Operation Modes of BJT and MOSFET Cutoff,Active and Saturation

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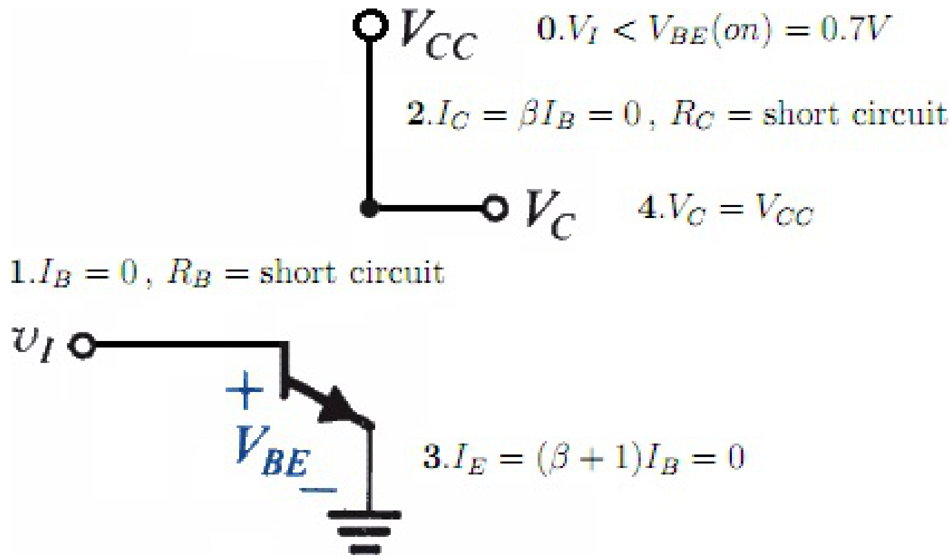
Reference
Sedra and Smith *Microelectronic Circuit*
Neamen *Microelectronics*

1 BJT

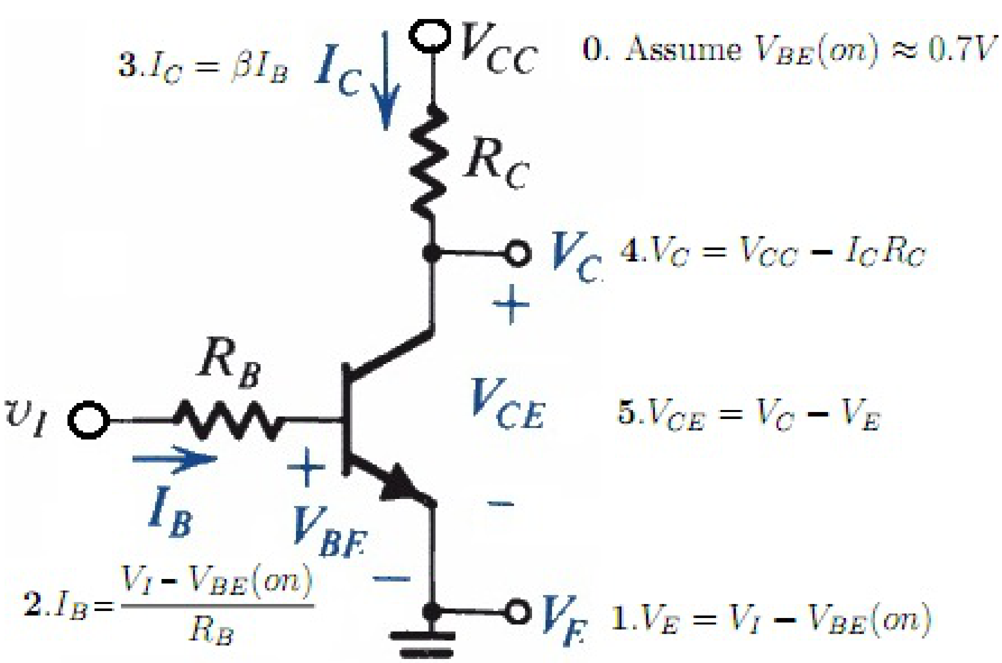
1.1 Cutoff Mode

- When $V_I < V_{BE}(on)$, it can not turn on the BE-Junction diode, the BJT is in cutoff mode



1.2 Forward Active Mode

- When $V_I > V_{BE}(on)$, $I_B \neq 0$ and $V_{CE} > 0.2V$



1.3 Saturation Mode

Re-consider the V_C again

$$V_C = V_{CC} - I_C R_C$$

$$= V_{CC} - \beta I_B R_C = V_{CC} - \beta R_C \left(\frac{V_I - V_{BE}(on)}{R_B} \right)$$

$$= \left(\underbrace{V_{CC} + \beta \frac{R_C}{R_B} V_{BE}(on)}_{Constant} \right) - \left(\underbrace{\beta \frac{R_C}{R_B}}_{Constant} \right) V_I$$

$$= A - BV_I$$

If V_I increase, V_C decrease

Re-consider the V_{CE} again

$$V_{CE} = V_C - V_E$$

$$= \left(\underbrace{V_{CC} + \beta \frac{R_C}{R_B} V_{BE}(on)}_{Constant} \right) - \left(\underbrace{\beta \frac{R_C}{R_B}}_{Constant} \right) V_I - [V_I - V_{BE}(on)]$$

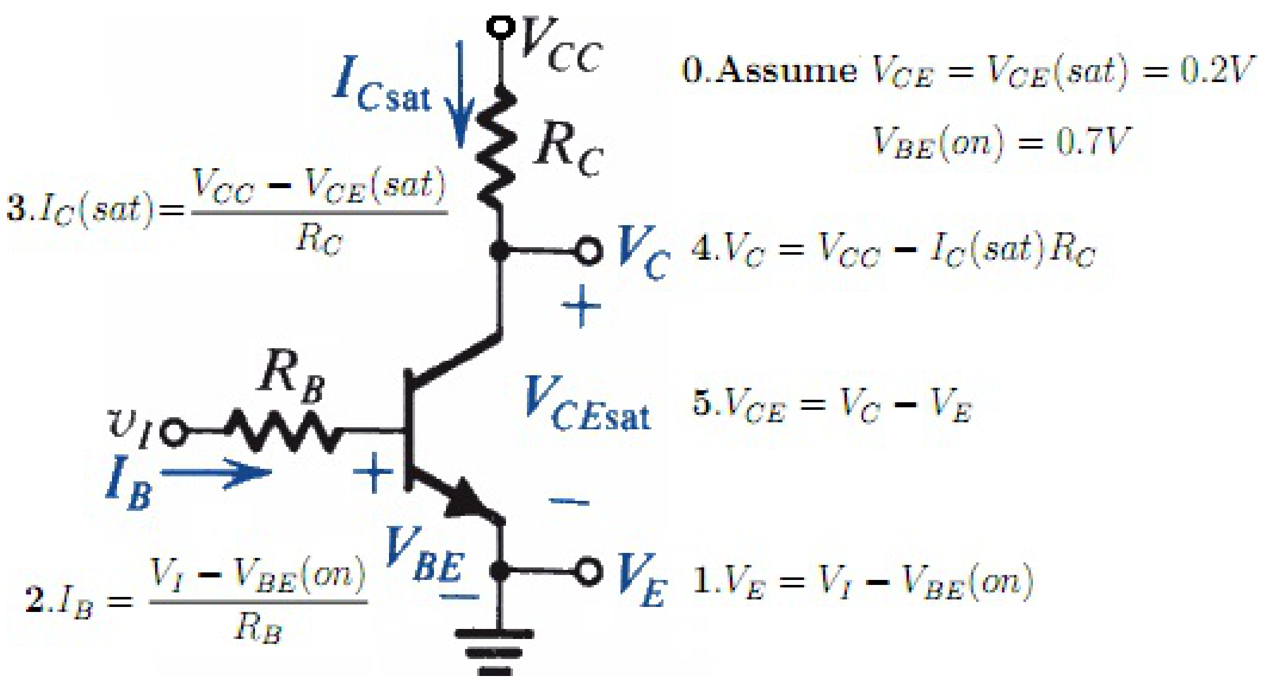
$$= \left(\underbrace{V_{CC} + \left(\beta \frac{R_C}{R_B} + 1 \right) V_{BE}(on)}_{Constant} \right) - \left(\underbrace{\beta \frac{R_C}{R_B} - 1}_{Constant} \right) V_I$$

$$= A' - B'V_I$$

If V_I increase, V_{CE} decrease

When V_{CE} drop down to a value that I_C is independent of I_B , the BJT is now working in saturation mode.

In saturation mode :



V_{CE} in this case will be smaller than $V_{CE}(sat) = 0.2V$:

$$V_{CE} = V_C - V_E$$

$$= (V_{CC} - I_C(sat)R_C) - (V_I - V_{BE}(on))$$

$$= (V_{CC} + V_{BE}(on)) - V_I - I_C(sat)R_C$$

$$V_{CE} = (V_{CC} + V_{BE}(on)) - V_I - \frac{V_{CC} - V_{CE}(sat)}{R_C} R_C$$

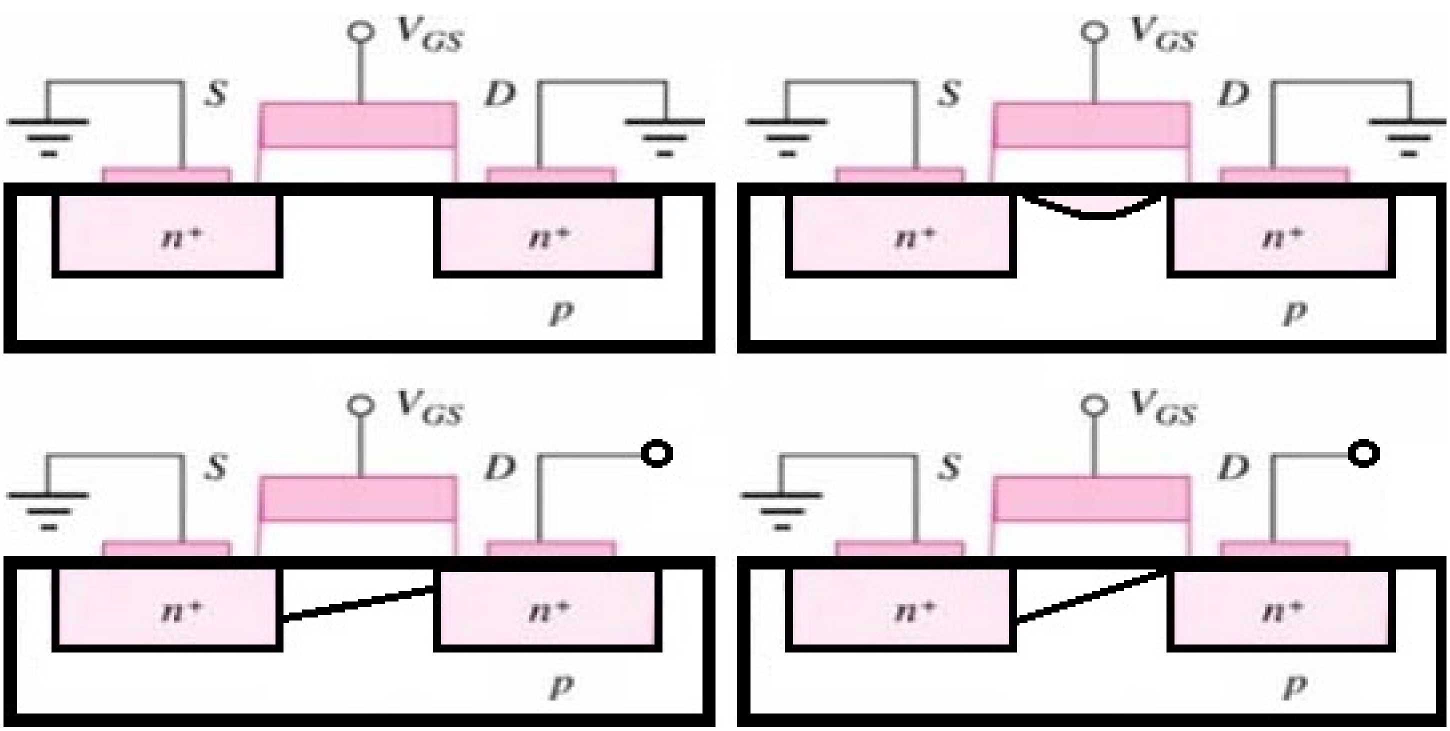
$$V_{CE} = V_{CE}(sat) - \left(\underbrace{V_I - V_{BE}(on)}_{>0} \right)$$

$V_I > V_{BE}(on)$, otherwise, cutoff mode (contradiction !), thus $V_I - V_{BE}(on) > 0$, and thus

$$V_{CE} = V_{CE}(sat) - \left(\underbrace{V_I - V_{BE}(on)}_{>0} \right) < V_{CE}(sat)$$

$$V_{CE} < V_{CE}(sat) \approx 0.2V$$

2 MOSFET



2.1 MOSFET Device

2.1.1 Cutoff

When $V_{GS} = 0$, the MOSFET is just like two back-to-back diode, no current, so cut off.
$I_{DS} = 0$
When $V_{GS} > 0$ but $V_{GS} < V_{TN}$, since the MOSFET structure looks like a capacitor, there is some positive charge stored in the metal plate, while in the semiconductor, there is some negative charge. Since the V_{GS} is not large enough , so there is no "$n-$channel" , there is still no current.

2.1.2 Triode / Active

When $V_{GS} > V_{TN}$, there is enough voltage or E-field attraction to establish a $n-$channel in the semiconductor, so the 2 n-semiconductor can now have current pass through. $I_{DS} \neq 0$

- The E-field that cause the current to drift : $E_{DS} = \frac{V_{DS}}{L}$
- Thus the drift velocity is $v_d = \mu_n E_{DS} = \mu_n \frac{V_{DS}}{L}$
- Thus the drift current density (in A/m) is $J_d = Qv_d = Q_{Cap}\mu_n \frac{V_{DS}}{L}$
- Where the Q (in C/m) is the charge that drift in the n-channel, it comes from the charges stored in MOS capacitor Q_{Cap}

Cosider the MOS capacitor $Q_{Cap} = CV_{cap}$

The V_{Cap} is the excess voltage of V_{GS} : $V_{Cap} = V_{GS} - V_{TN}$

$Q_{Cap} = C\left(V_{GS} - V_{TN}\right)$

$J_d = C\left(V_{GS} - V_{TN}\right)\mu_n \frac{V_{DS}}{L}$

$I = J_d W = C\mu_n \frac{W}{L}\left(V_{GS} - V_{TN}\right)V_{DS} = k_n \frac{W}{L}\left(V_{GS} - V_{TN}\right)V_{DS}$ (In the S-side)

$I = J_d W = C\mu_n \frac{W}{L}\left(V_{GS} - V_{TN}\right)V_{DS} = k_n \frac{W}{L}\left(V_{GS} - V_{TN} - V_{DS}\right)V_{DS}$ (In the D-side)

In the middle of the device, assume linear relationship, the average current

$$I_{DS} = k_n \frac{W}{L}\left(V_{GS} - V_{TN} - \frac{V_{DS}}{2}\right)V_{DS}$$

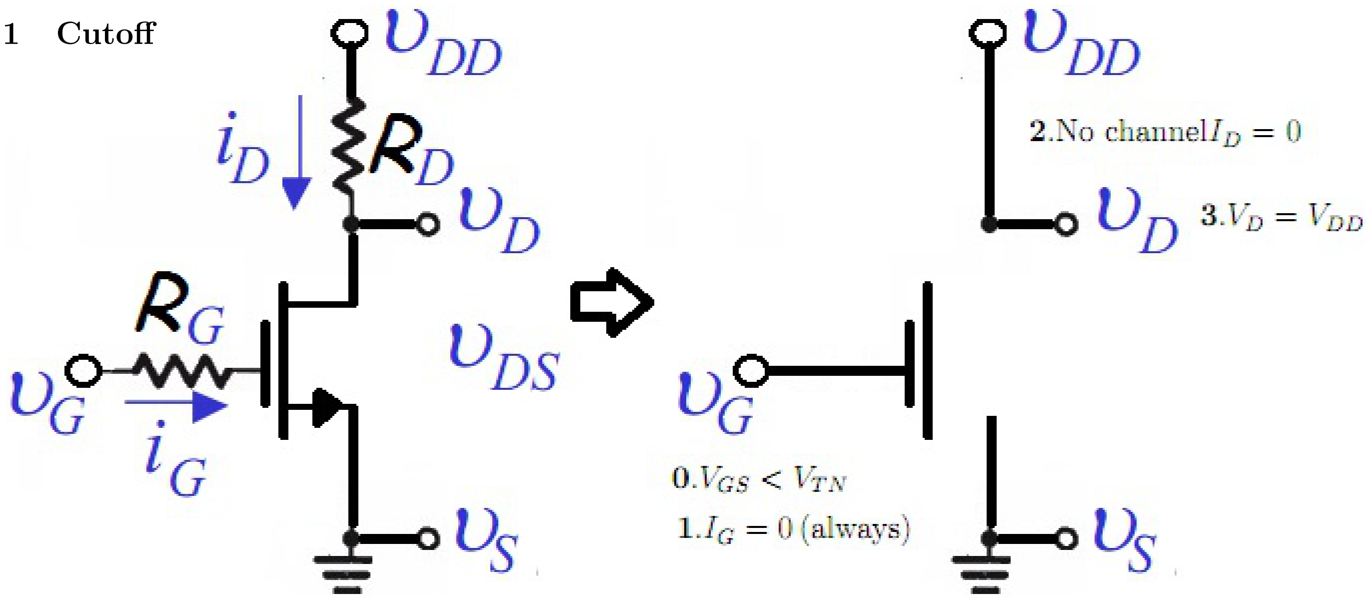
2.1.3 Saturation

When $V_{DS} = V_{GS} - V_{TN}$

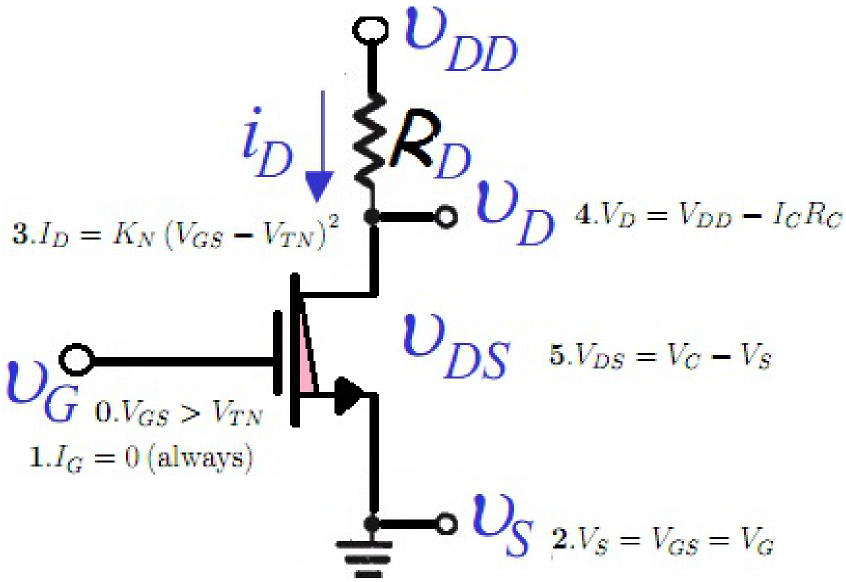
$I_{DS} = k_n \frac{W}{L}\left(V_{GS} - V_{TN} - \frac{V_{GS} - V_{TN}}{2}\right)\left(V_{GS} - V_{TN}\right) = \frac{k_n}{2}\frac{W}{L}\left(V_{GS} - V_{TN}\right)^2 = K_n\left(V_{GS} - V_{TN}\right)^2$

2.2 MOSFET Circuit Operation

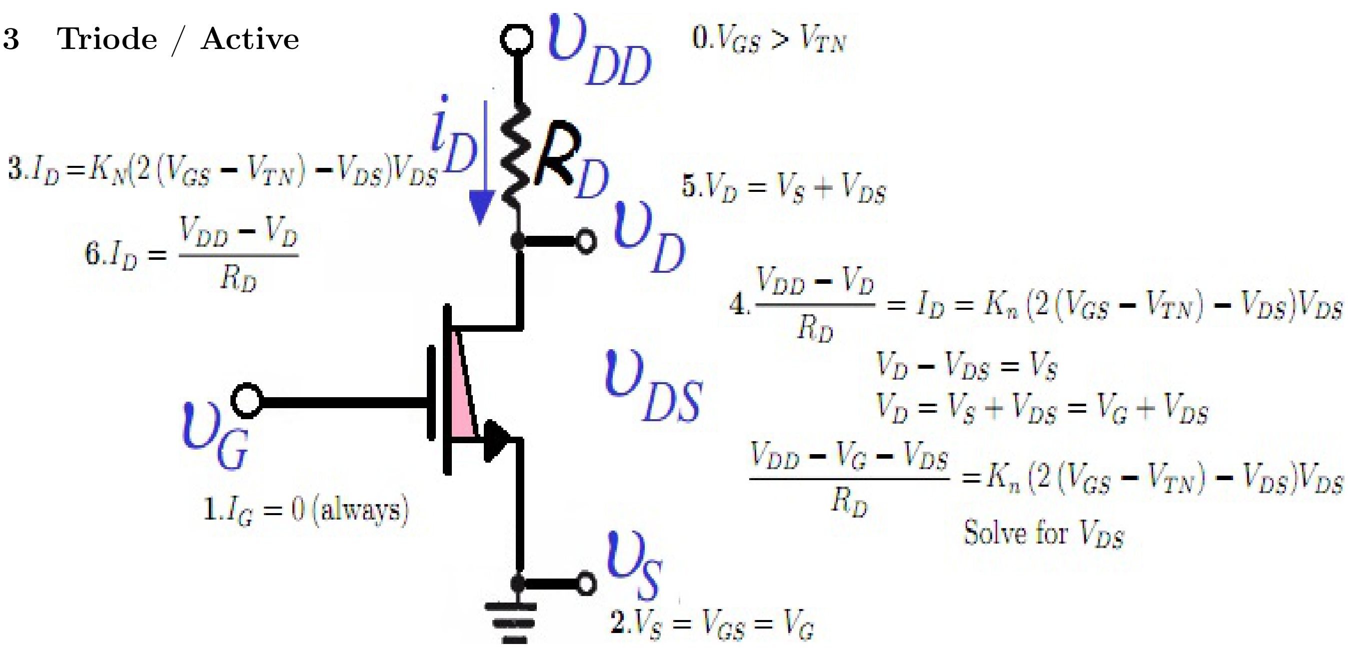
2.2.1 Cutoff



2.2.2 Saturation



2.2.3 Triode / Active



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