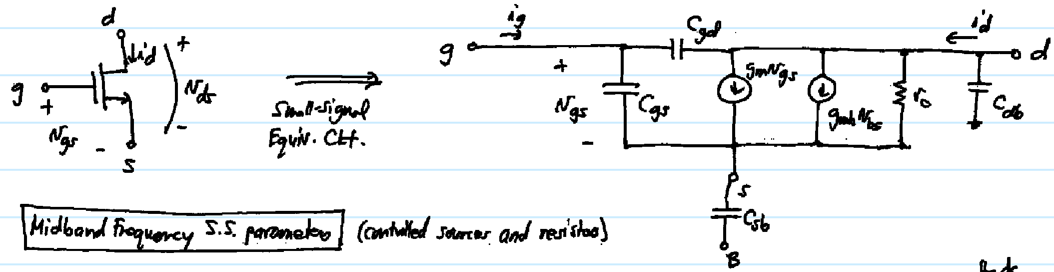
EE 140 | MOS Small-Signal Model | CTN | 18

**MOS Small-Signal Model** (for NMOS) → in saturation




**Midband Frequency S.S. parameters** (controlled sources and resistors)

Transconductance, $g_m$:

$$g_m = \frac{i_d}{v_{gs}} = \frac{\partial I_d}{\partial V_{gs}}\Big|_{Q\text{pt}} = \frac{\partial}{\partial V_{gs}}\left(\frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{gs}-V_{tn})^2\right)\Big|_{Q\text{pt}} = \mu_n C_{ox}\frac{W}{L}(V_{gs}-V_{tn})\Big|_{V_{gs}=V_{GS}}$$

(the dc $V_{GS}$)

$$\therefore \boxed{g_m = \mu_n C_{ox}\frac{W}{L}(V_{GS}-V_{tn}) = \sqrt{2\mu_n C_{ox}\frac{W}{L}I_D}}$$

$$\left[I_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS}-V_{tn})^2 \rightarrow (V_{GS}-V_{tn}) = \sqrt{\frac{2I_D}{\mu_n C_{ox}\frac{W}{L}}}\right]$$

$$\frac{i_d}{v_{bs}} = g_{mb} = -\frac{i_d}{v_{sb}} = -\frac{\partial I_d}{\partial V_{sb}}\Big|_{Q\text{pt}} = -\left(\frac{\partial I_d}{\partial V_{tn}}\cdot\frac{\partial V_{tn}}{\partial V_{sb}}\right)\Big|_{Q\text{pt}}$$

$$\frac{\partial I_d}{\partial V_{tn}}\Big|_{Q\text{pt}} = -\frac{\partial I_d}{\partial V_{gs}}\Big|_{Q\text{pt}} = -g_m \quad ; \quad \frac{\partial V_{tn}}{\partial V_{sb}}\Big|_{Q\text{pt}} = \frac{\partial}{\partial V_{sb}}\left[V_{t0} + \gamma\left(\sqrt{V_{sb}+2|\phi_p|} - \sqrt{2|\phi_p|}\right)\right]\Big|_{Q\text{pt}} = \boxed{\frac{\gamma}{2\sqrt{V_{SB}+2|\phi_p|}} = \eta}$$

$$\therefore \boxed{g_{mb} = \eta g_m}$$

← often neglected!

Note: $V_{SB}\uparrow \rightarrow V_T\uparrow \rightarrow \eta\downarrow \rightarrow I_d\downarrow$

↳ $g_{mb}$ is minimized by maximizing $V_{SB}$!

Output Resistance, $r_o$: $\left(=\frac{1}{g_{ds}}\right)$

$$\Rightarrow \text{output conductance} = g_{ds} = \frac{i_d}{v_{ds}} = \frac{\partial I_d}{\partial V_{ds}}\Big|_{Q\text{pt}} = \frac{\partial}{\partial V_{ds}}\left(\overbrace{\frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{gs}-V_{tn})^2}^{I_{dsat}}(1+\lambda V_{ds})\right)\Big|_{Q\text{pt}}$$

(explain what $\lambda$ is!)

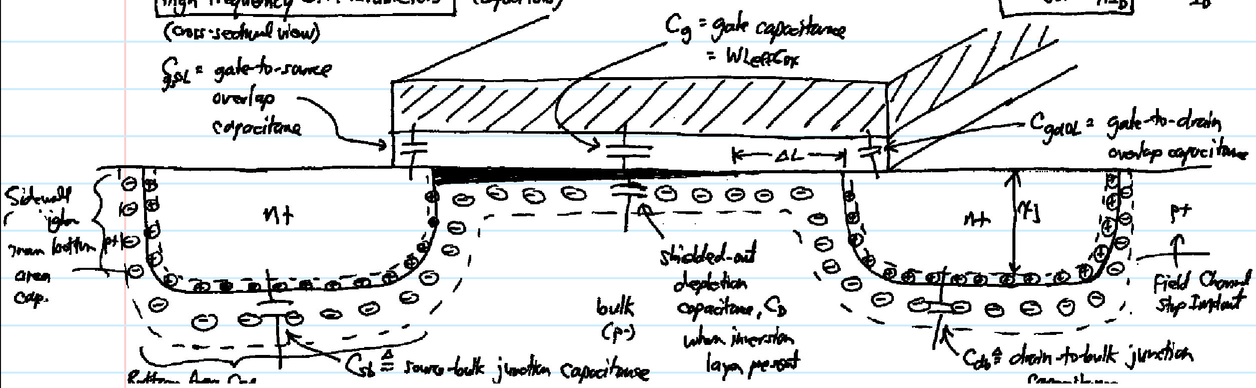
$$= \lambda I_{dsat} = \frac{\lambda I_D}{1+\lambda V_{DS}} \approx \lambda I_D = g_{ds}$$

$[1 \gg \lambda V_{DS}]$

$$\therefore \boxed{r_o = g_{ds}^{-1} = \frac{1}{\lambda I_D}} = \frac{\frac{1}{\lambda}+V_{DS}}{I_D}$$

(if $V_{DS}$ is very large)

**High Frequency S.S. Parameters** (capacitors)
(cross-sectional view)



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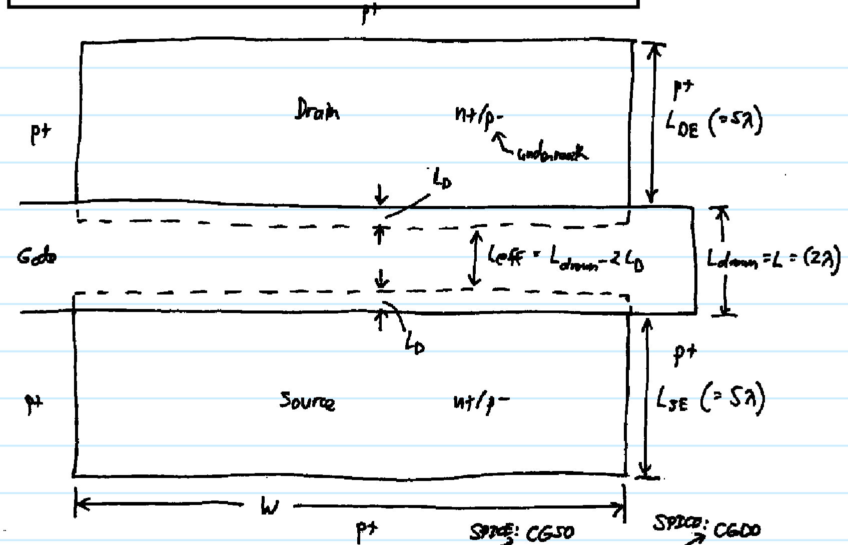
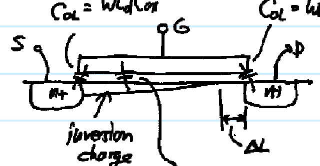
(layout view)




(still considering saturation region)

In saturation, the inversion charge is not present near the drain:




$\frac{2}{3}C_g = \frac{2}{3}WL_{eff}C_{ox}$ — obtained by integrating the charge over the gate length

Gate-to-Source Capacitor, $C_{gs}$:

$$C_{gs} = C_{OL} + \frac{2}{3}WL_{eff}C_{ox} \quad \text{(inversion charge integrated)}$$

Gate-to-Drain Capacitor, $C_{gd}$:

$$C_{gd} = C_{OL} \quad \text{(no inversion charge near the drain in saturation)}$$

Source/Drain Junction Capacitance, $C_{sb}$ & $C_{db}$: (must include these in SPICE simulations!)

⇒ there are depletion capacitors associated w/ the drain-to-bulk and source-to-bulk pn junctions

⇒ bottom-side capacitance per unit area is different from that at sidewalls due to higher bulk doping at the sidewalls (there is higher doping in the field areas to prevent channels from forming under interconnect wires)

⇒ take drain capacitance as an example:

$$C_{db} = \frac{C_{db0}}{\sqrt{1 + \frac{V_{DB}}{\phi_o}}}, \quad C_{db0} \triangleq \text{depletion capacitance with } V_{DB} = 0V$$

$$\left(\frac{q\epsilon_s N_A N_D}{2(N_A + N_D)\phi_o}\right)^{1/2}$$

$$= (\text{junction bottom-side area})\,C_{j0} + (\text{junction outside perimeter})\,C_{jsw}$$

$$= W(5\lambda)C_{j0} + (W + 2(5\lambda))C_{jsw}$$

SPICE: CJ

$C_{j0} = \sqrt{\frac{q\epsilon_s N_B}{2|\phi_j|}} \rightarrow \left(\frac{q\epsilon_s N_B}{2|\phi_j|}\right)^m$ — $N_B$: bulk doping level; m ≈ 2%?

depl. cap. per unit area @ bottom-side w/ $V_{SB} = 0V$

$C_{jsw}$: depletion cap. along sidewalls per unit length for $V_{DB} = 0V$

$$C_{jsw} = \sqrt{\frac{q\epsilon_s N_{cs}}{2|\phi_j|}} \times x_j \rightarrow \left(\frac{q\epsilon_s N_{cs}}{2|\phi_j|}\right)^m$$

$N_{cs}$: channel-stop implant doping level; $x_j$: S/D junction depth