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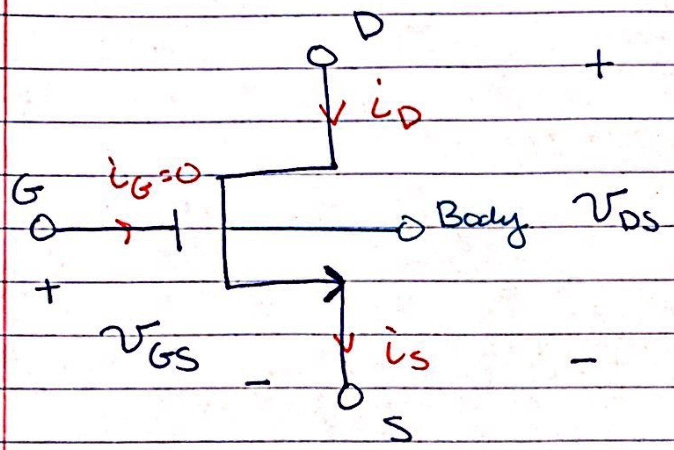
Circuits Eq. Sheet

Exam 2

- MOSFETS: NMOS ★ see MOSFET Eq. Summary



Symmetrical Device:

$i_D = i_S$

so: $i_G = 0$

$\mu_n C_{ox}$, $V_{tn} = V_t$

Triode:

① $v_{GS} > V_t$, v_{DS} is very small

$$i_D = k'_n \left(\frac{W}{L}\right)(v_{GS} - V_t)v_{DS}$$

$$r_{ds} = \frac{1}{k'_n \left(\frac{W}{L}\right)(v_{GS} - V_t)}$$

② $v_{GS} > V_t$, v_{DS} is small

$v_{DS} < (v_{GS} - V_t)$

$$i_D = k'_n \left(\frac{W}{L}\right)\left[(v_{GS} - V_t)v_{DS} - \frac{1}{2}v_{DS}^2\right]$$

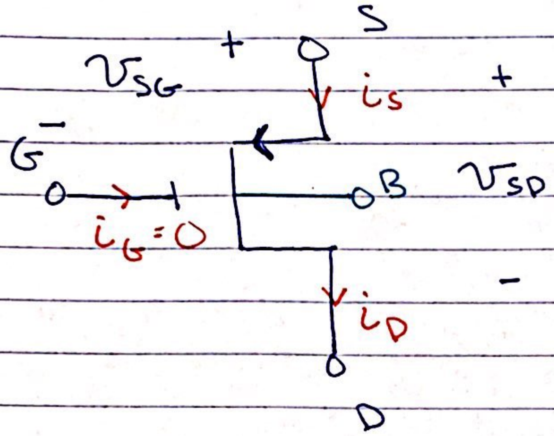
Saturation Region:

$v_{GS} > V_t$

$v_{DS} > v_{GS} - V_t$ → Edge at Saturation: $v_{DS} = v_{GS} - V_t$

$$i_D = \frac{1}{2}k'_n \left(\frac{W}{L}\right)(v_{GS} - V_t)^2$$

- MOSFETS: PMOS → also in MOSFET Eq. Summary



Symmetrical Device:

$i_D = i_S$

so: $i_G = 0$

$\mu_p C_{ox}$, $V_{tp} < 0$ so $|V_{tp}|$

Triode:

① $v_{SG} > |V_{tp}|$, v_{SD} is very small

$$i_D = k'_p \left(\frac{W}{L}\right)(v_{SG} - |V_{tp}|)\, v_{SD}$$

$$r_{ds} = \frac{1}{k'_p \left(\frac{W}{L}\right)(v_{SG} - |V_{tp}|)}$$

② $v_{SG} > V_t$, v_{SD} is small

$v_{SD} < v_{SG} - |V_{tp}|$

$$i_D = k'_p \left(\frac{W}{L}\right)\left[(v_{SG} - |V_{tp}|)\, v_{SD} - \frac{1}{2} v_{SD}^2\right]$$

Saturation:

$v_{SG} > |V_{tp}|$

Edge of saturation:

$v_{SD} \geq v_{SG} - |V_{tp}| \longrightarrow v_{SD} = v_{SG} - |V_{tp}|$

$$i_D = \frac{1}{2} k'_p \left(\frac{W}{L}\right)(v_{SG} - |V_{tp}|)^2$$

- **MOSFETS w/ Finite Output Resistance:**

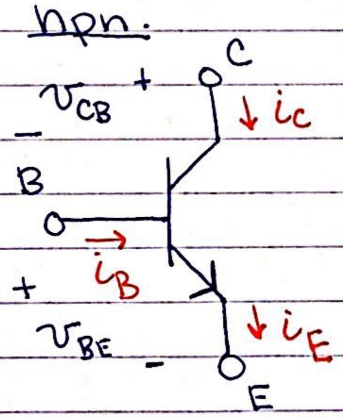
$\lambda \sim \frac{1}{L}$ $\quad\quad V_A = \frac{1}{\lambda}$

$r_o = \frac{V_A}{I_D} = \frac{1}{\lambda I_D}$ $\quad$ ★ Assume $\lambda = 0$ when no V_A, λ, or r_o values are given.

$$I_D = \underbrace{\frac{1}{2} k'_n \left(\frac{W}{L}\right)(v_{GS} - V_t)^2}_{\text{Original } I_D \text{ eq.}} (1 + \lambda v_{DS})$$

- **BJT Operation + DC Biasing:**

npn:



$i_c = I_s \exp\left(\frac{v_{BE}}{V_T}\right)$

$i_B = \frac{i_c}{\beta}$ $\quad\quad i_E = i_B + i_c$

$i_c = \alpha i_E$

$\beta = \frac{\alpha}{\alpha - 1}$ $\quad\quad \alpha = \frac{\beta}{\beta + 1}$

→ active: $v_{BE} > 0$ and $v_{CB} > -0.4V$

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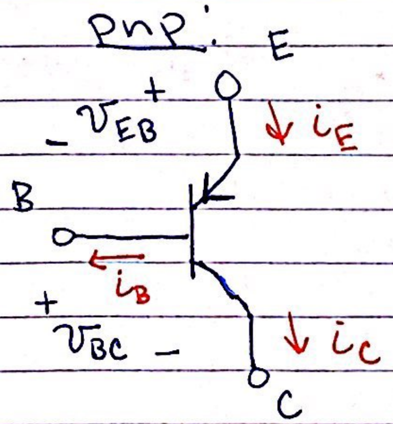
pnp:



$i_c = I_s \exp\left(\frac{v_{EB}}{V_T}\right)$

$i_E = i_c + i_B$ $\quad\quad i_B = \frac{i_c}{\beta}$

$i_c = \alpha i_E$ $\quad$ ★ α and β are same

active → $v_{EB} > 0$ and $v_{BC} > -0.4$

★ See Note on Diode Eq. →

- Forward Bias Eq.: (Came back from diodes)

→ These equations were used in the diode forward bias lectures and the BJT forward bias lecture.

★ Know how & when to use them.

General Forms:

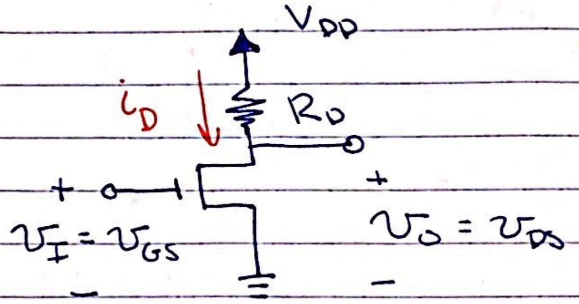
$$\frac{I_2}{I_1} = \exp\left(\frac{V_2 - V_1}{V_T}\right)$$

$$V_2 - V_1 = V_T \ln\left(\frac{I_2}{I_1}\right)$$

Example for BJT to find V_{BE2}:

$$V_{BE2} - V_{BE1} = V_T \ln\left(\frac{I_{C2}}{I_{C1}}\right)$$

- MOSFETS & Amplifiers



★ Know how we are using prev. MOSFET Eq.

Always true: (Ohm's Law)

$$i_D = \frac{V_{DD} - v_{DS}}{R_D}$$

combines w/ MOSFET eqs.

- Cutoff:

$v_{GS} < V_t$

$i_D = 0$

$v_{DS} = V_{DD}$

$$0 = \frac{V_{DD} - V_{DS}}{R_D}$$

$\Rightarrow v_{DS} = V_{DD}$

- Saturation: $(v_{DS} \geq v_{GS} - V_t)$

$$v_{DS} = V_{DD} - \underbrace{\tfrac{1}{2} R_D k'_n \left(\tfrac{W}{L}\right)(v_{GS} - V_t)^2}_{R_D i_D}$$

- Triode: $(v_{DS} < v_{GS} - V_t)$

$$v_{DS} = \frac{v_{GS}}{1 + R_D k'_n \left(\frac{W}{L}\right)(v_{GS} - V_t)}$$

max $v_{GS} = V_{DD}$

$$v_{DS} = \frac{V_{DD}}{1 + R_D k'_n \left(\frac{W}{L}\right)(V_{DD} - V_t)}$$

- Edge of Saturation:

$$v_{GS} = V_t + \frac{\sqrt{1 + 2\left(R_D k'_n \left(\frac{W}{L}\right) V_{DD}\right)} - 1}{R_D k'_n \left(\frac{W}{L}\right)}$$

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- MOS Amplifier Voltage Gain + the Q-Point:

$$v_{GS} = V_{GSQ} + v_{gs}(t)$$

$$v_{DS} = V_{DSQ} + v_{ds}(t)$$

$$i_D = \underbrace{I_{DQ}}_{\substack{\text{DC-bias} \\ \text{point} \\ \text{(Q-point)}}} + \underbrace{i_d(t)}_{\substack{\text{small} \\ \text{signal}}}$$

$$v_{ds} = A_v v_{gs}$$

A_v ← small signal volt. gain

$$A_v = -R_D \, k'_n \left(\frac{W}{L}\right)(V_{GSQ} - V_t)$$

* can pick resistors, transistors, and Q-point to get desired gain when designing.

- Small Signal Eq.:

$$i_d = k'_n \left(\frac{W}{L}\right)\left[v_{gs}(V_{GSQ} - V_t)\right]$$

$$g_m = \frac{i_d}{v_{gs}} = k'_n \left(\frac{W}{L}\right)(V_{GSQ} - V_t)$$

units $\left[\frac{A}{V}\right]$

$$A_v = -g_m R_D$$

reminder: $r_o = \frac{1}{\lambda I_{DQ}} = \frac{V_A}{I_{DQ}}$

* coupling capacitors act as open circuits to DC and as short circuits for AC.

- **MOS Amps:** * Combined w/ the small sig. eqs.

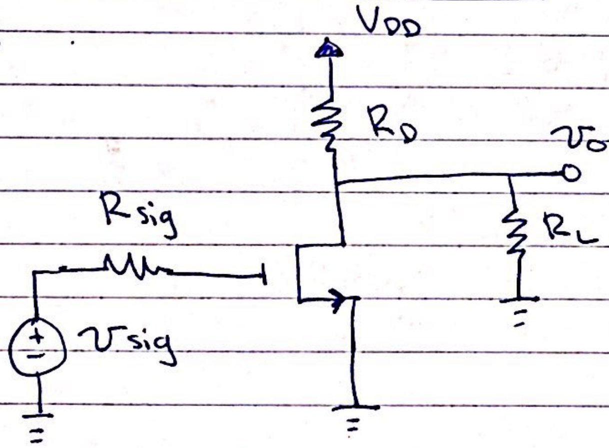
$$R_{in} = \frac{v_i}{i_i} \qquad v_i = \frac{R_{in}}{R_{in}+R_{sig}} \cdot v_{sig}$$

$$A_{v_o} = \left.\frac{v_o}{v_i}\right|_{R_L \to \infty} \qquad A_v = \frac{v_o}{v_i}$$

$$G_v = \frac{v_o}{v_{sig}}$$

- **Common Source Amp:** ("Source Grounded")

Given



so $v_i = v_{sig}$

$R_{in} = \infty \qquad i_i = 0$

$$R_o = R_D \| r_o$$

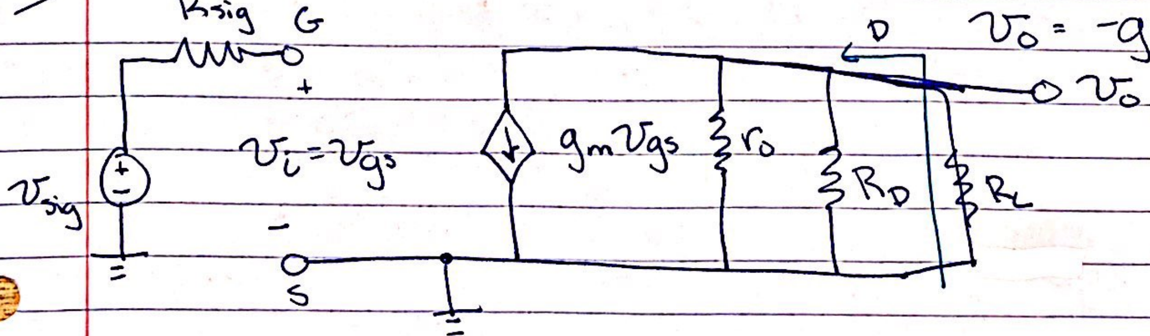
$$A_{v_o} = -g_m (r_o \| R_D)$$

$$A_v = -g_m (r_o \| R_D \| R_L)$$

$$G_v = -g_m (r_o \| R_D \| R_L)$$

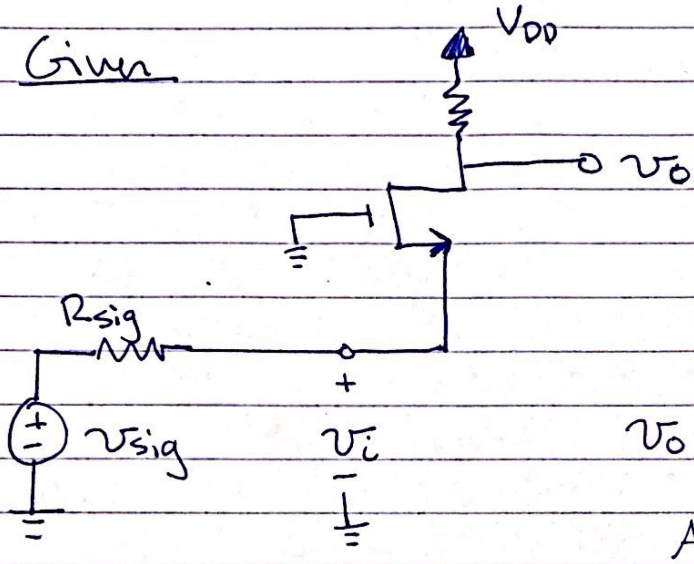
$$v_o = -g_m (v_i)(r_o \| R_D)$$

Hybrid-π



• Common Gate Amp: (gate grounded, v_i is @ source)

Given



$$R_{in} = 1/g_m$$

$$R_o = R_D$$

$$v_{gs} = -v_i$$

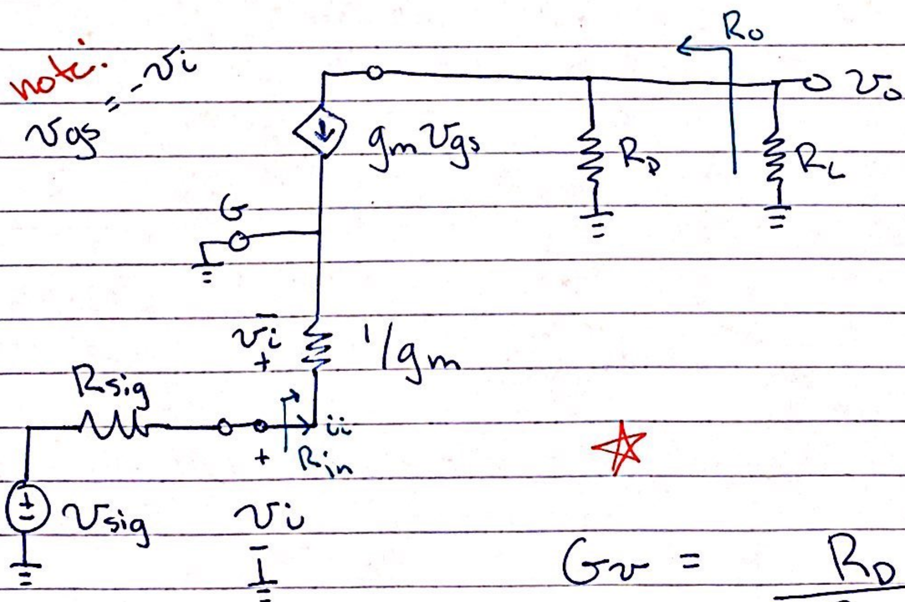
$$v_o = -g_m(R_D)(-v_i) = g_m R_D v_i$$

$$A_{vo} = g_m R_D$$

$$A_v = g_m(R_D \| R_L)$$

T-model

note: $v_{gs} = -v_i$



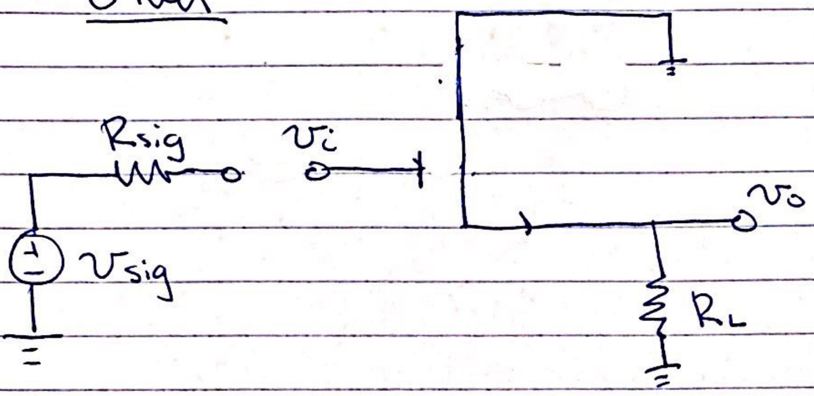
$$G_v = \frac{R_D \| R_L}{R_{sig} + 1/g_m}$$

or

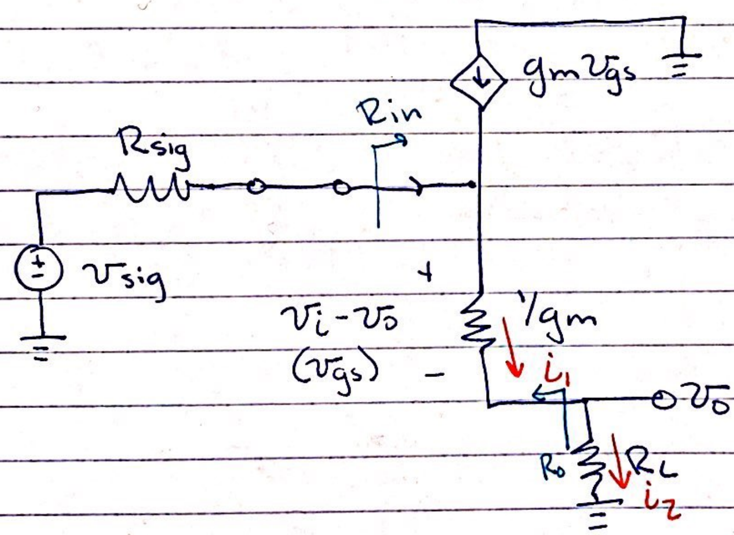
$$G_v = \frac{R_D \| R_L}{R_{sig} + R_{in}}$$

- Common Drain Amp: (voltage follower, v_i at gate)

Given



Model



$$i_1 = \frac{v_i - v_o}{1/g_m}$$

$$i_2 = \frac{v_o}{R_L}$$

$$i_1 = i_2$$

$R_{in} = \infty$

$R_o = 1/g_m$

$$A_{vo} = \left.\frac{v_o}{v_i}\right|_{R_L \to \infty} = 1$$

$$A_v = \frac{v_o}{v_i} = \frac{R_L}{R_L + 1/g_m}$$

$$G_v = \frac{v_o}{v_{sig}} = \frac{R_L}{R_L + 1/g_m}$$

if R_L is $\gg 1/g_m$ then $G_v \cong 1$