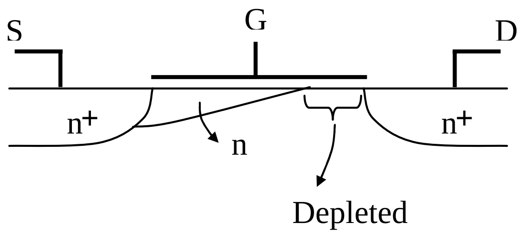
As you know increase V_{DS} → your channel narrows down close to drain until it pinches off.

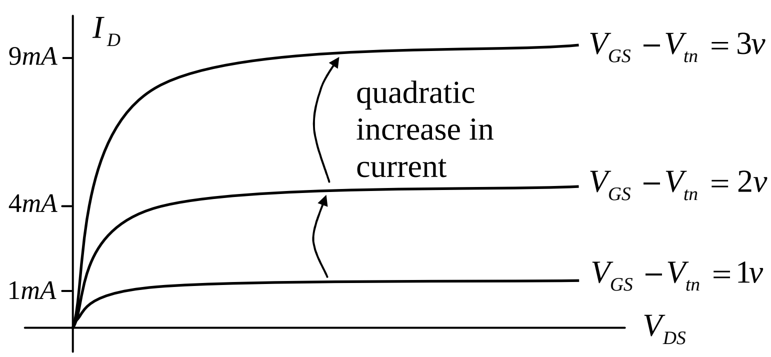


→ current saturates.

Set $V_{DS} = V_{GS} - V_{th}$ in equation (I)

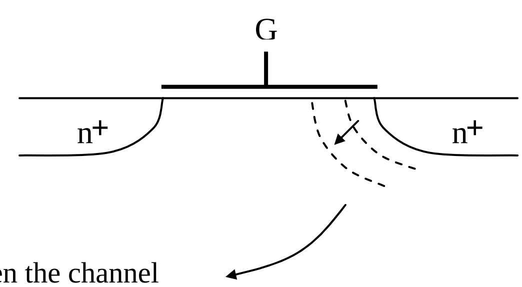
→ $I_D = \mu_n C_{ox} \dfrac{W}{2L}(V_{GS} - V_{th})^2$ independent of V_{DS}.

Condition for pinch off: $V_{DS} > V_{GS} - V_{th}$.



<u>Secondary effects</u>

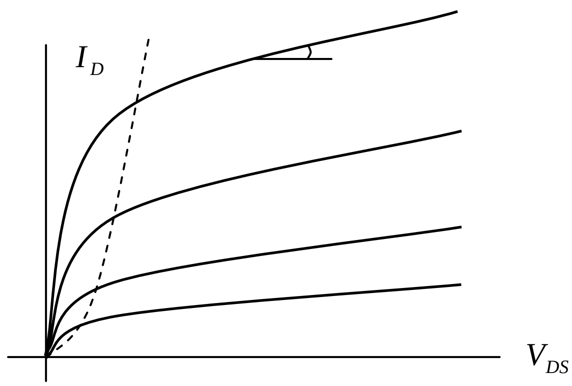
1. Channel length modulation



By changing the V_{DS} you effectively shorten the channel length → current increases.

$$I_D = \mu_n C_{ox} \frac{W}{2L} (V_{GS} - V_{th})^2 \left(1 + \lambda\left[V_{DS} - (V_{GS} - V_{th})\right]\right)$$

$\lambda \equiv \left(V^{-1}\right) \rightarrow$ Channel length modulation coefficient



$\rightarrow$

$$1/R_{out} = \frac{\partial I_D}{\partial V_D} = \lambda I_D$$

$$R_{out} = \frac{1}{\lambda I_D}$$

2. Body effect

Change in the threshold voltage as you bias the substrate.

$$V_{th} = V_{th0} + \gamma\left(\sqrt{V_{SB} + |2\Phi_F|} - \sqrt{|2\Phi_F|}\right)$$

γ : Body effect constant

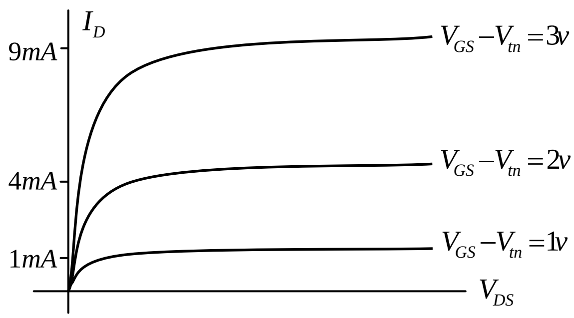
V_{th} increases as you increase the source-body voltage

3. Velocity saturation

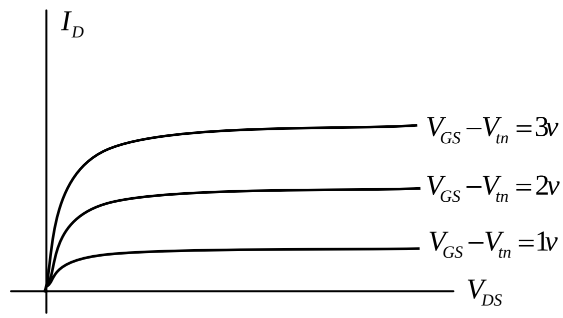
→ present in the short channel devices.

Take triode region equation and substitute V_{DS} with $V_{DS\,sat}$ (constant $\sim 0.3v$).

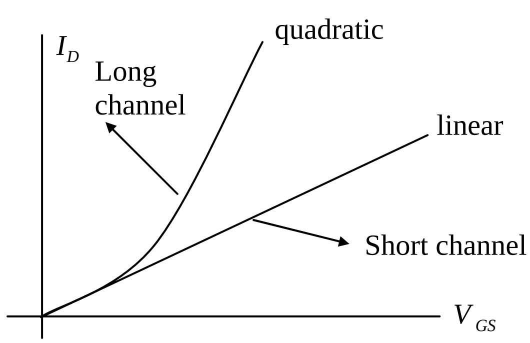
$$I_D = \mu_n C_{ox} \frac{W}{L}\left[(V_{GS} - V_{th})V_{DS\,sat} - \frac{V_{DS\,sat}{}^2}{2}\right]$$ → no longer a function of V_{DS} .



Long channel device → no velocity saturation.



Short channel device



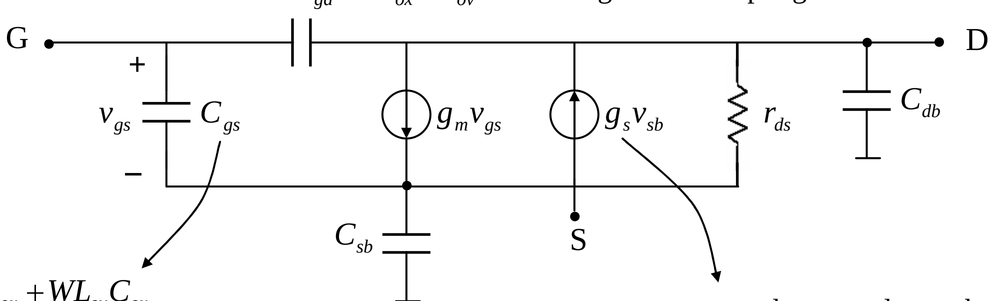
MOS small signal model

$$g_m = \frac{\partial I_D}{\partial V_{GS}} = \mu_n C_{ox}\frac{W}{L}\overbrace{(V_{GS} - V_{th})}^{V_{eff}} \quad \text{, for long channel}$$

$$= \sqrt{2\mu_n C_{ox}\frac{W}{L} I_D}$$

$$g_m = \mu_n C_{ox}\frac{W}{L} V_{DS\,sat} \quad \text{, for short channel}$$

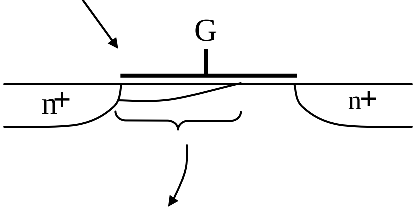
$C_{gd} = C_{ox} W L_{ov} \rightarrow$ length of overlap region.



$\frac{2}{3} W L C_{ox} + W L_{ov} C_{ox}$

body grounded

transconductance due to the body effect



Approximately $2/3$ of L.

$$g_s = \frac{\partial I_D}{\partial V_{SB}} = \frac{\partial I_D}{\partial V_{tn}} \cdot \frac{\partial V_{tn}}{\partial V_{SB}} \rightarrow g_s = \frac{\gamma g_m}{2\sqrt{V_{SB} + 2\Phi_f}}$$

This is a parasitic effect.

If source is grounded do not calculate g_s (although value from above equation is non-zero), but in reality $\Delta V_{SB} = 0 \rightarrow g_s = 0$.

g_s is body effect transconductance.

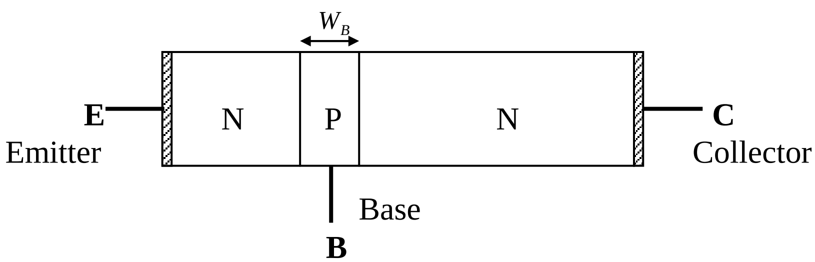
Channel length modulation → $I_D = \mu_n C_{ox} \frac{W}{2L}(V_{GS} - V_{th})^2 \left(1 + \lambda\left[V_{DS} - (V_{GS} - V_{th})\right]\right)$

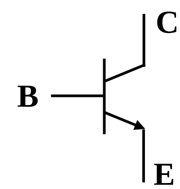
$$\frac{1}{r_{ds}} = \frac{\partial I_D}{\partial V_{DS}} = \lambda \mu_n C_{ox} \frac{W}{2L}(V_{GS} - V_{th})^2 \approx \lambda I_D$$

$$\rightarrow r_{ds} = \frac{1}{\lambda I_D}$$

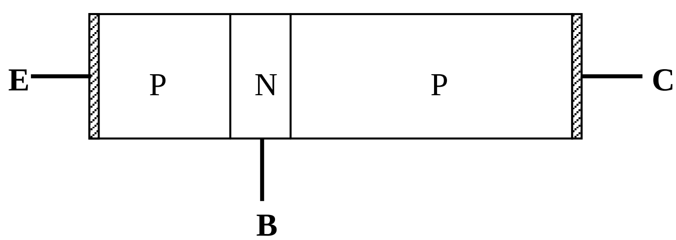
Bipolar Junction Transistors

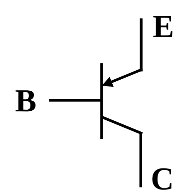
NPN transistor





PNP transistor





Actual NPN transistor