} = 0.96 \text{ mA}$$

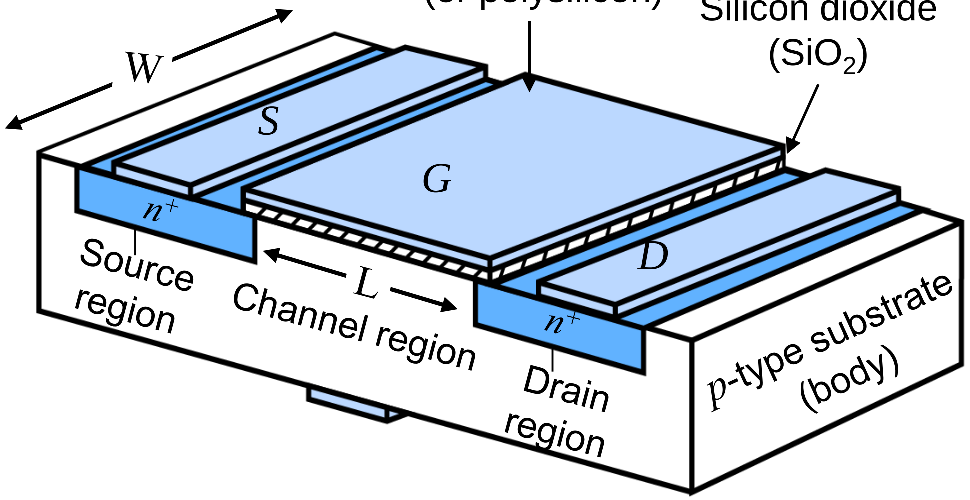
$$I_B = I_E - I_C = 1.6 - 0.96 = 0.64 \text{ mA}$$

$$\beta_{\text{forced}} = \frac{I_C}{I_B} = \frac{0.96}{0.64} = 1.5$$

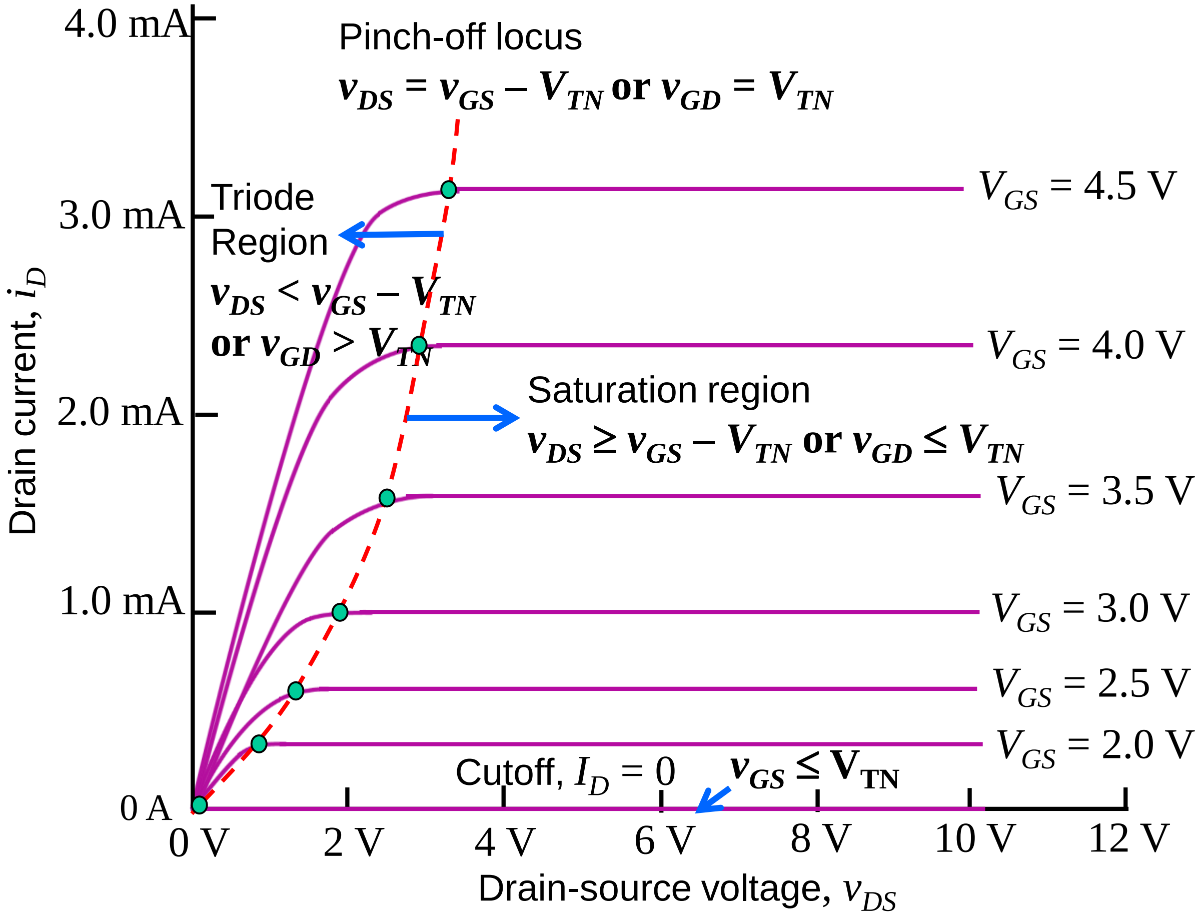
=> In saturation, $I_c \neq \beta I_B$.

nMOS Transistor Structure and I-V Characteristics

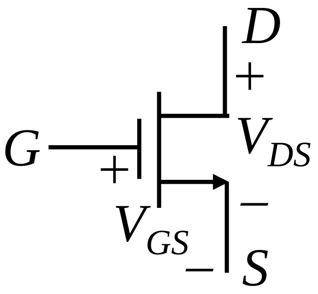




V_{TN}: Threshold Voltage of NMOS; V_{TN} = 1 V for this graph

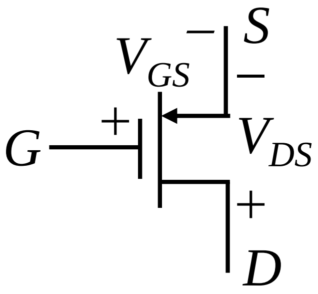


MOSFET Biasing for Different Regions of Operation



$V_{TN} > 0$

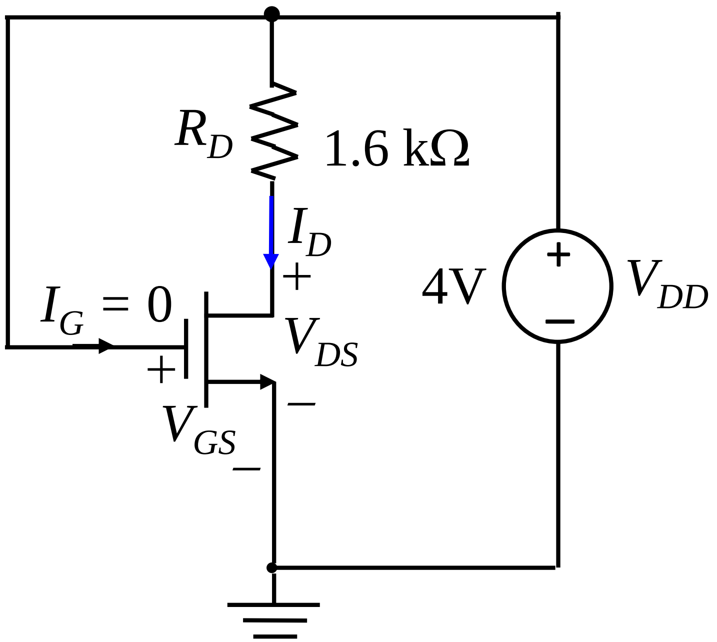
What is V(tn)



$V_{TP} < 0$

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

MOSFET Bias Analysis: Triode Region



$K_n = 250\ \mu\text{A/V}^2$

$V_{TN} = 1\ \text{V}$

$V_{GS} = V_{DD} = 4\ \text{V}.$

Assume transistor is saturated,

$$I_D = \frac{K_n}{2}(V_{GS} - V_{TN})^2$$

$$= \frac{250\ \mu}{2}(4-1)^2$$

$$= 1.13\ \text{mA}$$

$$V_{DD} = I_D R_D + V_{DS}$$

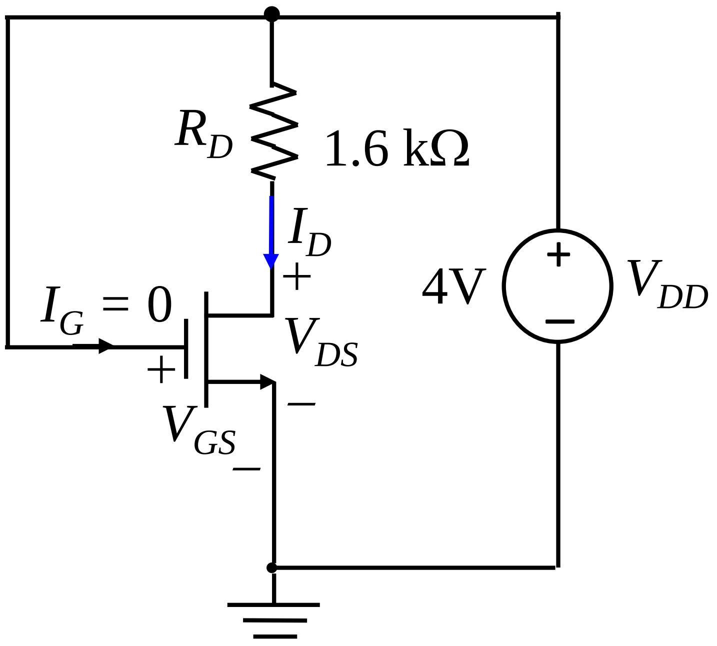
$$V_{DS} = 4 - 1.6 \times 1.13$$

$$= 2.19\ \text{V}$$

But $V_{DS} = 2.19 < V_{GS} - V_{TN} = 3$

Saturation region assumption is incorrect.

MOSFET Bias Analysis: Triode Region



$K_n = 250\ \mu A/V^2$
$V_{TN} = 1\ V$

(Cont…)

Using triode region equation,

$$I_D = K_n\left(V_{GS} - V_{TN} - \frac{V_{DS}}{2}\right)V_{DS}$$

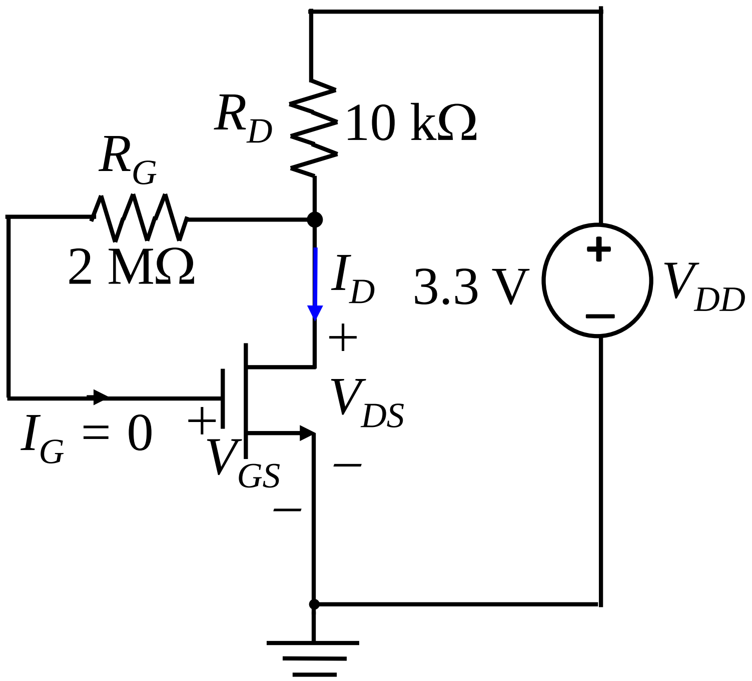
$$V_{DS} = 4 - 1600 \times 250\mu\left(4 - 1 - \frac{V_{DS}}{2}\right)V_{DS}$$

$$0.2V_{DS}^2 - 2.2V_{DS} + 4 = 0$$

$V_{DS} = 8.7$ (infeasible) or $\mathbf{2.3\ V}$ **(<** $V_{GS} - V_{TN} = 3$)

Hence, $V_{DS} = \mathbf{2.3\ V}$ and $I_D = \mathbf{1.06\ mA}$

MOSFET Bias Analysis: nMOS Two-Resistor Biasing



$K_n = 260\ \mu A/V^2$
$V_{TN} = 1$ V

Since $I_G = 0$, $V_{DS} = V_{GS}$.

Transistor is saturated because $V_{DS} > V_{GS} - 1$

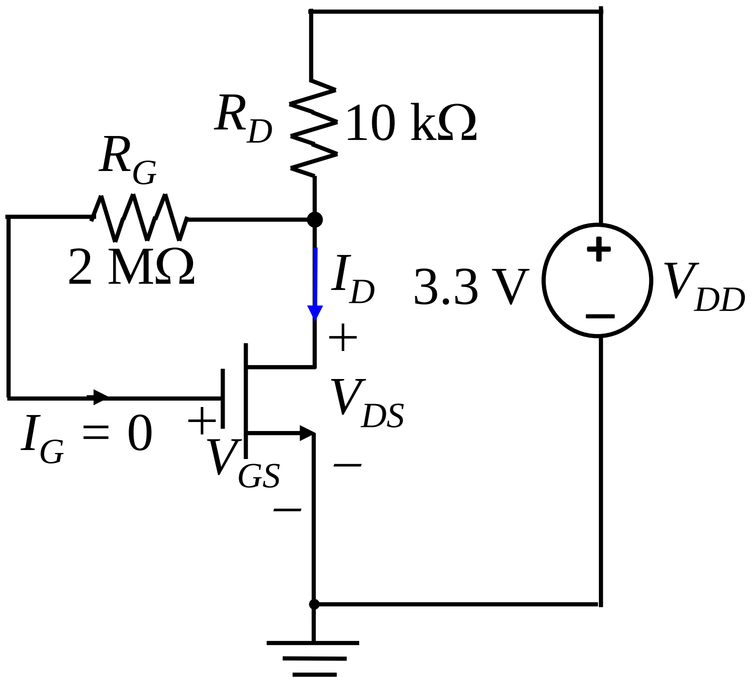
$$I_D = \frac{K_n}{2}(V_{GS} - V_{TN})^2$$

$$= \frac{260\ \mu}{2}(V_{GS} - 1)^2$$

$$V_{DS} = V_{DD} - I_D R_D$$

$$V_{GS} = 3.3 - \frac{260\ \mu}{2}(V_{GS} - 1)^2 \times 10000$$

MOSFET Bias Analysis: nMOS Two-Resistor Biasing



$K_n = 260\ \mu\text{A/V}^2$
$V_{TN} = 1\text{ V}$

(Cont.)

$$1.3V_{GS}^2 - 1.6V_{GS} - 2 = 0$$

$$V_{GS} = \frac{1.6 \pm \sqrt{1.6^2 - 4 \times 1.3 \times (-2)}}{2 \times 1.3}$$

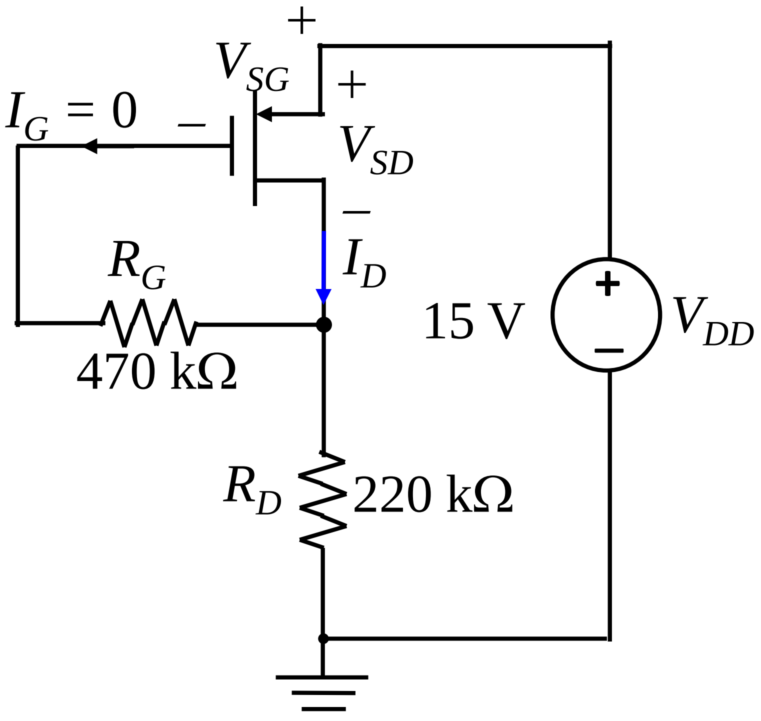
$$= -0.77\text{ V or } 2\text{ V}$$

$V_{GS} = -0.77$ V implies MOSFET is cutoff and contradicts the observation.

$V_{GS} = 2$ V and $V_{DS} = V_{GS} = 2$ V.

$I_D = 130\ \mu \times (2-1)^2 = 130\ \mu\text{A}$

MOSFET Bias Analysis: pMOS Two-Resistor Biasing



$K_p = 50\ \mu A/V^2$
$V_{TP} = -2$ V

Since $I_G = 0$, $V_{SG} = V_{SD}$.

Transistor is saturated because $|V_{DS}| > |V_{GS}| - |-2|$

$$I_D = \frac{K_p}{2}\left(|V_{GS}| - |V_{TP}|\right)^2$$

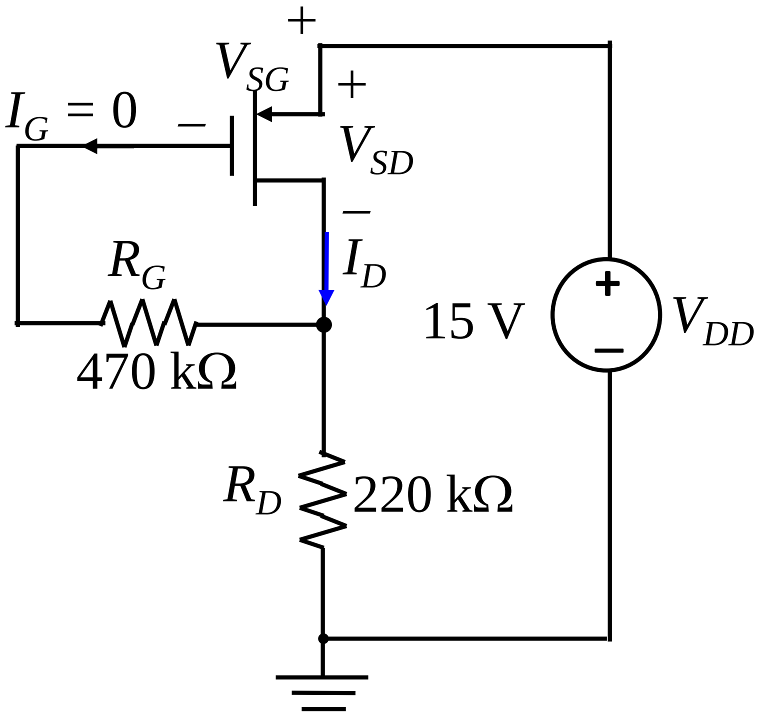
$$= \frac{50\ \mu}{2}\left(|V_{GS}| - 2\right)^2$$

$$|V_{DS}| = V_{DD} - I_D R_D$$

$$|V_{GS}| = 15 - 25\times 10^{-6}\left(|V_{GS}| - 2\right)^2 \times 220\times 10^3$$

$$= 15 - 5.5\left(|V_{GS}| - 2\right)^2$$

MOSFET Bias Analysis: pMOS Two-Resistor Biasing



$K_p = 50\ \mu A/V^2$

$V_{TP} = -2$ V

(Cont.)

$$5.5|V_{GS}|^2 - 21|V_{GS}| + 7 = 0$$

$$|V_{GS}| = \frac{21 \pm \sqrt{21^2 - 4\times 5.5\times 7}}{2\times 5.5}$$

$$= 0.37 \text{ V or } 3.45 \text{ V}$$

$|V_{GS}| = 0.37$ V $< |V_{TP}| = 2$ V,

$|V_{GS}| = 3.45$ V or $V_{SG} = 3.45$ V.

$V_{DS} = V_{GS} = -3.45$ V.

$I_D = 25\ \mu \times (3.45 - 2)^2 = 52.5\ \mu A$