Circuits Cheat Sheet

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Exam 1

- ## Amplifiers
  - Gain

$$A_v = \frac{v_O}{v_I}\left(\frac{V}{V}\right) \quad A_i = \frac{i_O}{i_I}\left(\frac{A}{A}\right) \quad A_p = \frac{p_O}{p_I} = \frac{v_O i_O}{v_I i_I} \quad \left(\frac{W}{W}\right)$$

in dB

$$A_v \text{ or } A_i = 20 \log |A_{v \text{ or } i}|$$
$$A_p = 10 \log |A_p|$$

- Power Balance: ← dis. in amp.

$$P_{dc} + P_I = P_L + P_{loss}$$
$$\frac{P_L}{P_{dc}} \times 100 = \%\text{ efficiency}$$

- Standard Amp. (Amp. Models concept lec)

$$\frac{v_o}{v_i} = A_{vo}\left(\frac{R_L}{R_L+R_o}\right)\left(\frac{R_i}{R_s+R_i}\right)$$

- ## Ideal Op-Amps $v_O = A(v_+ - v_-)$

① Draws zero input current : $i_- = i_+ = 0\ A$
② v_O is not a func. of i_O : $R_o = 0$
③ Open loop gain is inf: $v_+ = v_-$
④ Inf. Common Mode Rejection: $v_o = 0$
⑤ Inf. Bandwidth: A is not a func. of freq.

- ## Non-Ideal Op-Amps (Finite A)

inverting: $$\frac{v_O}{v_I} = \frac{-R_2/R_1}{1 + \frac{1}{A}\left(1 + \frac{R_2}{R_1}\right)}$$

This is the one where you make tables

non-inverting: $$\frac{v_O}{v_I} = \frac{(1 + R_2/R_1)}{1 + \frac{1}{A}\left(1 + \frac{R_2}{R_1}\right)}$$

★ Know how to Draw all Op-Amp Configs.

★ Know how to solve w/ Pots or dividers

- Inverting Op-Amps

Closed Loop Gain:

$\frac{v_O}{v_I} = \frac{-R_2}{R_1} \rightarrow G = \frac{-R_2}{R_1}$

$R_i = \frac{v_I}{i_1} = R_1 \qquad R_O = 0$

$i_1 = \frac{v_I}{R_1}$

$i_2 = \frac{0 - v_O}{R_2}$

★ Know how to Design an Op-Amp → see ex. lec.

- Weighted Summer

$v_O = v_{O1} + v_{O2} + v_{O3}$

$v_O = -\frac{R_f}{R_1} v_1 - \frac{R_f}{R_2} v_2 - \frac{R_f}{R_3} v_3 \ldots$

$i_f = \frac{v_{O\,max}}{R_f}$ (?)

- Non-Inverting Op-Amps (Rev. V.S.P.)

$R_i = \frac{v_I}{i_I \to 0} = \infty \qquad R_O = 0$

$G = 1 + \frac{R_2}{R_1}$

- Voltage Follower:

$R_1 = \infty \qquad R_2 = 0 \qquad v_O = v_I$

Difference Amplifier:

$v_O = v_{O1} + v_{O2}$

$v_O = A_{cm} v_{Icm} + A_d v_{ID}$

$v_{O1} = \left(\frac{-R_2}{R_1}\right) v_{I1}$

$v_{O2} = \left(1 + \frac{R_2}{R_1}\right)\left(\frac{R_4}{R_3+R_4}\right) v_{I2}$

$v_{I1} = v_{ICM} - \frac{1}{2} v_{ID}$

ICM = common mode

$v_{I2} = v_{Icm} + \frac{1}{2} v_{ID}$

ID = differential

- Common Mode Rejection Ratio:

$$CMRR = 20 \log \left|\frac{A_d}{A_{cm}}\right| \quad (dB)$$

☆ if A_{cm} is zero (ideal) then $CMRR = \infty$.

$$A_{cm} = \frac{-R_2}{R_1} + \left(1 + \frac{R_2}{R_1}\right)\left(\frac{R_4}{R_3+R_4}\right)$$

$$A_d = \frac{1}{2}\left(\frac{R_2}{R_1} + \left(1 + \frac{R_2}{R_1}\right)\left(\frac{R_4}{R_3+R_4}\right)\right)$$

☆ When $A_{cm} = 0$:

$A_d = \frac{R_2}{R_1}$

$R_1 = R_3$

$R_2 = R_4$

When true $A_d = \frac{R_2}{R_1}$

$R_{id} = 2R_1$

☆ know how to solve when Rs have a ~~[illegible]~~ % tolerance.

- ## Instrumentation Amplifier

$$v_O = \frac{R_4}{R_3}\left(1 + \frac{R_2}{R_1}\right) v_{ID}$$

w/ R_2 mismatch:

$$\hookrightarrow v_O = \frac{R_4}{R_3}\left(1 + \frac{R_{2_1} + R_{2_2}}{R_1}\right) v_{ID}$$

$$v_{ID} = v_{I2} - v_{I1}$$

$$i_1 = \frac{v_{I1} - v_{O1}}{R_2}$$

★ Know how to solve w/ a pot.

$$i_2 = \frac{v_{I2} - v_{O2}}{R_2}$$

$$i_x = \frac{v_{ID}}{2R_1}$$

- ## IDEAL DIODES

OFF: Reverse Bias Region: $v < 0$, $i = 0$
↳ looks like an open circuit

ON: Forward Bias Region: $v > 0$, $i > 0$
↳ looks like a short circuit

→ Assume Diode state & solve to check.

★ Know how to read both types of circs.

- ## Forward Bias Diodes

$$V_T = \frac{kT}{q} \qquad V_T = 25\text{ mV (room temp.)}$$

$$k = 8.62 \times 10^{-5}\ eV/K$$

$$q = 1.6 \times 10^{-19}\ C$$

$$i \cong I_s \exp\left(\frac{v}{nV_T}\right)$$

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

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

- ## Modeling Diodes:

iterate: $I_D = \dfrac{V_{DD} - V_D}{R}$

constant drop: use ↑ w/ $V_D = 0.7$ unless told otherwise

ideal: solve w/ $V_D = 0$.

- ## Zener Diodes

$$V_Z = V_{Z0} + I_Z r_Z \quad \text{or} \quad V_{Z0} = V_Z - I_Z r_Z$$

$$\Delta V_O = \frac{r_z}{R + r_z}(\Delta V_S)$$

Circuits Eq. Sheet

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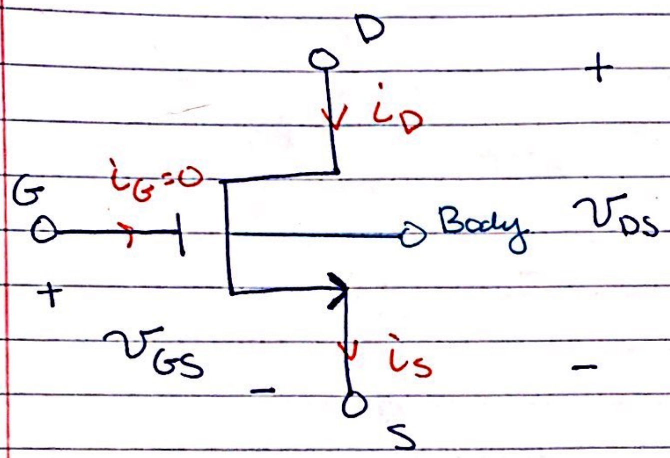
Exam 2

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

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

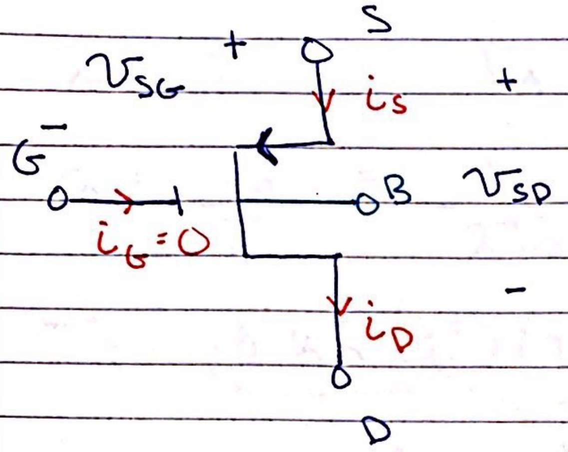
Saturation Region:

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

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

→ for I_{DQ}: $I_{DQ} = \frac{1}{2}k'_n \left(\frac{W}{L}\right)(v_{GSQ} - V_t)^2$

- 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:

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

$v_{SD} \geq v_{SG} - |V_{tp}| \longrightarrow$ Edge of saturation: $v_{SD} = v_{SG} - |V_{tp}|$

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

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

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

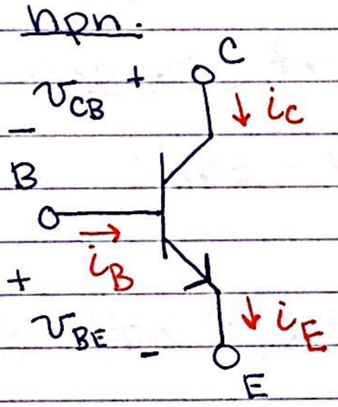
$$r_o = \frac{V_A}{I_D} = \frac{1}{\lambda I_D}$$

★ 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:



$$i_C = I_S \exp\left(\frac{v_{BE}}{V_T}\right)$$

$$i_B = \frac{i_C}{\beta} \qquad i_E = i_B + i_C$$

$$i_C = \alpha i_E$$

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

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

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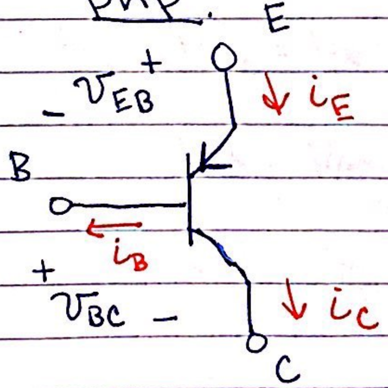
pnp:



$$i_C = I_S \exp\left(\frac{v_{EB}}{V_T}\right)$$

$$i_E = i_C + i_B \qquad i_B = \frac{i_C}{\beta}$$

$$i_C = \alpha i_E$$

★ 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 lectures.

★ 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}:

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

- Transition Equations

A: $V_{GS} = V_t$ $V_{DS} = V_{DD}$

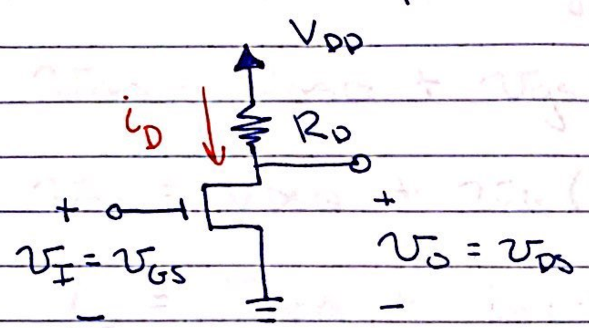
B: $V_{GS} = V_t + \dfrac{\sqrt{1 + 2R_D k'_n\left(\frac{W}{L}\right)V_{DD}} - 1}{R_D k'_n\left(\frac{W}{L}\right)}$

$V_{DS} = V_{GS} - V_t$

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

- 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: $v_{GS} < V_t$, $i_D = 0$, $v_{DS} = V_{DD}$ → $0 = \frac{V_{DD} - V_{DS}}{R_D}$ ⇒ $v_{DS} = V_{DD}$

- 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:

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

MOS Amplifier Voltage Gain + the Q-Point:

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

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

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

Finding Max v_i:

$V_{DSQ} - |A_v| v_i = V_{GSQ} + v_i - V_t$

↳ solve for v_i

comes from:

$v_{DS_{min}} = v_{GS_{max}} - V_t$

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

↳ 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.:

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

$g_m = \frac{i_d}{v_{gs}} = k'_n \left(\frac{W}{L}\right)(V_{GSQ} - V_t)$ 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 for DC and as short circuits for AC.

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

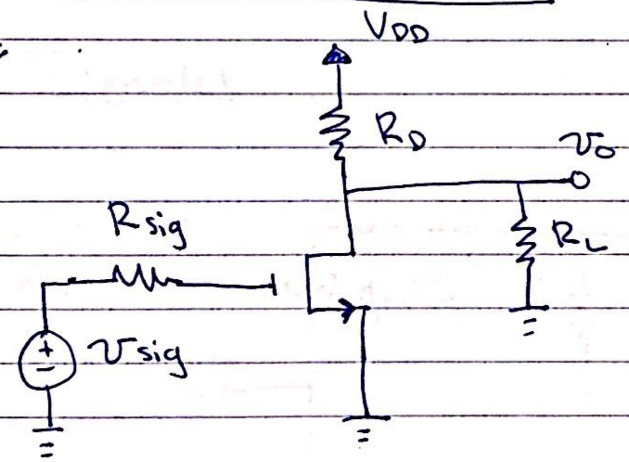
$$R_{in} = \frac{v_i}{i_i} \qquad v_i = \frac{R_{in}}{R_{in}+R_{sig}} \cdot v_{sig}$$

$$A_{vo} = \frac{v_o}{v_i}\Big|_{R_L \to \infty} \qquad A_v = \frac{v_o}{v_i}$$

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

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

Given



so $v_i = v_{sig}$

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

$$R_o = R_D \| r_o$$

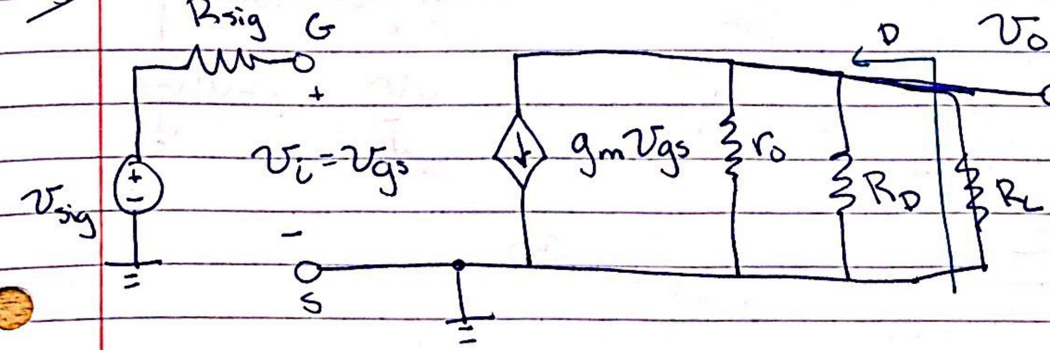
$$A_{vo} = -g_m (r_o \| R_D)$$

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

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

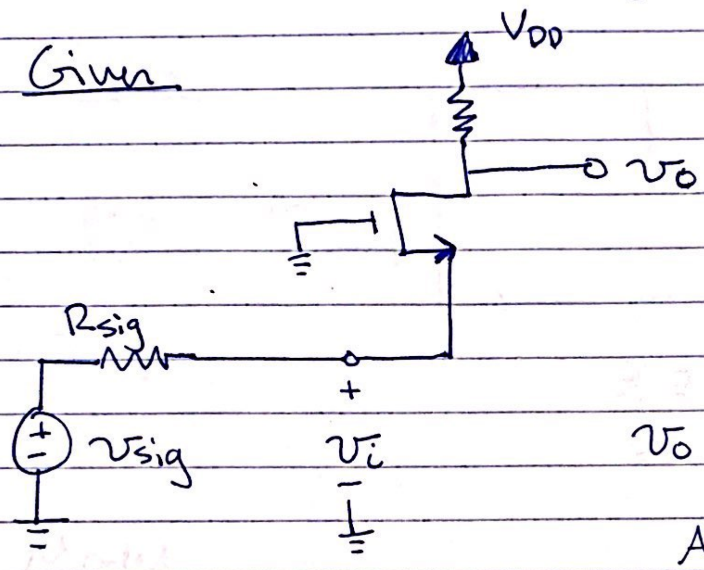
$$v_o = -g_m (v_i)(r_o \| R_D)$$

Hybrid-π



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

Given



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

$$R_o = R_D$$

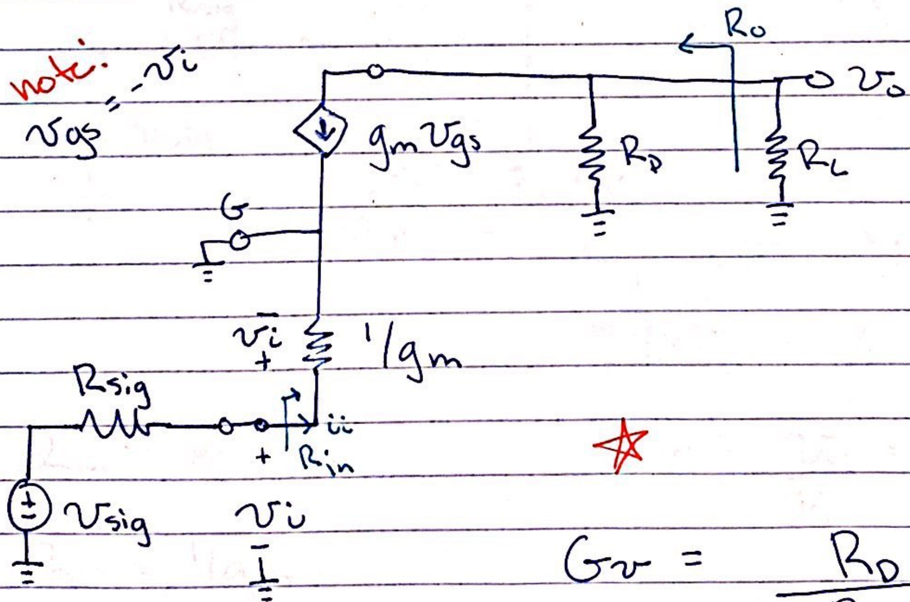
$$v_{gs} = -v_i$$

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

$$A_{vo} = g_m R_D$$

$$A_v = g_m(R_D \,//\, R_L)$$

T-model



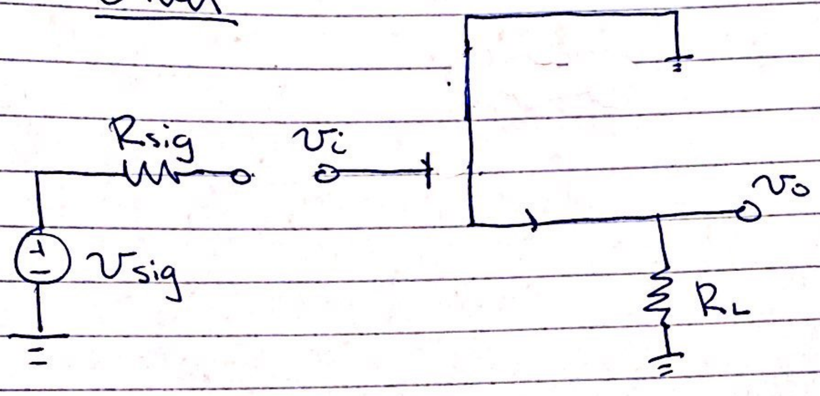
$$G_v = \frac{R_D \,//\, R_L}{R_{sig} + 1/g_m}$$

or

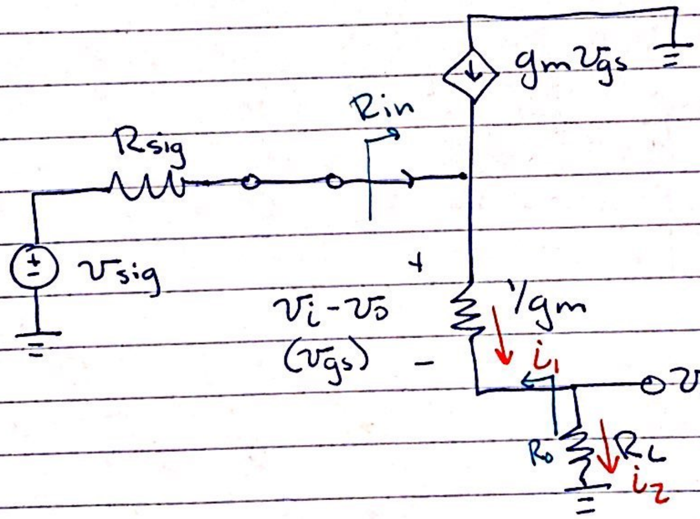
$$G_v = \frac{R_D \,//\, R_L}{R_{sig} + R_{in}}$$

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 $G_v \cong 1$

Scanned with CamScanner