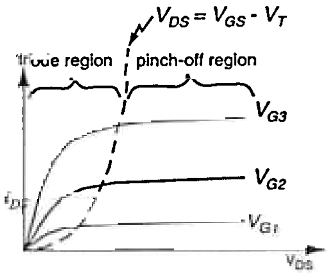
Transistor Characteristics (N Channel)



Simple Square Law Equations

Triode: $I_{DS} = k_p \frac{W}{L}\left(V_{GS} - V_T - \frac{V_{DS}}{2}\right)V_{DS}$ $\quad V_{DS} < V_{GS} - V_T$

Pinch Off: n: $I_{DS} = \frac{k_p}{2}\frac{W}{L}(V_{GS} - V_T)^2$ $\quad V_{DS} > V_{GS} - V_T$

(use $|V|$ for pmos) $\quad |I_{DS}|_p = \frac{k_{pp}}{2}\left(\frac{W}{L}\right)_p (|V_{GS}| - |V_T|)^2$

$K_{pn} = \frac{\mu_n \varepsilon_{ox}}{t_{ox}} = \mu_n C_{ox} \quad K_{pp} = \frac{\mu_p \varepsilon_{ox}}{t_{ox}} = \mu_p C_{ox}$

Channel Length Modulation slope factor λ: $\frac{\Delta i_d}{I_D} = \lambda \Delta v_d$, $\lambda \propto 1/L$.

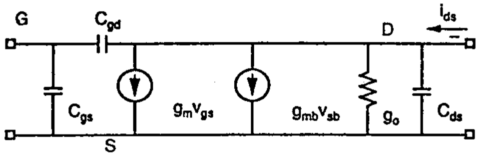
Transistor equations including channel length modulation:

Triode: $I_{DS} = K_P \frac{W}{L}\left(V_{GS} - V_T - \frac{V_{DS}}{2}\right)V_{DS}(1 + \lambda v_{DS})$ $\quad$ Pinch Off: $I_{DS} = \frac{K_P}{2}\frac{W}{L}(V_{GS} - V_T)^2(1 + \lambda v_{DS})$

Body Effect γ - nonzero V_{SB} changes the threshold voltage as:

$V_T = V_{T0} + \gamma[\sqrt{2|\phi_F| + V_{SB}} - \sqrt{2|\phi_F|}]$ typically $2|\phi_F| = 0.7$ V $\quad$ Result: threshold is increased

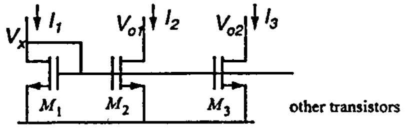
Small Signal Parameters in Pinch-Off

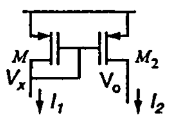


$g_m = \frac{di_{ds}}{dv_{gs}} = \sqrt{2k_p \frac{W}{L} I_{DS}} = k_p \frac{W}{L} v_{on}$

$g_o = I\lambda \quad \lambda \alpha \frac{1}{L}$

Diode Connection and Current Mirrors: Diode Connection: as M_1 below, connect drain and gate, hence $V_{DS} = V_{GS}$, if $V_{DS} > V_T$, then always in pinch off. Small signal model with $g = g_m + g_o$.





Cuurent Mirror: $I_2 = I_1$ if $V_{o1} = V_x$.Otherwise currents will not match exactly because of output impedance e.g., at V_{o1} it is given by r_o of M_2. Can increase by using cascode or other types of mirrors.

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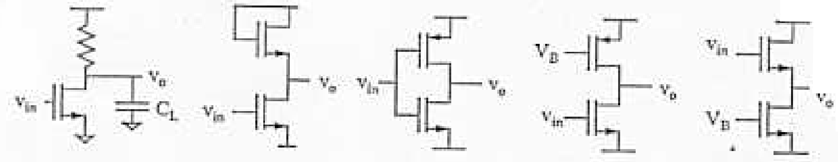
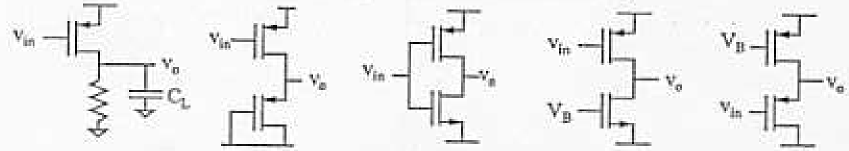
Gain Stages (Shown with NMOS Drivers)



Resistive Load | Diode Load | Digital Style | Current Source Load | Source Follower

$\frac{v_o}{v_{in}} = \frac{g_m}{g_L + g_{ds}}$ $\quad \frac{v_o}{v_{in}} = \frac{g_{m1}}{g_{m2} + g_{ds1} + g_{ds2}}$ $\quad \frac{v_o}{v_{in}} = \frac{g_{m1} + g_{m2}}{g_{ds1} + g_{ds2}}$ $\quad \frac{v_o}{v_{in}} = \frac{g_{m1}}{g_{ds1} + g_{ds2}}$ $\quad \frac{v_o}{v_{in}} = \frac{g_{m1}}{g_{m1} + g_{ds1}}$

Gain Stages (Shown with PMOS Drivers)

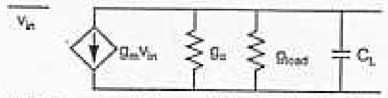


Resistive Load | Diode Load | Digital Style | Current Source Load | Source Follower

$\frac{v_o}{v_{in}} = \frac{g_m}{g_L + g_{ds}}$ $\quad \frac{v_o}{v_{in}} = \frac{g_{m1}}{g_{m2} + g_{ds1} + g_{ds2}}$ $\quad \frac{v_o}{v_{in}} = \frac{g_{m1} + g_{m2}}{g_{ds1} + g_{ds2}}$ $\quad \frac{v_o}{v_{in}} = \frac{g_{m1}}{g_{ds1} + g_{ds2}}$ $\quad \frac{v_o}{v_{in}} = \frac{g_{m1}}{g_{m1} + g_{ds1}}$

Small Signal Model

The gain of each, except for the last two is $\frac{g_m}{g_{eq}}$ where $g_{eq} = g_m + g_{load}$, and model is as below



where g_{load} and C_L are determined by the load

Digital Style

low frequency gain = $\frac{(g_{mn} + g_{mp})}{g_{eq}}$

Source Follower

low frequency gain = $\frac{g_m}{g_m + g_{eq}} \approx 1$

Slew Rate . Use current into capacitor, calculate $I = C\frac{\Delta v}{\Delta t}$ where $\frac{\Delta v}{\Delta t}$ is the slew rate.

Pole Frequency. $\omega_p = \frac{1}{r_{eq}C}$ $\quad$ where $r_{eq} = \frac{1}{g_{eq}}$ $\quad$ Unity Gain Bandwidth: $UGBW = \frac{g_m}{C_L}$

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