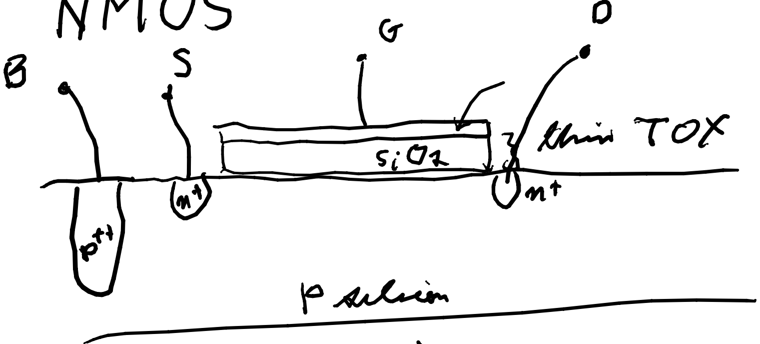
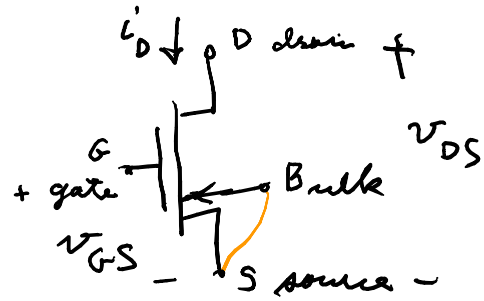
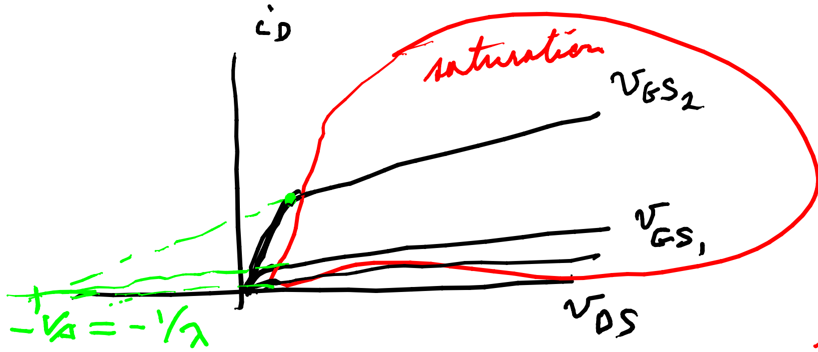
NMOS







if $v_{GS} < VTO$ then $i_D = 0$

In saturation, for $v_{GS} > VTO$ and $v_{DS} > (v_{GS} - VTO)$ (for saturation)

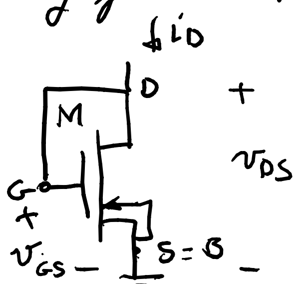
$$i_D = \frac{KP}{2} \cdot \frac{W}{L} \left(v_{GS} - VTO \right)^2 (1 + \lambda v_{DS})$$

In Ohmic (triode) region, for $v_{GS} > VTO$, $v_{GS} - VTO < v_{DS}$

$$i_D = \frac{KP}{2} \frac{W}{L} \left(2 (v_{GS} - VTO) v_{DS} - v_{DS}^2 \right) (1 + \lambda v_{DS})$$

Checks at $v_{DS} = v_{GS} - VTO$

These are key formulas



$VTO > 0$ for NMOS enhancement mode

$v_{GS} - VTO < v_{GS}$

here $v_{GS} = v_{DS}$

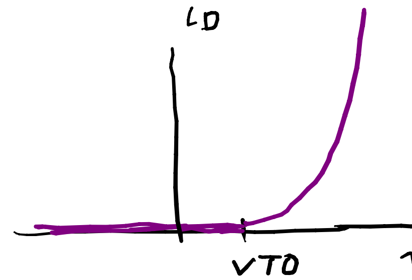
so $v_{GS} - VTO < v_{DS}$

here M is in saturation

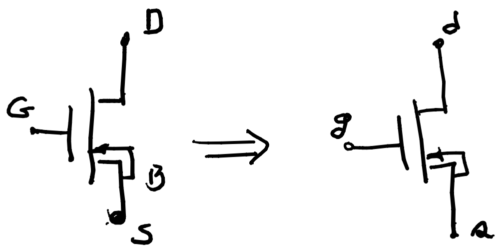
$$i_D = \frac{KP}{2}\frac{W}{L}(v_{GS}-VTO)^2(1+\lambda v_{GS})$$ give a cubic law

$$\approx \frac{KP}{2}\frac{W}{L}(v_{GS}-VTO)^2 \quad \text{if} \quad v_{GS} > VTO$$

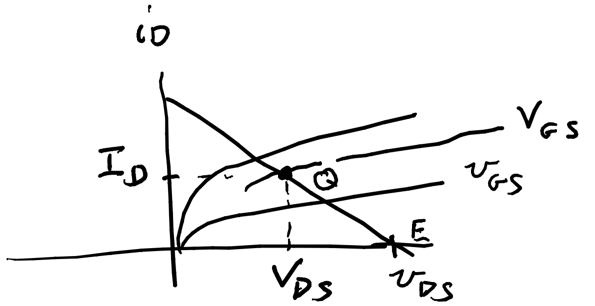
$(= 0$ if $v_{GS} \le VTO)$



$v_D = v_{GS} = v_{DS}$



small signal



$$i_{DS} = f(v_{GS}, v_{DS})$$

$$= \begin{cases} 0 & \text{if } v_{GS} < VTO \\ \frac{KP}{2}\frac{W}{L}(v_{GS}-VTO)^2 (1+\lambda v_{DS}) & v_{GS}-VTO < v_{DS} \\ \frac{KP}{2}\frac{W}{L}\left(2(v_{GS}-VTO)v_{DS} - v_{DS}^2\right)(1+\lambda v_{DS}) & \text{if } 0 < v_{DS} < v_{GS}-V_{TO} \end{cases}$$

$$i_{D\cancel{S}} = \overset{f(V_{GS},V_{DS})}{\overset{=}{I_{D\cancel{S}}}} + \left.\frac{\partial i_D}{\partial v_{GS}}\right|_Q (v_{GS}-V_{GS}) + \left.\frac{\partial i_D}{\partial v_{DS}}\right|_Q (v_{DS}-V_{DS}) + \left.\frac{1}{2}\frac{\partial^2 i_{DS}}{\partial v_{GS}\partial v_{DS}}\right|_Q (v_{GS}-V_{GS})(v_{DS}-V_{DS})$$

$$Q = \begin{bmatrix} v_{GS} = V_{GS} \\ v_{DS} = V_{DS} \end{bmatrix}$$

$$\underbrace{+ \ldots}_{\text{nonlinear terms}}$$

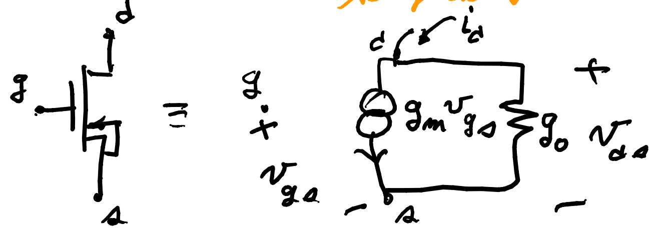
ignore for small signals

$i_d = i_D - I_D =$ signal drain current

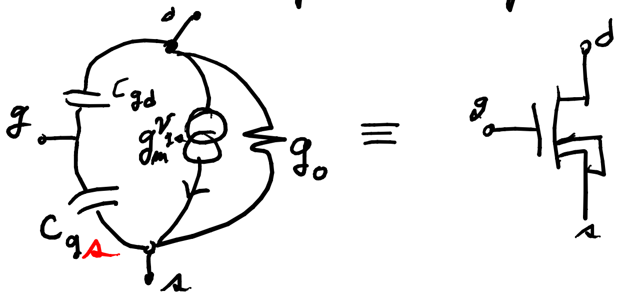
$=$ total $-$ bias ('' Q point)

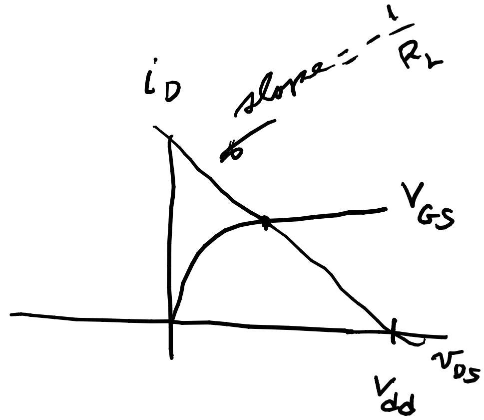
$$= \underbrace{\left.\frac{\partial i_D}{\partial v_{GS}}\right|_Q}_{g_m} v_{gs} + \underbrace{\left.\frac{\partial i_D}{\partial v_{DS}}\right|_Q}_{g_o} v_{ds}$$

$$i_d = g_m \cdot v_{gs} + g_o v_{ds}$$

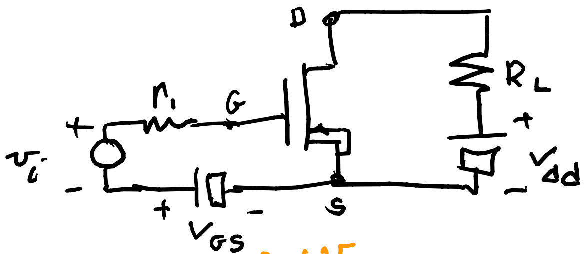


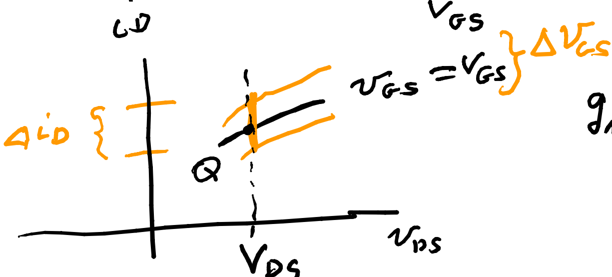
also have a capacitor for the gate



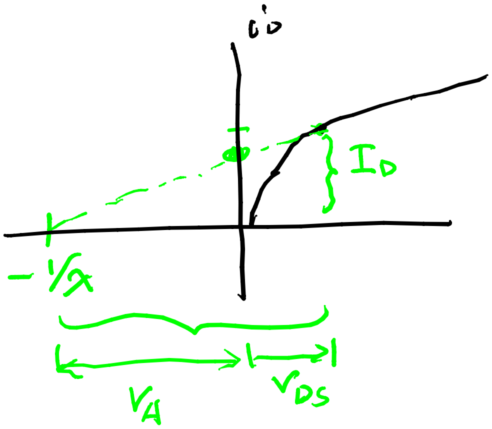


To use:





$$g_m = \left.\frac{\partial i_D}{\partial v_{GS}}\right|_{\substack{V_{DS} = v_{DS} = \text{constant} \\ \text{about } v_{GS} \approx V_{GS}}}$$



$$g_o = \left.\frac{\partial i_D}{\partial v_{DS}}\right|_Q$$

$$= \frac{I_D}{V_{DS} + V_A} \approx \frac{I_D}{V_A} = \lambda I_D$$

If in saturation

$$i_D = \frac{KP}{2}\frac{W}{L}(v_{GS} - VTO)^2(1 + \lambda v_{DS})$$

$$g_m = \left.\frac{KP}{2}\frac{W}{L} \cdot 2(v_{GS} - VTO)(1 + \lambda v_{DS})\right|_Q$$

$$= \frac{2 I_D}{V_{GS} - VTO}$$